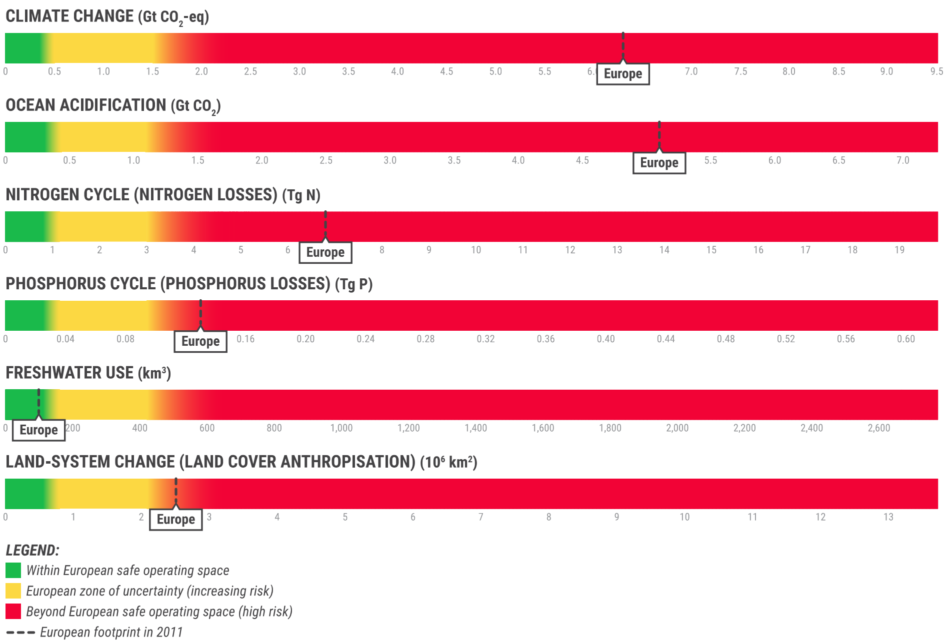
Assessment of environmental footprints at the European level based on the planetary boundaries framework.

Background report of the joint EEA/FOEN publication “Is Europe living within the limits of our planet?”



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Executive summary

Context and objectives

The Planetary Boundaries (PB) framework has attracted a large interest from policy makers, from researchers and from the business community. According to this framework, several global environmental limits are currently exceeded and this could severely affect humankind. In order to address these global environmental issues, several approaches are possible, among which considering them as environmental resources with a global limit (i.e. a maximum acceptable use). In order to be compatible with the principles of sustainable development, a reflexion on these global limits is required both in terms of efficiency and in terms of fairness. This means thinking not only about how to reduce current overshoots but also about how to allocate these global resources among human beings or among countries, on a yearly basis or over time.

The first objective of this report is to explore possible allocation strategies for sharing these global resources between people and countries. These allocation strategies are then operationalised and the European shares and limits are computed per PB.

The second objective of this report is to evaluate whether current European production and consumption patterns are compatible with global environmental limits. The European footprints are computed and the performance is evaluated by comparing them with the limits.

Exploration of possible allocation principles

Few allocation concepts have been applied to the Planetary Boundaries: (Nykvist et al., 2013; Hoff et al., 2014; Dao et al. 2015; Dao et al., 2018; Fang et al., 2015, Häyhä et al., 2016b, Sala et al., 2016; Lucas and Wilting 2018) and meta discussions have been conducted (Sabag, Gladek 2017). These studies provide initial insights on the allocation of Planetary Boundaries, but rarely build on a broad selection of allocation rationales. Climate change offers, on the contrary, a large number of examples of how equity and fairness notions can be implemented in international environmental policy.

We consider here six allocation principles. Three for an allocation to people (Equality, Needs, Rights to development) and three for an allocation to countries (Sovereignty, Capability and Responsibility).

Allocation principle	Description
A. Equality	People have equal rights to resources, resulting in an equal share per capita. Equality can be envisaged between people living in a particular year or between people over time.
B. Needs	People have differentiated 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.
C. Right to development	People have rights for 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 or contribute less to mitigation efforts in order to enable meeting development objectives.
D. Sovereignty	Excepted from engagements from international treaties, countries are managed based on internal policy rules. Countries have a legal right to use their own territory as they decide. 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 to 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 the mitigation efforts or use less than their allocated share of resource since their ability to pay is higher.
F. Responsibility	Countries have already used resources in the past. It is thus possible to consider a date in the past to compute the remaining current rights.
G. Cost-effectiveness **(not considered further in this report)**	Rather than considering rights or duties, an allocation can be based on economic objectives, e.g. the equalisation of the marginal costs of mitigation among countries, or on technical aspects. Reductions should focus in priority on countries or sectors with higher or more cost-effective potential for reduction.

The potential shares resulting from possible allocation principles are explored with several computation methods. While additional computations would have been possible, the ones proposed here provide a broad range of different shares for Europe and thus effectively represent different normative choices associated with the allocation of the global concept of Planetary Boundaries to the European scale.

European shares

Most current studies have mainly applied an equal share per capita. This approach leads, based on the EEA[1] member countries' share of world population, depending on the reference year assumed, to a share between 8.4% to 10.2%. Expanding this approach to an equal share over time leads to a share between 6.2% and 7.8%. These two approaches can be attributed to the "Equality principle" (A).

Taking the Equality principle (A) as starting point, the application of all other principles reduces the European share except when applying the principle of Sovereignty (i.e. an allocation based on the current situation). Considering an equal share per capita approach results in the second highest share for Europe.

Going beyond this approach and considering other principles like Needs (B), Rights to development (C), Capability (E) or Responsibility (F) would be more in line with the sustainable development concept and with the idea of "living well within the limits of our planet" (7th EAP). This is already implicitly accepted since the implicit commitments following the Paris agreement are close to an application of the Responsibility and Capability principles (Sheriff, 2016). Considering median values, this would mean a European share of 6.3% and 6.2% respectively (compared to 8.1% with the Equality principle). Another interesting principle is "Sovereignty" (D) which considers an allocation based on the current European share of global footprints or global GDP for example.

The results are considered robust enough for the purpose, i.e. to understand the possible range of European shares. These results have thus to be considered as estimates which are enough to understand the situation, but they do not represent "an absolute truth". In addition, due to the fact that the uncertainties of the global PB limits computed by Steffen et al. (2015) are much higher (for example a factor 10 for Phosphorus) than the uncertainties we are dealing with here when considering median values, the choice of a reference share for Europe is not the most critical aspect for the application of the Planetary Boundaries to Europe. It is thus, in our perspective, more a decision of an ethical or policy nature than a scientific one, hence the suggestion to consider a median value which can be perceived as a compromise.

[1] We consider the territory of EEA-33 region as a whole, i.e. the region defined by the 33 member countries of the European Environment Agency, which includes the 28 European Union Member States together with Iceland, Liechtenstein, Norway, Switzerland and Turkey.

	Principles & computation methods (nbr of scenarios)		Min European share	Average	Median	Max European share
Allocation to people	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. Equivalence between adults and children	1	----------------	----------------	9.2%	----------------
	4. Accessibility	2	3.3%	5.0%	5.0%	6.7%
	5. Nutrition	1	----------------	----------------	7.3%	----------------
	C. Rights to development	3	2.7%	4.1%	4.1%	5.1%
	6. Poverty line	1	----------------	----------------	5.1%	----------------
	7. Development level	2	2.7%	3.2%	3.2%	3.6%
Allocation to countries	D. Sovereignty	5	4.3%	11.4%	12.5%	21.0%
	8. Land	1	----------------	----------------	4.3%	----------------
	9. Bio-capacity	1	----------------	----------------	10.6%	----------------
	10. Economic throughput	2	11.2%	16.1%	16.1%	21.0%
	11. Grandfathering	1	----------------	----------------	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%
	F. Responsibility*	9	0.2%	5.8%	6.3%	8.4%
	14. Past emissions	3	5.7%	7.2%	7.5%	8.4%
	15. Past emissions & population over time	6	0.2%	4.3%	5.1%	7.3%
	All (climate change/ocean acidification)*	**36/33**	**0.2%**	**7.1%**	**6.8%**	**21.0%**
	All except Responsibility	**27**	**2.7%**	**7.3%**	**7.3%**	**21.0%**

* Can only be applied to Climate change and Ocean acidification since they are the only budgets over time

* The number of scenarios differs due to the start date: Climate change (1990), Ocean acidification (2005)

* Climate change considers a climate change scenario with a 2° increase with p>66% (IPCC AR5)

Several options are possible to set a reference European share. Setting a reference European share equivalent to the median share considering all principles (even if Responsibility is formally only applicable to Climate change and Ocean acidification) would result in a European share of 7.3%. The reference share would be slightly lower when not including the Responsibility principle: 6.8%. Another possibility would be to set the reference European share equivalent to the average of the range based on median values. It happens that this value represents the Equality principle (8.1%). Setting a 50% larger value would result in the maximum median value, Sovereignty (12.5%) while setting a 50% lower value would result in the minimum median value, Rights to development (4.1%).

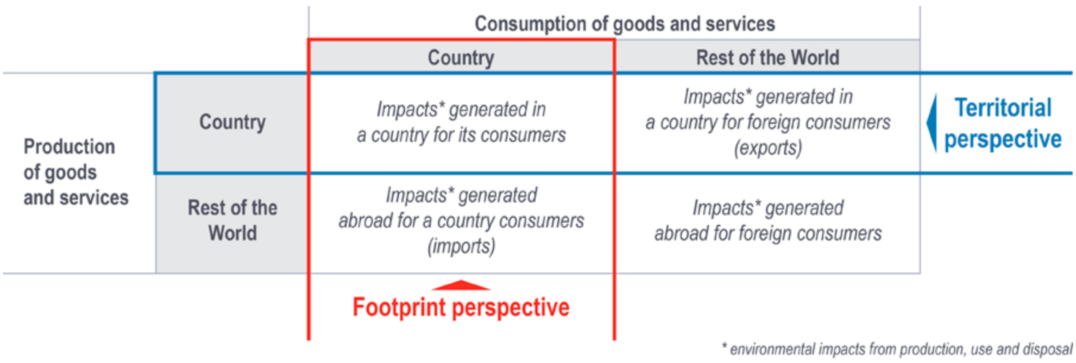
Evaluation of the compatibility of current European production and consumption patterns (footprints) with global environmental limits

In this report, we follow the proposal[2] of Steffen et al. (2015) and quantify five global limits for which data is available: Climate change, Ocean acidification, Land-system change, Biogeochemical flows (Phosphorus and Nitrogen, addressed separately in this report) and Freshwater use. Genetic diversity as part of Biosphere integrity is discussed (as a case study from Switzerland) but not quantified for Europe. We do not consider Novel entities, Functional diversity as part of Biosphere integrity and Atmospheric aerosol loading because there is currently no published global limit. In addition, we do not consider Stratospheric ozone depletion because it is already addressed with notable, if not complete success by the Montreal Protocol.

The methodology, indicators and limits are based on the report "Environmental limits and Swiss footprints based on Planetary Boundaries" (Dao et al. 2015). This method was later extended in the blueDot project (www.bluedot.world). Updates have been performed to consider the revision of the PB framework in Steffen et al. (2015) and the specificities of the database used to compute the footprints, i.e. Exiobase v.3.4 (Wood et al., 2015).

Footprint indicators are different from traditional territorial indicators at country level. Territorial indicators consider emissions or impacts occurring on the territory of a country, e.g. the domestic greenhouse gases emissions reported under the Kyoto Protocol. Footprint indicators aggregate environmental impacts and/or resource uses along global production-consumption chains according to a life cycle perspective. They allow quantifying the environmental impacts induced by the consumption of the inhabitants of a country wherever these impacts occur on Earth.

A footprint perspective is increasingly relevant in our interlinked global economy: due to a growing international trade, a rising part of the environmental impacts on a territory is generated to satisfy consumers in other countries. For many developed economies, more than half of the environmental impacts induced by their consumption are thus induced elsewhere in the world (Dao et al. 2015).



Global performance

Current global production and consumptions patterns are not compatible with long-term limits for four Planetary Boundaries as shown in Table 6 (adapted from Dao et al. (2018). Current production and consumption patterns (reference year 2011) are considered as *a high risk* with respect to Climate change and Ocean acidification. They are considered as *an increasing risk* with respect to Nitrogen losses and

[2] According to current knowledge and data, questions remain however to know if some of the physical global limits really exist (because the environmental phenomenon is occurring at regional scale). This is the case for three Planetary Boundaries: Atmospheric aerosol loading, Freshwater use and Novel entities. (Dao et al., 2015).

Phosphorus losses. They are however considered as *safe* with respect to Freshwater use and Land cover anthropisation. This does not however preclude local overconsumption of freshwater or land use.

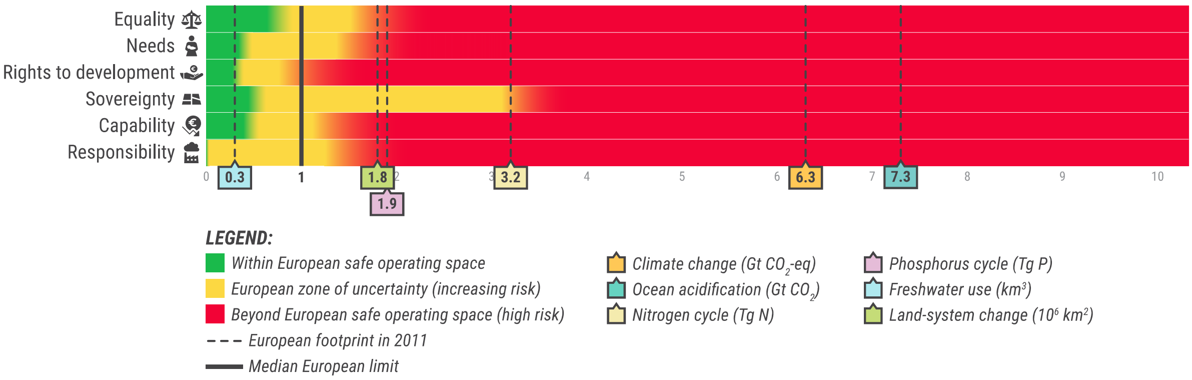
Such results are compatible with the ones proposed by Steffen et al. (2015). They differ however because the control variables differ, hence the limits. Steffen et al. (2015) use bio-physical control variables while we adopt a yearly perspective of current production and consumption patterns (PCP).

As a result, the overshoot is larger, in this report, for Climate change than in Steffen et al. (2015). In addition, Ocean acidification is also largely overshoot in this report while it is *safe* in Steffen et al. (2015). For both indicators, this is because current PCP produce a high level of emissions which is too high to stay within the long-term bio-physical limits set by Steffen et al. (2015). Nitrogen and Phosphorus overshoots are considered less critical in this report than in Steffen at al. (2015) since while they are clearly overshot they are however evolving slowly at global scale. The classification of Land-system change as *safe* differs from Steffen et al. (2015) because while the global footprint is close to the global limit, it is however evolving slowly at global scale. For Steffen et al. (2015), this PB is *an increasing risk*.

European performance

Climate change and Ocean acidification are clearly overshot in Europe as in the global situation. The European footprint for Nitrogen losses and Phosphorus losses are also larger than the computed median limits for Europe (like the global situation) except when considering the Sovereignty principle based on grandfathering (#11) and economic throughput (#10), i.e. an allocation based on the current European share of global footprints or global GDP. The situation is the same for Land cover anthropisation except that the result differs from the global limit which is not overshot. The European footprint for global Freshwater use is, as in the global situation, the only one which is not overshot.

The size of the European under/overshot for 2011 is shown for each PB in the figure below. In this table, the European limit, based on the median of the median values (6.8%), is set to 1 and the numbers indicate size of the under/overshot (e.g. 6.3 times the European limit for Climate change). Considering the latest available year for median values show a very similar picture except for Climate change and Ocean acidification, where the yearly European limit has been already reduced between 7% to 9%, respectively 8% to 12%, over the 2011 to 2015 period.



The large overshoots mean that European consumption and production patterns could not be scaled up to the globe without crossing planetary boundaries. Note that this evaluation does not consider regional boundaries but only global ones. Regional phosphorus and land use boundaries may thus be overshot. In addition, European consumption may be associated with regional freshwater overconsumption within or outside Europe. The regional patterns of the European land use, phosphorus and freshwater use footprints are however not analysed in this report.

Detailed results per Planetary Boundary

For *Climate change*, the performance is computed by comparing yearly GHG emissions (without land cover changes) with several world budgets corresponding to the remaining cumulative GHG emissions (including land cover changes) computed from IPCC (2013) and EGR (2015).

At European scale, applying a 2°C with p>66% climate change scenario and considering the median value for the allocation of the global limit to Europe, the yearly European limit is between 1.0 and 2.3 Gt CO_2-eq (1.7 and 3.8 t CO_2-eq per capita respectively) (depending on the time horizon). The computed European footprint for 2011 is larger (6.3 Gt CO_2-eq or 10.5 t CO_2-eq per capita). This means that current European production and consumption patterns are not compatible with the global limit in the long run. This conclusion is valid for all allocation principles. The trend of the European footprint over the period 1995-2011 is almost flat (+ 1.9%). The European budget of GHG emissions (89.2 Gt CO2-eq, for the median scenario from IPCC (2°, p > 66% (IPCC, AR5) corresponds to (in 2011) 14/27 years of emissions (until 2026/2038) at the 2011 European yearly emissions rate followed by zero emissions from then on. It is however sustainable, i.e. in line with the Planetary Boundaries, with an ongoing yearly reduction of 7%.

For *Ocean acidification*, the performance is computed by comparing CO_2 emissions with the world budget corresponding to the remaining cumulative emissions of carbon dioxide (CO_2) from human activities to maintain an acceptable calcium carbonate saturation state Ω (2.75 Ω arag), computed from IPCC data. The European yearly limit is overshot and current European production and consumption patterns are not compatible with the global limit in the long run. Between 0.7 and 1.7 Gt CO_2 using median values for the allocation (1.2 – 2.8 t CO_2 per capita), it is smaller than the European footprint (2011) which is equivalent to 5.1 Gt CO_2 (8.5 t CO_2 per capita). The trend of the European footprint over the period 1995-2011 is almost flat (+ 0.9%). The European budget of CO_2 emissions (median value equivalent to 68.1 Gt CO_2) corresponds to (in 2011) 14/less than 24 years of emissions (until 2025/2035) at the 2011 European yearly emissions rate, followed by zero emissions from 2026 on. It is however sustainable, i.e. in line with the Planetary Boundaries, with an ongoing yearly reduction of 7%.

For *Biogeochemical flows (Nitrogen)*, the performance is computed in terms of nitrogen losses from agriculture considering both leaching to water and NH_3 air releases. The yearly European limit (2011) is overshot. Estimated at 2.1 Tg N using the median value for the allocation (3.5 kg N per capita), it is smaller than the European footprint (2011) which is equivalent to 6.8 Tg N (11.4 kg N per capita). The European overshoot is thus proportionally larger than the global overshoot. The trend of the European footprint over the period 1995-2011 is slightly positive (+ 4.3%).

For *Biogeochemical flows (Phosphorus)*, the performance is computed in terms of phosphorus losses from agricultural activities and urban wastewater. The yearly European limit (2011) is overshot. Estimated at 0.07 Tg based on the median value for the allocation (0.11 kg P per capita), it is smaller than the European footprint which is equal to 0.13 Tg P (0.23 kg P per capita). The European overshoot is thus very similar to the global overshoot: using median values, Europe exceeds the limit by a factor 2. The trend of the European footprint over the period 1995-2011 is negative (- 15.4%).

For *Freshwater use*, the performance is computed in terms of blue water consumption from socio-economic activities. The yearly European limit (2011) is not overshot. Estimated at 291 km^3 (488 m^3 per capita) using the median value for the allocation, it is larger than the European footprint (2011) which is equivalent to 99 km^3 (167 m^3 per capita). The European situation is thus very similar to the global situation (almost three times under the limit). The trend of the European footprint over the period 1995-2011 show an important increase (+25.3%).

For *Land-system change*, the performance is computed in terms of 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. The European limit is overshot while the global limit is not. Estimated at 1.4 million km^2 (2'364 m^2 per capita) using the median value for the allocation, it is smaller than the European footprint (2011) which is equivalent to 2.5 10^6 km^2 (4'150 m^2 per capita). The European situation is thus totally different from the global situation since there is an overshoot. Using median values, Europe exceeds the limit by a factor 1.8. The trend of the European footprint over the period 1995-2011 is almost flat (+ 1.3%).

Conclusion

This proposal seems adequate to consider the possible range of European shares. It should be noted that since this range is much lower than the uncertainty with respect to the evaluation of the limits of the Planetary Boundaries by Steffen et al. (2015). The main messages related to the choice of a reference share are thus of ethical and policy nature.

The current global footprints using Exiobase yield similar results than in the previous studies by Dao et al. (2015 and 2018) and in the blueDot project. Differences can be explained by the use of another dataset or the inclusion of better data and knowledge to compute the global limits (for Nitrogen and Phosphorus losses). While not all environmental aspects are considered within Exiobase (e.g. no consideration of land use changes for climate change), we believe that the provided results are robust enough to be used. They enable showing the interest of considering global issues beyond climate change and the role of Europe in terms of impacts in the rest of the world. The overall finding is in line with recent assessments[3]: Häyhä et al. (2018) for example stated that "based on equal-per capita allocation of the global safe operating space, the EU does not appear to be "living within the limits of our planet" for most of the boundaries analysed, and that from a consumption-based (footprint) perspective, Europe's per-capita contribution to the different PBs is significantly higher than the global average.

While approximations had to be performed to generate limits and footprints (related to socio-economic activities), they are in line with current practices in this field and in accordance with the current status of scientific developments in this area. However further research is needed. Further work is particularly needed to generate results for Biodiversity and to improve the evaluation of Phosphorus losses. The European performance is influenced by the choice of an allocation method. Based on median values computed in this report, Climate change, Ocean acidification, Nitrogen losses and Phosphorus losses are overshot in 2011 at global scale and for Europe. Land cover anthropisation is overshot for Europe but not for the world. Freshwater use is not overshot.

A need for action

The Planetary Boundaries framework has come to light for a reason: the extent of human activities and their impacts on the environment are increasing faster than ever due to the large increases in global population and global wealth of the last decades.

The Planetary Boundaries framework and this report confirm some common knowledge with respect to climate change: it is a key issue and should be tackled in priority. In addition, this report show (as in Dao et al. (2018)) that ocean acidification is also a critical issue that should be tackled in priority since this limit is at risk of being overshot even more rapidly than climate change. Furthermore, there is an increasing need for action on nitrogen and phosphorus footprints.

In order to contribute to staying within a safe operating space, the European footprint should thus be reduced, in priority, by a factor 3 to 6 for Climate change and 3 to 7 for Ocean acidification. Then, as a second priority (because the evolution is less rapid at global scale), the European footprint should be reduced by a factor 3 for Nitrogen losses and 2 for Phosphorus losses. A reduction by almost 2 would also be needed for Land cover anthropisation but it is less of a priority since there is not global overshoot. Based on the Planetary Boundaries framework, there is no reduction needed for Freshwater Use. These results consider however only global issues and do not preclude that there are not regional issues which should be also considered.

The magnitude of the need for action is huge. Postponing action would be a risky option. The longer we wait, the smaller the remaining budget. Furthermore, given that transitions take time, and that future

[3] see e.g. Lucas and Wilting (2018)

possibilities depend on paths taken in the past, even small steps in an early stage may be crucial for achieving ambitious goals. In order to transform current unsustainable consumption and production patterns to patterns that are in line with planetary boundaries, a combined effort of companies, governments, research and civil society is necessary (see e.g. Sabag Muñoz, Gladek (2017)). Such transformation processes are complex and should be simultaneously addressed at multiple levels, using various governance styles at different stages (see e.g. EEA (2017)).

In the light of the heterogeneity of possible allocation approaches we see the need for a public dialogue both within countries and between countries on how to share burdens, roles and responsibilities in implementing the UN Agenda 2030. In addition to the public dialogue a dialogue among experts is needed as well. In addition to quantitative aspects, the latter should also deal with normative (ethical and juristic) aspects of the allocation principles and what they mean for implementation. While such decisions are in the end political, clarifications on their normative foundations would, indeed, clarify the debate.

1 Introduction

1.1 Purpose of the report

The Planetary Boundaries (PB) framework has attracted a large interest from policy makers, from researchers and from the business community. According to this framework, several global environmental limits are currently exceeded and this could severely affect humankind. In order to address these global environmental issues, several approaches are possible, among which considering them as environmental resources with a global limit (i.e. a maximum acceptable use). In order to be compatible with the principles of sustainable development, a reflexion on these global limits is required both in terms of efficiency and in terms of fairness. This means thinking not only about how to reduce current overshoots but also about how to allocate these global resources among human beings or among countries, on a yearly basis or over time.

The first objective of this report is to explore possible allocation strategies for sharing these global resources between people and countries. These allocation strategies are then operationalised and the European shares and limits are computed per PB.

The second objective of this report is to evaluate whether current European production and consumption patterns are compatible with global environmental limits. The European footprints are computed and the performance is evaluated by comparing them with the limits.

The third objective is to ease the understanding of and communication of the PB framework, its challenges and performances. Several visualisations are proposed, targeting different public and objectives.

1.2 Background

This report is the intermediary outcome of the joint EEA-FOEN[4] project "Assessment of environmental footprints at the European level based on planetary boundaries" financed by the FOEN. This project is the second phase of the collaboration between the two agencies on this topic and aims at providing inputs to the upcoming European State of the Environment Report SOER 2020.

This report builds and expands on the approach developed for the study "Environmental limits and Swiss footprints based on Planetary Boundaries" commissioned by the FOEN in 2015 to the authors of this report (Dao et al., 2015; Dao et al., 2018).

[4] FOEN: Swiss Federal Office for the Environment

1.3 Report content

In the second chapter of this report, we briefly describe the Planetary Boundaries framework and the need to consider the drivers of the bio-physical indicators proposed by Rockström et al. (2009) and by Steffen et al. (2015). Then, we explore possible allocation approaches for sharing the global PB limits between people and regions. In Chapter 3, we cover theoretical aspects (sharing logics and allocation principles) and operational ones (computation methods). In Chapter 4, we implement a selection of computations methods and analyse the resulting European shares. The range of possible shares is described with statistical values. The current European limits, footprints and performances are presented in Chapter 5. In Chapter 6, we briefly explore regional limits (Steffen et al., 2015) and the possible improvements of the footprint's metric by using regional data from the EEA.

When speaking of Europe in this report, we mean the combined territory of the 33 member countries of the European Environment Agency (EEA), including Switzerland.[5] Results for EU-28 are also summarised in Appendix 3.

[5] Limits are provided for the EEA-33 region as a whole, which includes the 28 European Union Member States together with Iceland, Liechtenstein, Norway, Switzerland and Turkey. Due to a lack of country-specific data, the calculated footprints however do not include Iceland and Liechtenstein. Their additional contribution can however be estimated to be small due to their very low share of the European population (0.06%).

2 Planetary Boundaries: an overview

2.1 Definition

The Planetary Boundaries are a set of nine bio-physical limits of the Earth system that should be respected in order to maintain conditions favourable to further human development. Rockström et al. (2009) and Steffen et al. (2015) suggest that crossing the suggested limits could lead to a drastic change in human societies by disrupting some of the ecological bases underlying the current socio-economic system.

The best-known global limit is Climate change but other global limits have been identified (Figure 1). Steffen et al. (2015) identify three global limits beyond the zone of uncertainty (high risk): Nitrogen, Phosphorus (both part of Biogeochemical flows) and Genetic diversity (part of Biosphere Integrity). Two are in the zone of uncertainty (increasing risk): Land-system change and Climate change. Three are below boundary (safe): Freshwater use, Ocean acidification and Stratospheric ozone depletion. The last three a not quantified yet: Functional diversity (part of Biosphere integrity), Novel entities and Atmospheric aerosol loading.

In addition, for three boundaries (Phosphorus, Freshwater use and Atmospheric aerosol loading), regional limits are also proposed.

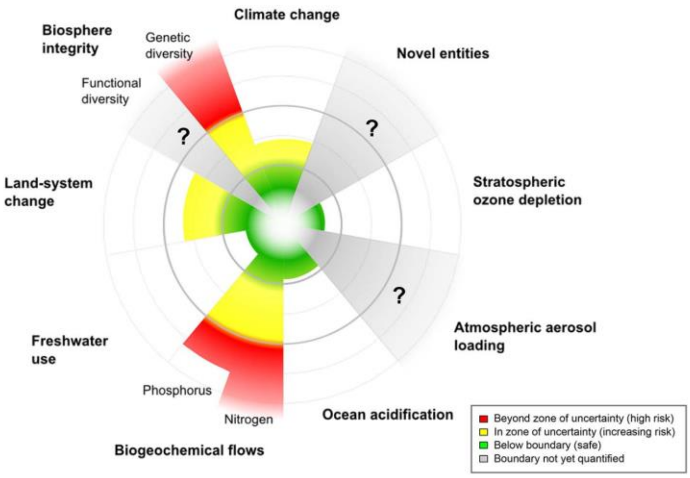


Figure 1. Global status of the Planetary Boundaries in terms of bio-physical indicators. (Steffen et al., 2015).

Due the large number of discussions about the Planetary Boundaries framework, it is to be expected that changes to the framework will be again proposed in the future, particularly with respect to the control variables and the setting of their thresholds. This is mainly due to two reasons:

- First, there is currently no scientific evidence of the magnitude of the impact for some of the issues, e.g. biosphere integrity for which there is a large consensus on the rapid rate of change but few assessments of its consequences. In addition, while some (Barnosky et al. 2012) assume that a planetary-scale tipping point of the biosphere is plausible, it is however still a matter of intense research to find suitable indicators and to set limits for biodiversity from a functional perspective (Huitric et al. 2010).
- Second, as mentioned in Dao et al. (2018), Planetary Boundaries cover phenomena with varying spatial scopes. Applying a classification based on physical/biological aspects (unrelated to policy), some of the environmental aspects considered can be qualified as phenomena with a global scope while some other phenomena are rather local or regional in scope (the local/regional conditions play a key role in the assessment of the environmental issue). An example of the first type is climate change because it is the total amount of greenhouse gas emissions that is important, not the location of emissions. An example of the second type is freshwater use.

Rockström et al. (2009b) classify the Planetary Boundaries according to the scale of their process and their character, resulting in four groups shown in Figure 2.

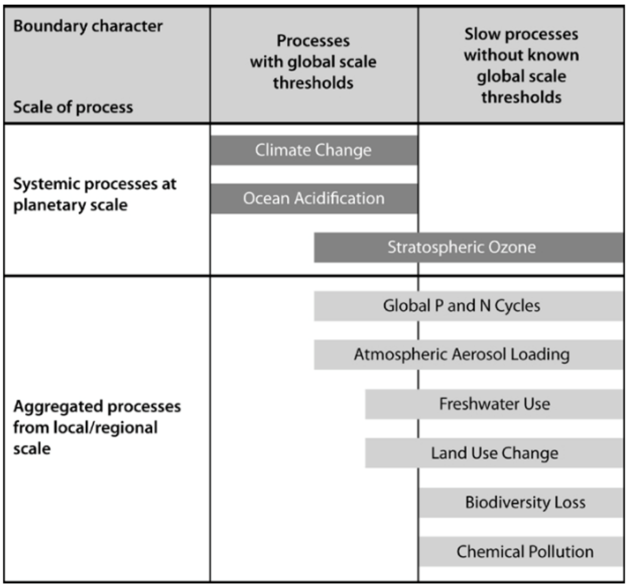


Figure 2 Categories of Planetary Boundaries (Rockström et al., 2009b)

To better consider the aggregated processes from local/regional scale and to avoid 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 thus to complement the global limits with sub-global limits for five PB: Functional diversity (as part of Biosphere integrity), Phosphorus (as part of Biogeochemical flows), Land-system change, Freshwater use and Atmospheric aerosol loading.

In this report, we follow the proposal from Steffen et al. (2015) and quantify five global limits for which data is available[6]: Climate change, Ocean acidification, Land-system change, Biogeochemical flows (Phosphorus, Nitrogen, addressed separately in this report) and Freshwater use. Genetic diversity (part of Biosphere integrity) is discussed as a case study from Switzerland but not quantified for Europe. We do not consider Novel entities, Functional diversity (part of Biosphere integrity) and Atmospheric aerosol loading because there is currently no published global limit. In addition, we do not consider Stratospheric ozone depletion because it is already addressed with notable, if not complete, success by the Montreal Protocol. Sub-global limits are not evaluated but discussed in Chapter 6.

2.2 Selection of indicators

The control variables proposed by Steffen et al. (2015) are bio-physical, e.g. the atmospheric CO_2 concentration for climate change. In this study, we focus on the drivers of these control variables, e.g. on the greenhouse gas (GHG) emissions inducing climate change. In this way, it is possible to evaluate the compatibility of the yearly European production and consumption patterns (i.e. footprints) with a yearly theoretical amount of resources allocated to Europe to guaranty the compatibility with the long-term bio-physical limits.

As in Dao et al. (2018), the names of the indicators in this report are thus different from the ones proposed by Rockström et al. (2009) and by Steffen et al. (2015) in order to represent this change of

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[6] According to current knowledge and data, questions remains however to know if some of the global limit really exist (because the environmental phenomena are occurring at regional scale). This is the case for one considered PB (Freshwater use) and two PB not considered in this report (Atmospheric aerosol loading and Novel entities). (Dao et al., 2015).

perspective. The computed global performances are thus also different from the performances in Rockström et al. (2009) and in Steffen et al. (2015). Due to the use of different data sources and an updated methodology, numbers are also different from Dao et al. (2018) (see Chapter 5.3 for an overview of results).

3 Approaches for allocating the Planetary Boundaries to countries/regions

Few allocation concepts have been applied to the Planetary Boundaries: (Nykvist et al., 2013; Hoff, et al., 2014; Dao et al., 2015; Dao et al., 2018; Fang et al., 2015, Häyhä et al., 2016b, Sala et al., 2016; Lucas and Wilting, 2018) and meta discussions have been conducted (Sabag, Gladek 2017). These studies provide initial insights on the allocation of Planetary Boundaries, but rarely build on a broad selection of allocation rationales. Climate change offers, on the contrary, a large number of examples of how equity and fairness notions could be implemented in international environmental policy.

The exploration of the possible allocation approaches for sharing global limits between countries/regions is performed in four steps (Figure 3). Theoretical aspects are covered in Chapter 3.1 (rights to use vs. duties to conserve) and 3.2 (allocation principles). Possible ways to operationalise these principles (computation methods) are covered in Chapter 3.3. The application of the computation methods using scenarios is then described in Chapter 4.

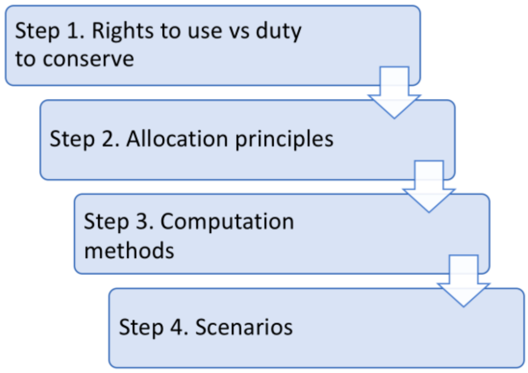

Figure 3. An exploration of the allocation approaches in four steps.

3.1 Theoretical aspects: rights to use and duties to conserve

Natural resources are mainly needed for three reasons: inputs (energy and resources), sinks (energy, heat, pollutants), and ecosystem services (e.g. forests provide, among others, wood and recreation areas). In the context of the Planetary Boundaries framework, keeping human activity within the Planetary Boundaries can be considered as a global common, i.e. a global common property resource or a public good[7,8,9].

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

[7] "Global commons is a term typically used to describe international, supranational, and global resource domains in which common-pool resources are found. Global commons include the earth's shared natural resources, such as the high oceans, the atmosphere and outer space and the Antarctic in particular". Wikipedia (01.07.18)

[8] While GHG emissions are not resources, we can consider the atmosphere as a global common.

[9] See for example (Harris and Roach, 2013) for a discussion of public goods and global commons.

duties to conserve (effort-sharing) (M.G.J. den Elzen et al. 2003; Fleurbaey et al. 2014). With respect to climate change, Fleurbaey et al. (2014) mention 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 originate from different sources, e.g. religious, moral, political or legal. We discuss here the potential principles that could be applied in a situation where such rights and duties would be accepted but do not discuss here about their potential origins.
- Allocation principles are normative concepts. In this report, we do not make any judgement on which allocation principle should be applied or not (alone or in combination with others).
- We are not interested here in understanding the deep philosophical implications of various kinds of equity and fairness notions we are dealing with but rather in trying to understand what happens if we try to implement them.

3.2 Theoretical aspects: allocation principles

International climate negotiations represent the only example of 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 (Rio de Janeiro, 1992), "Common But Differentiated Responsibilities" (CBDR) is a central principle 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 different efforts depending on its past or current contribution to environmental degradation as well as on its capability to act.

Since the 1990's more than 40 studies have proposed quantitative operationalisations of this central principle in order to compute sharing schemes, GHG emissions allowances or reductions at national or regional levels in a fair and equitable way (Höhne, Elzen, and Escalante, (2014a)). Each of these studies consider a specific aspect, e.g. historical trajectories of countries/regions, development needs, responsibility, capacity, equality, sovereignty or efficiency (Fleurbaey et al., 2014; Häyhä et al., 2016a; Höhne, Elzen, and Escalante 2014a).

In this report, we build on two existing synthetic classifications of the main allocation principles. The first classification is proposed by Höhne et al. (2014)[10]: (1) Responsibility (concerns the historical contribution 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, proposed by Sabag and Gladek (2017), based on Shue (1999), discuss four categories of approaches for allocating planetary boundaries to country and company levels: (1) Egalitarian approaches, (2) Economic throughput, (3) Economic capacity and efficiency, and (4) Historical justice and inertia (incl. polluters payers, grandfathering).

[10] Actually, Höhne et al. (2014) combine both what we call, in this report, allocation principles and computation approaches.

We extend these classifications in several ways. First, we group allocation principles:

- A first group assumes that people are the recipients of the allocation of resources or of the allocation of duties.
- A second group assumes that countries are the recipients.
- A third group has for objective technical and economic considerations without any specific group of recipients.

Second, we explicitly consider Sovereignty, which is mentioned as a staged category by Höhne et al. (2014), but also in Fleurbay et al. (2014) in Den Elzen and Lucas (2005) as well as in Lucas and Wilting (2018). Third, we distinguish Capability (ability to pay) from Needs and add a further distinction between Rights to Development and Needs (related to personal aspects such as age or household structure).

In Figure 4, we propose a schema of the principles considered. The attribution of the principles to people or countries is somewhat arbitrary but in line with usual considerations. We usually think about people when talking about needs and rights to development while capability and responsibility are however rather discussed at the level of countries. Definitions are provided for these allocation principles in Table 1.

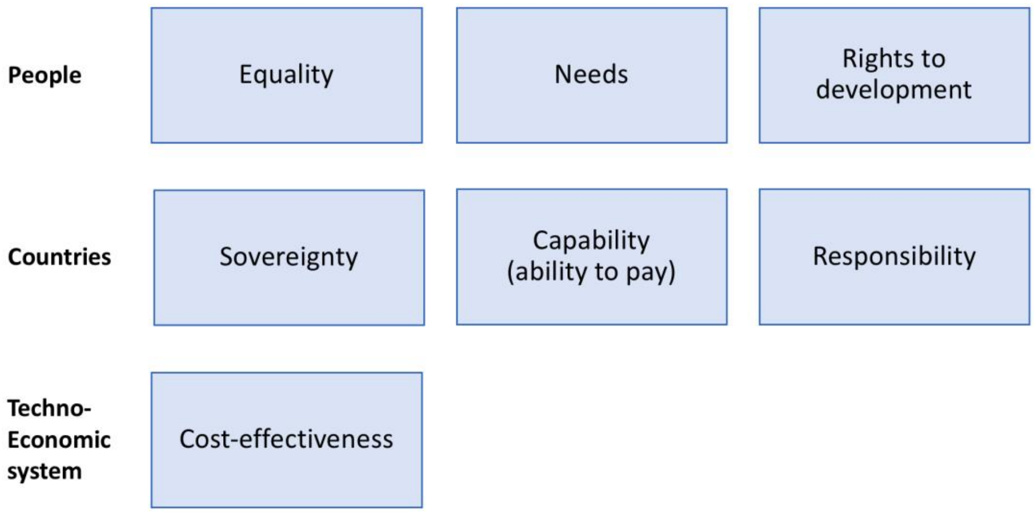

Figure 4. Main allocation principles for equity and its differentiations.

It should be noted that other frameworks could have been applied to characterize the allocation approaches. Rose et al. (1998), for example, classify alternative equity criteria for global warming policy in three categories. The first one, “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. the negotiation process is fair).

Allocation principle	Description
A. Equality	People have equal rights to resources, resulting in an equal share per capita. Equality can be envisaged between people living in a particular year or between people over time.
B. Needs	People have differentiated 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.
C. Right to development	People have rights for 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 or contribute less to mitigation efforts in order to enable meeting development objectives.
D. Sovereignty	Excepted from engagements from international treaties, countries are managed based on internal policy rules. Countries have a legal right to use their own territory as they decide. 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 to 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 the mitigation efforts or use less than their allocated share of resource since their ability to pay is higher.
F. Responsibility	Countries have already used resources in the past. It is thus possible to consider a date in the past to compute the remaining current rights.
G. Cost-effectiveness **(not considered further in this report)**	Rather than considering rights or duties, an allocation can be based on economic objectives, e.g. the equalisation of the marginal costs of mitigation among countries, or on technical aspects. Reductions should focus in priority on countries or sectors with higher or more cost-effective potential for reduction.

Table 1. Definition of allocation principles.

Principle G deals with techno-economic considerations for the management and optimisation of resource uses. It is thus rooted in totally different rationales (i.e. not on sharing a limit). Cost-effectiveness approaches covering aspects like mitigation efficiency (reduction costs, reduction potentials, etc.), costs (adaptation costs, health or economic or environmental damages, etc.) and opportunities are thus not computed in this report. They are complex to quantify (see for example below the Triptych sectoral approach based on assumptions about future productions and efficiency improvements). These approaches having been developed for climate change would need to be extended to take into account the specificities of each Planetary Boundary (e.g. energy efficiency is probably not the most relevant factor in the case of biodiversity loss), which goes beyond the scope of this study.

Former application of allocation principles in Europe

The Triptych approach (Phylipsen et al., 1998) has been used to support decision-making on nationally differentiated emissions targets before and after the Kyoto conference. The Triptych is a mix of Sovereignty, Equity, Right to development and Cost-effectiveness. Emission allowances are determined by different rules applied to three economic sectors: industry, domestic (households) and power-production sectors. Industrial emissions are calculated on the basis of the estimated future growth of production, domestic (households) emissions are computed based on population growth expectations and convergence of per capita domestic emissions. Power emissions are defined according to the growth expectations in electricity consumption (Den Elzen and Lucas, 2005).

It should be noted that even if no allocation approach is explicitly defined, more or less formalised allocation criteria are always present in negotiations about access to resources (see e.g. the expected "fair and ambitious" commitments under the UNFCCC INDCs - Intended Nationally Determined Contributions). Sheriff (2016) evaluates the Nationally Determined Contributions (NDCs) submitted by countries for GHG mitigation as part of the December 2015 Paris Agreement. He finds that projected GDP growth has a highly significant effect, i.e. countries with a higher expected growth accept a larger share of the burden. He also finds that the arrangement implied by the distribution of Paris targets is broadly consistent with a combination of two allocation principles mentioned in this report: Capability (GDP per capita in this case, not GDP) and Responsibility (cumulative emissions per capita).

3.3 Operational aspects: computation methods

The operationalization of allocation principles aims at generating quantitative results. A large number of computation methods have been implemented and described in the literature, each author proposing a specific approach supposed to better reflect a particular principle or a smarter use of the available data.

The computation methods proposed here provide a broad range of different shares for Europe and thus effectively represent the different normative choices associated with the allocation of the global concept of Planetary Boundaries to the European scale. They are based on subjective choices and other choices would have been possible. They are however the ones possible with existing data and project constraints (time and budget).

It should be noted that we consider allocation principles and computation methods one by one in this report. They could however be combined in different ways since there is not exclusive relationships between them.

Past applications of the allocation principles to climate change

In the literature on climate change, two computation methods have mainly been applied to evaluate the needed mitigation efforts:

1. Convergence approaches, i.e. the achievement of a common level of GHG emissions per capita at a future date (= a target), through differentiated pathways.
2. A budget over time, i.e. knowing how much greenhouse gas can still be emitted, before attaining the global bio-physical limit.

Many computation methods actually combine both approaches by defining budget-compatible pathways (see e.g. Elzen and Lucas (2005), Raupach et al. (2014)).

The identified target or budget can lead to the application of different sharing logic: it can become a right to emit, a duty to reduce or a cost to assume according to each country current emissions and the applied principles. Several refinements have also been developed to consider additional allocation principles. Convergence approaches, for example, have been refined to consider capabilities (e.g. who could cope with the costs of mitigation in terms of income), or to consider rights to developments (e.g. who should be exempted below a minimum level of individual income). Both approaches have also been refined to consider responsibilities for past events.

Applications of the allocation principles to the Planetary Boundaries

The Planetary Boundaries framework sets new challenges for the application of the allocation principles. All PB cannot be considered in the same way because they differ in terms of their current global status from a socio-economic perspective (overshoot or not in terms of drivers), and in terms of their current scientific understanding and modelling.

Some of them, like climate change, are already overshot when considering yearly indicators in terms of socio-economic activities: they require sharing a mitigation burden. This is however not the case for other PBs like freshwater use for example: in this case, sharing does not concern burdens but rights to use current resources.

Considering current scientific knowledge and modelling, we have to consider that knowledge is much lower for the other PB than it is for climate change. Modelling pathways as well as scenarios of future possible trajectories (as developed by IPCC or IEA for climate change) have not currently started. This is, in our perspective, the main reason why, except for climate change and for ocean acidification, the estimation of a global budget over time is currently lacking. It is thus only meaningful to estimate a global yearly limit (budget) for the other PB.

The following points should be noted on pathways:

- Pathways are interesting for those Planetary Boundaries which are overshot or for those that tend to rise rapidly but much less when this is not the case.
- For budgets over time, pathways enable considering policy, technical and economic aspects. Pathways can thus be considered as a more realistic way to move from current resource use to future reduced use than using budgets only.

With current knowledge on the Planetary Boundaries (except for the carbon-related climate change and ocean acidification PBs), pathways would imply going away from the principles of equality since they could only be based on simple decay functions (diminishing resource use). Such approach would mean shifting the issues over time, i.e. favouring current populations over future ones. As a result, past operationalisations for allocating the global limits of PBs to countries and regions have been pretty basic in terms of modelling. So far, the main applications are:

- A basic application of the equality principle, i.e. an equal share per capita considering the global population at a fixed year without any consideration for the needs of future populations, see e.g. Nykvist et al., (2013), Fang et al., (2015).
- A more complex application of equality and responsibility principles (Dao et al., 2015; Dao et al., 2018) considering:
    - A two-stage allocation: first to people (based on an equal share per capita) and then to countries (by maintaining the population-based country share fixed over time) in order to account for population growth as a source of responsibility in addition to past emissions.
    - Cumulative global population over a certain period (rather than at a reference year only) to compute an equal share per capita matching both the intra and intergenerational equity principles from sustainable development.
    - Past emissions per country when possible and meaningful (climate change and ocean acidification).

Importance of the parameters

- Past studies have shown that the possible differences resulting from the modification of parameters when computing shares with a specific allocation principle can be as a large as when switching between allocation principles. Comparing GHG sharing schemes, Höhne, Elzen, and Escalante (2014a) conclude 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".
- Taking CO_2 emissions over time as an example to understand the importance of parameters, we can show the importance of selecting a relevant period when considering past emissions (i.e. the importance of time in this case). In Figure 5, the yearly share of the cumulative global

CO_2 emissions has been computed since 1751 using data from CDIAC[11] to represent the share of cumulative CO_2 emissions over time.

- During the period 1751 to 1950, i.e. over the first 200 years following the industrial revolution, only 15% of the cumulative CO_2 emissions have been emitted. This amount corresponds to the global emissions of the seven years' period from 2007 to 2014. This example shows, for example, that, computing CO_2 emissions to apply the Responsibility principle before 1950 will not add a lot to the equation.

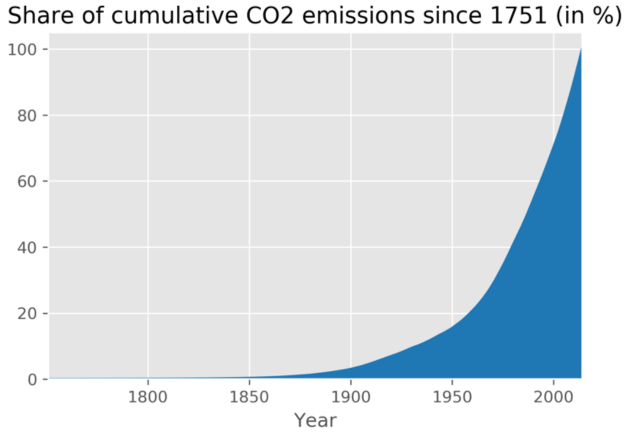

Figure 5. Share of cumulative CO_2 emissions since 1751 (in percent).

Lessons

- The main limitations of the allocation computations performed with respect to the Planetary Boundaries are, in our perspective, due to the early stage of the scientific knowledge, hence the yearly nature of the computed indicators, except for Climate change and Ocean acidification. Any yearly indicator could be turned into a pathway over time with sufficient information.
- Thinking in terms of allocation principles and computations approaches is more important than thinking in terms of the sharing logic (right vs duties) since both logics can be applied to the same question (they are just another way to look at the same issue).
- Apart from Lucas and Wilting (2018), Sovereignty, Capability, Needs and Rights to development principles have not been implemented yet in relation to the Planetary Boundaries (except for Climate change).
- Considering a cumulative population is interesting when computing the Equality principle in order to consider current and future populations.
- The Responsibility principle applied with a temporal approach, e.g. a budget over time, enables considering both population growth and past emissions. Past resource use cannot however be considered when yearly budgets are considered.
- Considering a two-stage approach (people then country) is interesting since it addresses one of the key driver of resource use, i.e. population growth, and it is one way to implement the Responsibility principle.

[11] http://cdiac.ess-dive.lbl.gov/

4 Application of the allocation approaches to Europe

In order to apply the allocation approaches to Europe, we first briefly discuss how we selected the computation methods. Then, we present the selected methods (additional details are provided in Appendix 1 for each of them). Eventually, quantitative shares are provided for Europe.

The objective here is to have a broad overview of possible results. The exploration is however not exhaustive and is driven by the desire to understand the influence of considering additional aspects and parameters compared to the most common applied approach, i.e. a simple equal share per capita approach.

4.1 Methodology

Applying the lessons learned in Chapter 3, we consider six allocation principles. Three for an allocation to people (Equality, Needs, Rights to development) and three for an allocation to countries (Sovereignty, Capability and Responsibility).

We extend thus current practice with respect to the Planetary Boundaries which considers until now only the principles of Equality and Responsibility (outside of the very recent report by Lucas and Wilting (2018)). In addition, we extend the Needs from current practices considering income by also considering nutrition and accessibility. The application of the Rights to development are also going beyond current practices in the climate change literature by considering the Human Development Index (HDI) rather than considering only GDP. We also explore several possibilities for Sovereignty in terms of current GDP, current environmental impacts, surface and bio-capacity. In terms of Capability, we consider cumulative GDP in addition to current GDP. In terms of Responsibility, we go further than existing practices in the climate change literature by applying a combined responsibility in terms of past resource use and population growth by considering a two-stages allocation (first to people then to countries).

The deviations from results based on an equal share per capita are explored using computation methods and scenarios. Three main aspects are considered to get an idea of the range of results:

- Allocation key: the criterion (or criteria) used to perform the allocation. It can be a driver of environmental impacts according to the IPAT formula (i.e. population, affluence or technology), or any other relevant key such as environmental impact, land area or development level. We mainly use one key at a time, but examples in the climate change literature show the use of several if not many keys (e.g. GDP and emissions in the Greenhouse Development Rights framework (Baer et al., 2007)). Each key is quantified by a specific indicator, e.g. the Human Development Indicator (HDI) for the key “development level”.

- Transformation function: indicators may be transformed to modify their relative influence on the share, e.g. logarithmic transformations can be applied in order to reduce the effects of high or low values, or saturation levels can be defined to set poverty or luxury thresholds beyond which the influence of the variable is considered constant.

- Time: the reference year (for yearly budgets) or period (for budget over time) considered for computing the allocation key. History shows that the reference year is not always the most recent one (e.g. 1990 was taken as base year in the Kyoto Protocol adopted in 1997). We thus explore a range of recent dates for the reference year in case of yearly budgets (from 1990 to 2011). When considering Responsibility (for budgets over time only) both the start year and end date are varied. As in Dao et al. (2015), the choice of the start date is based on the date of the political (international agreement) or scientific recognition of an issue. The start date is thus 1990 for climate change (Kyoto Protocol) and 2005 for ocean acidification (the turning point in term of awareness[12]). In both cases, two end date are tested: 2050 and 2100 (other dates could have been chosen).

- No assumptions are made on trajectories or pathways of resource use in the future (as it is done in many allocation methods in the climate change literature). All the computations result in a quantified European share of the global limit.

4.2 Selected computation methods

Fifteen computations methods are presented below, classified by principle. Starting from an overview in Table 2, each method is then described. Results are presented in Chapter 4.3. Additional information on the technical aspects (when relevant) and data sources are provided in Appendix 1. More details on the computations are provided in the joined Excel files.

Principles & computation methods	Allocation key
A. Equality	
1. Equal share per capita	Population
2. Equal share per capita over time	Cumulative population
B. Needs	
3. Equivalence between adults & children	Population weighted by age
4. Accessibility	Travel time to major cities
5. Nutrition	Food Nutrient Adequacy
C. Rights to development	
6. Poverty line	Poverty headcount ratio
7. Development level	Population weighted by Human Development Index
D. Sovereignty	
8. Land	Territorial land surface
9. Bio-capacity	Territorial Bio-capacity
10. Economic throughput	GDP
11. Grandfathering	Consumption-based environmental impacts
E. Capability	
12. Income	Inverse GDP
13. Cumulative income	Inverse cumulative GDP
F. Responsibility *	
14. Past emissions	Population and past use of resources
15. Past emissions & population over time	Cumulative population and past use of resources

* Can only be applied to Climate change and Ocean acidification since they are the only budgets over time.

Table 2. Allocation principles, computations methods and allocation keys.

[12] http://www.oceanacidification.org.uk/pdf/IOA_KnowledgeBase-pdf.pdf

Allocation to people

A. Equality

1. *Allowance to people then to countries proportionally to their share of the global population (equal share per capita).*

All inhabitants of the planet are assumed to have the same right to use the resources on a specific year. The allocation to countries is based on the country share of the world population on that year. Three scenarios are built by varying the considered year: 1990, 2000 and 2011. Further information is available in Appendix 1 (computation method 1).

2. *Allowance to countries proportionally to their cumulative share of the global population (equal share per capital over time).*

All inhabitants of the planet over a 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 and 2011) and the end year (2050 and 2100). Further information is available in Appendix 1 (computation method 2).

B. Needs

3. *Allowance to people then to countries proportionally to their share of the world population, considering the difference in terms of needs between adults and children (equivalence scale).*

The OECD equivalence scale is based on the principle that children only need 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.

Additional scenarios could be built for other years (similarly as in computation method 1). In addition, a cumulative perspective could also be built (like computation method 2). Other interesting extensions would be to consider additional information on needs, e.g. by population groups considered by dependency (old-age, others) or by type of household type (single, family). Further information is available in Appendix 1 (computation method 3).

4. *Allowance to people then to countries proportionally to their share of the world population, considering the difference in terms of accessibility.*

Accessibility is considered as a potential for interactions and for reaching opportunities to fulfil personal needs. The quantification is based on the accessibility map “Travel time to major cities” developed by Uchida & Nelson (2008). The proposed metric 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 was combined with a population map in order 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 more difficult the opportunities to be reached, 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 (raw values, log of values in order to lower the influence of high travel times) are considered for the year 2011. Further information is available in Appendix 1 (computation method 4).

5. *Allowance people then to countries proportionally to their share of the world population, considering the difference in terms of nutrition level.*

The quantification is based on the multidimensional metric “Food Nutrient Adequacy” proposed by Chaudhary et al. (2018). This metric is the average score (normalised scale 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, 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. Further information is available in Appendix 1 (computation method 5).

C. Rights to development

6. *Allowance to people then to countries proportionally to their share of the world population below a certain level of income (poverty line).*

An application of the rights to development in contract & convergence approaches 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 here adapted 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 at the World Bank. Two scenarios have been built. The first one considers an allocation to countries based on their share of the world population earning up to USD 5.50 in the year 2011. In this extreme scenario, all people earning above USD 5.50 per day do not get any "rights" to resources and the larger the number of poor people in a country, the higher its share. This scenario provides a premium to poverty and is not included in the summary table but mentioned in brackets in the discussion of the results. In order to consider this approach but reducing the "poverty premium" from the previous scenario, lower and upper boundaries (corresponding to the min (0.1%) and max (95%) values observed in the countries dataset) are set and a log scale is adopted in order to lower the relative influence of high percentages of people below the poverty line.

This approach is rough and could be improved to include a declining right to resource relatively to income levels (rather than zero rights above USD 5.50). Two issues have however to be solved to enable this better approach. First, getting information per income groups for all countries in the world: this could be solved using data from the world inequality database. Second, choosing a rate of decline of the rights to resources (resource unit per additional unit of income). We did not find clear evidence of an accepted rate of decline, and as a result we did not go further on this path.

Additional scenarios could be built for different years (similarly as in computation method 1). In addition, a cumulative perspective could also be built (like computation method 2). Further information is available in Appendix 1 (computation method 6).

7. *Allowance to people then to countries proportionally to their development needs with respect to the Human Development Index (HDI).*

The HDI is a composite index of life expectancy, education and per capita income (HDR 2015). Considering the HDI provides a richer perspective than with computation method 6. 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 one weights countries using the distance to the maximum HDI level (= 1), e.g. 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 a minimum and maximum cap (at 0.55 and 0.8 corresponding to limits of "low" and "very high" HDI categories): below a HDI equal to 0.55, the rights to resources is equivalent to the country share of the world population, between 0.55 and 0.8, the share is linearly declining and above a HDI equal to 0.8, there is a weighting equal to 0.2 (to allow for a minimum use of resources in each country). The 0.2 weighting means that Europe is favoured in this second scenario compared to the first one.

Additional scenarios could be built with different caps, as well as for different years (similarly as in computation method 1). In addition, a cumulative perspective could also be built (like computation method 2). Further information is available in Appendix 1 (computation method 7).

Allocation to countries

D. Sovereignty

8. Allowance to countries proportionally to their territorial share of the global land surface.

Countries are allowed to use natural resources in proportion of their geographic 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.

Additional scenarios could be built for different years (similarly as in computation method 1). Further information is available in Appendix 1 (computation method 8).

9. Allowance to countries proportionally to their territorial share of the global bio-capacity.

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 bio-capacity computed by the Ecological Footprint Network) at a specific date. A single scenario is considered for the year 2017.

Other measures of the territorial natural resources could have been used but this one is a single summary indicator facilitating the computation. Additional scenarios could be built for different years (similarly as in computation method 1). Further information is available in Appendix 1 (computation method 9).

10. Allowance to countries proportionally to their share of the global economic throughput (GDP).

Countries are allowed to continue maintaining their level of current production and consumption activities relatively to other countries. The allocation to countries is based on the country share of the world GDP in Purchasing Power Parity (PPP) at a specific date. Results are computed for 2011 for two scenarios (with and without cap on income). Additional scenarios could be built for different years (similarly as in computation method 1). Further information is available in Appendix 1 (computation method 10).

11. Allowance to countries proportionally to their share of the global environmental impacts (from a consumption perspective), i.e. grandfathering.

Countries are allowed to use the remaining resources or contribute to reduction efforts in proportion of their current impacts. The allocation to countries is based on their share of the global environmental impacts computed from a consumption perspective (the ones measured by the footprint indicators calculated within this report, PB per PB). 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. Further information is available in Appendix 1 (computation method 11).

E. Capability

12. Allowance to countries considering an inverse proportional relationship to their share of the global income (inverse GDP).

An application of the capability principle (ability to pay) in contact & convergence approaches is based on the idea that wealthy countries should contribute proportionally more to the reduction of carbon emissions that developing economies. This idea is here adapted to match the concept of a budget rather than a reduction target: Countries with higher financial capabilities (income) have less rights to the resources (or should be able to use less resources due to a 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 USD based on mix/max values from the Madison data set[13]. The second scenario considers saturation points at USD 100 and USD 75'000 based on min/max values used for the standardisation of the income component in the HDI. The third scenario considers saturation

[13] https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018

points at USD 7’500 and USD 50'000 based on min/max values proposed in the CERP Responsibility & Capability calculator[14].

Additional scenarios could be built with different thresholds and for different years (similarly as in computation method 1). Further information is available in Appendix 1 (computation method 12).

13. *Allowance to countries considering an inverse proportional relationship to their share of the cumulative global income (inverse cumulative GDP).*

The allocation is similar to computation method 12 but considering cumulative income over the 1950-2011 period. Three scenarios are also proposed based on the same saturation points.

Additional scenarios could be built with different thresholds and for different years (similarly as in computation method 1). Further information is available in Appendix 1 (computation method 13).

F. Responsibility (for climate change and ocean acidification only)

In the climate change community, responsibility is usually modelled in terms of past emissions. Thinking explicitly in terms of allocation, as in this report, opens an additional possibility to model responsibility in terms of past structural changes (i.e. population and income growth as well as technological changes). The computation methods 14 and 15 can only be computed for climate change and for ocean acidification because they are based on budgets over time. Computations are PB-specific since they require the integration of the use of past resources.

For climate change, the budget considered is based on a climate change scenario considering a 2° increase with p>66% (IPCC AR5). The results with other climate change scenarios are discussed separately.

14. *Allowance to countries proportionally to their share of the global population and considering their past use of rights (past emissions).*

Exactly as in the first computation method, all inhabitants of the planet have the same right to use the resources on a specific year. The allocation to countries is based on the country share of the world population on that year. In addition, past emissions between that year and 2011 are subtracted from the allocated budget to get the remaining budget for 2011. For climate change, three scenarios are built by varying the considered year: 1990 and 2000 for climate change, 2005 for ocean acidification. Further information is available in Appendix 2 (computation method 14).

15. *Allowance to countries proportionally to their cumulative share of the global population and their past use of the rights (past emissions).*

Exactly as in the second computation method, all inhabitants of the planet during a specific period have the same yearly right to use the resources. The allocation to countries is based on the country share of the world population over time. The country share varies according to the ratio of the country over the global cumulative yearly population over the length of the considered period (influenced by the choice of the start and end dates, e.g. from 1990 to 2030 or from 1995 to 2050). In addition, exactly as in computation method 14, past emissions between that year and 2011 are subtracted from the allocated budget to get the remaining budget for 2011. For climate change, 4 scenarios are built by varying the start year (1990 and 2000) and the end year (2050 and 2100). For ocean acidification, 2 scenarios are constructed by selecting a start year in 2005 (and two end years: 2050 and 2100). Further information is available in Appendix 1 (computation method 15).

This is the approach applied in Dao et al. (2015) for climate change and for ocean acidification.

[14] https://calculator.climateequityreference.org/

4.3 Range of European shares per allocation principle and computation method

A summary of the computed European shares is provided in Table 3. The minimum, average, median and maximum share resulting from the computations in Chapter 4.2 are presented for each computation method and for each principle.

By Europe we mean the combined territory of the 33 EEA Member countries. The 6 EEA Cooperating countries are not included in calculations. Median and average values are computed using the number of scenarios mentioned in the table for the year 2011 (or earlier when relevant). Their calculations are done step-by-step to account for the different number of scenarios per computation and methods per principle. First, if applicable, they are computed for each of the computation method considering the different scenarios (several periods, etc.). Then for each of the principle by considering an equivalent weighting for each of the computations methods. Eventually, they are computed for all allocation principles. When a single value has been computed, it is shown in the table as the median. Detailed results are available in the Excel documents provided with this report. The discussion below considers the median values unless otherwise mentioned.

	Principles & computation methods (nbr of scenarios)		Min European share	Average	Median	Max European share
Allocation to people	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. Equivalence between adults and children	1	----------------	----------------	9.2%	----------------
	4. Accessibility	2	3.3%	5.0%	5.0%	6.7%
	5. Nutrition	1	----------------	----------------	7.3%	----------------
	C. Rights to development	3	2.7%	4.1%	4.1%	5.1%
	6. Poverty line	1	----------------	----------------	5.1%	----------------
	7. Development level	2	2.7%	3.2%	3.2%	3.6%
Allocation to countries	D. Sovereignty	5	4.3%	11.4%	12.5%	21.0%
	8. Land	1	----------------	----------------	4.3%	----------------
	9. Bio-capacity	1	----------------	----------------	10.6%	----------------
	10. Economic throughput	2	11.2%	16.1%	16.1%	21.0%
	11. Grandfathering	1	----------------	----------------	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%
	F. Responsibility*	9	0.2%	5.8%	6.3%	8.4%
	14. Past emissions	3	5.7%	7.2%	7.5%	8.4%
	15. Past emissions & population over time	6	0.2%	4.3%	5.1%	7.3%
	All (climate change/ocean acidification) *	**36/33**	**0.2%**	**7.1%**	**6.8%**	**21.0%**
	All except Responsibility	**27**	**2.7%**	**7.3%**	**7.3%**	**21.0%**

* Can only be applied to Climate change and Ocean acidification since they are the only budgets over time

* The number of scenarios differs due to the start date: Climate change (1990), Ocean acidification (2005)

* Climate change considers a climate change scenario with a 2°increase with p>66% (IPCC AR5)

Table 3. Summary of European shares (for 2011) grouped by allocation principle.

Considering all principles for Climate change and Ocean acidification results in a median European share of 7.3%. This median share is slightly lower for the other indicators (i.e. not including the principle of responsibility which can only be computed for indicators over time): 6.8%.

Allocation to people

An allocation to people results in a European range going from 2.7% (#7 Development level) to 10.2% (#1 Equal share per capita), with a median value of 7.3%.

Considering an allocation in terms of Equality (A), the median value is equal to 8.1%. The equal share per capita (#1) is diminishing over time (going from 8.4% to 10.2% over the period 1990 to 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 (#2) results in a lower European share over time (between 6.2% and 7.8%) for the same reason.

Introducing a differentiation in terms of Needs (B) results in a lower allowance for Europe compared to an allocation based on the Equality (A) principle when considering the median: 7.3% rather than 8.1%. While considering an equivalence between children and adults (#3) results in a higher European share considering the same year (9.2% vs 8.4% in 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 computation methods. Considering Accessibility (#4), the European needs are lower that based on the Equality principle (A) since there is a larger accessibility in Europe than in the rest of the world. The same is true for an allocation considering Nutrition (#5).

Introducing another differentiation but this time considering the Rights to development principle (C) results in a lower allowance for Europe compared to an allocation based on the Equality principle (A). This is due to the fact that development levels (measured by the poverty line and HDI) are higher in Europe than in the rest of the world. The method based on the poverty line (#6) results in a lower European share (5.1%) since the number of people below a USD 5.50 daily income is lower in Europe than in the rest of the world. The result of the extreme scenario which is not included in Table 4 because of its “poverty premium” would result in a 0.6% share for Europe (see description of computation method 6 above). Considering the development level (HDI) (#7) results in the lowest 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.

Allocation to countries

An allocation to countries results in a European range going from 0.2% to 21%, with a median value of 6.3%. The median value is thus lower than with an allocation to people.

Considering an allocation based on the Sovereignty principle (D) results in a higher allowance (12.5%) for Europe compared to an allocation based on the Equality principle (A) (when considering the median). These are the most contrasted results since the current situation is accepted as a starting point for allocating the global budget to national scales and very different aspects are considered as a basis. Based on median values, the European share is lower when considering the Land surface (#8) (4.3%) and higher when considering its Bio-capacity (#9) (10.6%). It is even higher when considering its Economic throughput (#10) (between 11.2% (log function to attenuate extreme values) and 21% (linear function) or Grandfathering (#11) (14.4%) (i.e. assuming a similar reduction per region). Except when considering the land surface, the European range is thus slightly to largely higher than when considering an allocation to people.

Introducing a differentiation in terms of Capability (E) results in a lower allowance for Europe (6.2%) compared to an allocation based on the Equality principle (A) (when considering the median). An allocation based on income (#12) reduces the European share between 3.8% and 6.5% while it is between 5.0% and 7.5% when considering cumulative income (#13). A low European share means here that Europe has a large income and can thus support more costs or use less resources.

Specific case for Responsibility (F), considering a 2° increase with p>66% (IPCC AR5) climate change scenario

A differentiation in terms of Responsibility (F) is meaningful for budgets over time (climate change and ocean acidification) only. It results in a lower allowance for Europe (6.3%) compared to an allocation based on the Equality principle (A) (when considering the median). Considering past emissions (#14), the resulting median European share is 7.5%: Europe has emitted more emissions in the past than the rest of the world and its current share is thus now lower. Considering past emissions and past population over time (#15), the European share is even lower: ranging between 0.2% and 7.3% with a median value equals to 5.1%.

Considering additional climate change scenarios for Responsibility (F)

As mentioned in Chapter 4.2, computation method 15 requires including information on past emissions. The budget considered in Table 3 is based on a climate change scenario considering a 2° increase with p>66% (IPCC AR5) climate change scenario, i.e. the most referenced scenarios in policy agreements. This is however only one of the currently internationally discussed budgets, particularly since the Paris Agreement.

The other budgets presented in Table 4 are stricter (except for the 2° increase with p>50% (IPCC AR5) scenario) than the one selected in Table 3 in terms of average temperature increase (1.5° rather than 2° Celsius), uncertainty (p > 0.66% rather than p > 0.5%) or are more recent (EGR, 2015) and representing minimum values rather than median values.

The influence of the climate change scenario on the European share is shown in Table 4. Considering median values, three results in a lower European share. Considering minimum values even results in negative European shares. The oldest the start date of the period (1990), the longer the period (up to 2100) and the more stringent the climatic scenario (e.g. 1.5° at 66%), the more chance there is to get a negative European budget (hence a negative share). In these case, this means that emissions should be stopped now and carbon should even be removed from the atmosphere.

It should be noted that there is only a single budget for ocean acidification which does not depends on the climate change scenarios.

Climate change scenarios	**Min share**	**Average**	**Median**	**Max share**
GHG emissions (1.5° with p > 50%, EGR 2015 min)	-0.4%	5.6%	6.2%	8.4%
GHG emissions (1.5° with p > 66%, EGR 2015 min)	-3.9%	4.3%	5.3%	8.4%
GHG emissions (2° with p > 50%, IPCC AR5)	0.8%	6.0%	6.5%	8.4%
GHG emissions (2° with p > 66%, IPCC AR5)	0.2%	5.8%	6.3%	8.4%
GHG emissions (2° with p > 66%, EGR 2015 min)	-0.8%	5.4%	6.1%	8.4%
All climate change scenarios	**-3.9%**	**5.4%**	**6.2%**	**8.4%**

Table 4. Additional computations of European shares, for climate change, according to other climate change scenarios.

Concluding remarks

Taking the Equality principle (A) as starting point, the application of all other principles reduces the European share except when applying the principle of Sovereignty (i.e. an allocation based on the current situation). Considering an equal share per capita approach results in the second highest share for Europe.

Current studies have mainly applied an equal share per capita. Going beyond this approach and considering needs, rights to development, capability or responsibility would be more in line with the sustainable development concept and with the idea of "living well within the limits of our planet" (7th EAP). This is already implicitly accepted, as mentioned in Chapter 3, since the implicit commitments following the Paris agreement are close to an application of the Responsibility and Capability principles (Sheriff, 2016). Considering median values, this would mean a European share of 6.3% and 6.2% respectively (compared to 8.1% with the Equality principle).

Several options are possible to set a reference European share. Setting a reference European share equivalent to the median share considering all principles (even if Responsibility is formally only applicable to Climate change and Ocean acidification) would result in a European share of 7.3%. The reference share would be slightly lower when not including the principle of responsibility: 6.8%.

We recommend here to set a reference European share equivalent to the average of the range based on median values. It happens that this value represents the Equality principle (8.1%). Setting a 50% larger value would result in the maximum median value, Sovereignty (12.5%) while setting a 50% lower value would result in the minimum median value, Rights to development (4.1%).

We emphasize that we are not here promoting the Equality principle. This principle is questionable for several reasons. First, its acceptability in the international arena, e.g. by developing economies, is doubtful since considerations of needs of rights for development are usually mentioned during the international discussions about climate change. In addition, since equality is driven by population, this raise two key questions. First, is promoting an equality principle a good idea knowing that population growth is one of the key drivers of global impacts (with affluence and technology)? Second, since the European share will decline over time, this choice will lead to a reduction of the European share over time. Is that acceptable from a European perspective?

This value of 8.1% is lower than the share computed for Europe for 2011 based on an equal share per capita approach (8.4%). We believe that it represents a central value that can be taken as a compromise between the different approaches explored in this report. Another possibility would be to take only the most recent data at the time of the computation of the share rather than considering various years in the past as done in this report.

What is the robustness of the here presented results? While the exploration is not systematic (a larger number of years could, for example, have been considered for several computation methods), the interest of exploring additional years seems limited since the overall picture is clear. It should also be noted that results would probably also slightly vary when using other databases, e.g. on population. These results have thus to be considered as estimates which are enough to understand the situation, but they do not represent the truth. In addition, due to the fact that the uncertainties of the global PB limits computed by Steffen et al. (2015) are much higher (for example a factor 10 for Phosphorus) than the uncertainties we are dealing with here when considering median values, the choice of a reference share for Europe is not the most critical aspect for the application of the Planetary Boundaries to Europe.

The selection of a reference European share is thus, in our perspective, more a decision of an ethical or policy nature than a scientific one, hence the suggestion to consider a median value which can be perceived as a compromise.

5 European and world limits, footprints and performance

Starting with a description of the methodology (Chapter 5.1), the selected control variables are then described (Chapter 5.2). In Chapter 5.3, an overview of the global and European limits, footprints and performances is presented. Detailed results for each of the PB are then discussed in the chapters 5.4 to 5.9. The Swiss case study on biodiversity is described in Chapter 5.10. Since Europe is here considered as the EEA-33, results are also provided for the EU28 in Appendix 3. Additional information on the computed footprints is provided in Appendix 4.

5.1 Methodology

The methodology, indicators and limits are based on the report “Environmental limits and Swiss footprints based on Planetary Boundaries” (Dao et al. 2015) mandated to the authors of this report by the Swiss Federal Office For the Environment (FOEN). This method was later extended in the blueDot project[15], co-funded by the authors and the Boninchi foundation, to consider international datasets rather than Swiss specific datasets. In this report, some updates have been applied to the methodology to consider the revision of the PB framework in Steffen et al. (2015) and the use of a specific database to compute footprints.

The Swiss study followed a three-stage approach presented in Figure 6 in order to a) understand which limits can effectively be currently quantified, and translate these limits expressed with bio-physical indicators into indicators that can be linked to socio-economic activities, b) compute global and national limits as well as footprints, and c) suggest priorities for action.

a) Preliminary analysis	1. Identification of Planetary Boundaries recognised as global
	2. Selection of indicators
b) Computation	3. Limits (global & national)
	4. Footprints (global & national)
	5. Performance (global and national)
c) Priority assessment	6. Priority areas

Figure 6. Three-stage approach applied in the Swiss study

[15] www.bluedot.world

In this report, as in the Swiss study, the Planetary Boundaries are modelled in two ways, either as yearly budgets or budgets over time (Table 5).

Scale of processes / *Type of limit*	Global issues	Regional issues with a global limit
	Global by essence and a global limit exists	A global limit can be identified as cumulated effects at global scale
Budget over time Available once for given period of time	Climate Change Ocean Acidification	
Yearly budget Available year after year		Nitrogen Phosphorus Freshwater use Biosphere integrity * Land-System change

* Not computed in this report.

Table 5. Planetary Boundaries: scale of process and type of limit (Dao et al. 2015).

Footprint indicators are different from traditional territorial indicators at country level (see Figure 7). Territorial indicators consider emissions or impacts occurring on the territory of a country, e.g. the domestic GHG emissions reported under the Kyoto Protocol. Footprint indicators (also named consumption-based indicators) aggregate environmental impacts and/or resource uses along global production-consumption chains according to a life cycle perspective. They allow quantifying the environmental impacts induced by the consumption of the inhabitants of a country wherever these impacts occur on Earth.

A footprint perspective is increasingly relevant in our interlinked global economy: due to a growing international trade, a rising part of the environmental impacts on a territory is generated to satisfy consumers in other countries. For most developed economies, more than half of the environmental impacts induced by their consumption are thus induced elsewhere in the world (Tuker et al., 2014).

This study therefore considers footprints indicators since they are considered as particularly relevant in the context of the Planetary Boundaries.

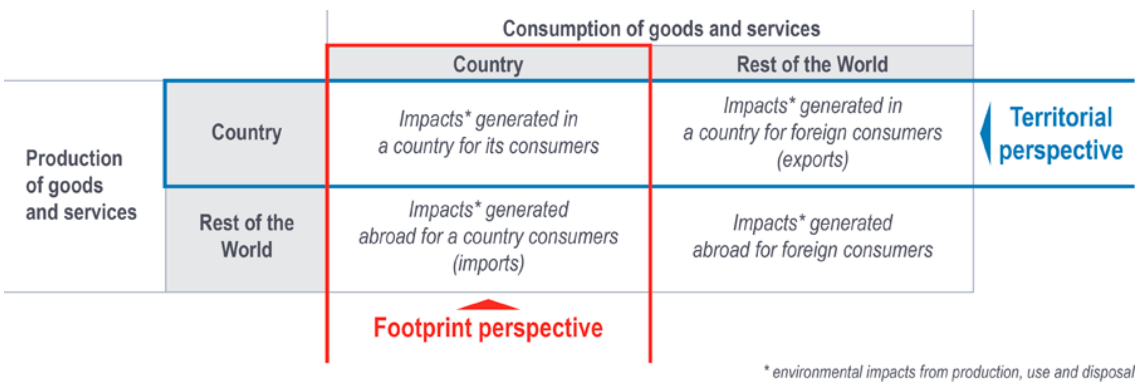

Figure 7. Territorial and footprint perspectives (Dao et al., 2015).

Like the computation of the European shares, global limits are computed from public data sources and the literature. Footprints are also computed with a public database (Exiobase 3.4, a Multi-Regional Input-Output (MRIO) model (Wood et al., 2018)), and data from EDGAR (Janssens-Maenhout et al., 2017). Specific care has been taken to ensure that global limits and footprints are comparable although they are based on different data sources.

MRIO models are interesting since they enable computing footprints linking:

- All economic activities required for producing a particular good in a specific country, accounting for international trade.
- All emissions of pollutants and use 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 chains.

Limits are provided for Europe considered as the EEA-33 region as a whole, i.e. the region defined by the 33 EEA member countries, which includes the 28 European Union Member States together with Iceland, Liechtenstein, Norway, Switzerland and Turkey. The six West Balkan EEA cooperating countries (Albania, Bosnia and Herzegovina, the Republic of North Macedonia, Montenegro, Serbia as well as Kosovo) are not considered.

Due to a lack of country-specific data the footprints calculated however do not include Iceland and Liechtenstein. Their additional contribution can however be estimated to be small due to their very low share of the European population (0.06%).

Please refer to (Dao et al., 2018) and www.bluedot.world for additional information on the methodology.

5.2 Description of the control variables

The control variables in terms of socio-economic activities used in this report are presented in this chapter. A summary table of the control variables from Steffen et al. (2015) and the control variables of this report are provided in Appendix 2.

Climate change (CC)

Steffen et al. (2015) (as in Rockström et al. (2009)) consider a control variable in terms of atmospheric CO_2 concentration (in ppm) or in terms of the energy imbalance at the top-of-atmosphere (in Wm^2). The pathway from socio-economic activities to greenhouse gas (GHG) emissions and to global temperature increase is well described, enabling thus a robust pressure indicator in terms of GHG emissions (including land cover changes) (Dao et al. 2018).

In this study, the performance is computed by comparing a GHG footprint (without land cover changes) with a world budget corresponding to the remaining cumulative GHG emissions (including land cover changes) computed for a climate change scenario considering a 2° increase with p>66% (IPCC AR5) from (IPCC 2013). Additional climate change scenario from (IPCC 2013) and (EGR, 2015) are also discussed.

Ocean acidification (OA)

Steffen et al. (2015) (as in Rockström et al. (2009)) consider a control variable in terms of carbonate ion concentration (average global surface ocean saturation state with respect to aragonite (Ωarag)). The concentration of aragonite in oceans can be related to the increase in atmospheric CO_2 concentration hence to carbon dioxide emissions thus enabling a robust pressure indicator in terms of carbon dioxide (CO_2) emissions (Dao et al. 2018).

In this study, the performance is computed by comparing a CO_2 footprint with the world budget corresponding to the remaining cumulative emissions of carbon dioxide (CO_2) from human activities to maintain an acceptable calcium carbonate saturation state Ω (2.75 Ω arag), computed from IPCC data.

Biogeochemical flows (Nitrogen) – Nitrogen losses (NL)

Rockström et al. (2009) consider a control variable in terms of the amount of N_2 removed from the atmosphere for human use. Steffen et al. (2015) consider a control variable in terms of industrial and intentional biological fixation of N. Dao et al. (2015) propose a limit in terms of Nitrogen losses from agriculture considering both leaching to water and NH_3 air releases.

In this study, we follow Dao et al. (2015) and consider Nitrogen losses from agriculture only but the limit is updated in order to be fully compatible with the global limit proposed by Steffen et al. (2015) and to be computable with the database selected for this report.

As in Steffen et al. (2015), the selected limit is coming from De Vries et al. (2013). They compute three different limits for N concentration in freshwater: for N runoff, NH_3 and N_2O. From there, they compute back three related losses and three intended N fixation. Steffen et al. (2015) select the limit for N runoff in terms of N fixation. We also use the value for runoff but considering losses rather than N fixation. The value in this report is however different from the one in the article: It is a corrected value generated based on personal communication with Vim de Vries to match our needs and correct mistakes in the article.

The exact same scope as in Steffen et al. (2015) is thus covered. The name is however different in this report compared to Steffen et al. (2015). We consider effectively the losses from runoff and leaching from agriculture while Steffen et al. (2015) use the intended N fixation (i.e. not unintended NO_x from industry and transport). Knowing that intended N fixation is however mostly agriculture (less than 20% is industrial and not generating losses to water) it is thus similar but at a different level.

For computing the footprint, the conversion from air releases to water losses is based on the marine eutrophication characterization factors from the Life Cycle Impact Assessment methodology Recipe 2016 (Huijbregts et al., 2017).

Biogeochemical flows (Phosphorus) – Phosphorus losses (PL)

Steffen et al. (2015) consider two control variables. A global one in terms of the quantity of P flowing into the oceans (as in Rockström et al. (2009)) and a regional one in terms of the P flows from fertilizers to erodible soil. Dao et al. (2018) propose a limit in terms of the use of P- fertilisers.

In this study, we follow Dao et al. (2018) but compute the performance by considering P from urban wastewater in addition to the P releases from agricultural activities. In addition, the limit is modified in order to be compatible with the global limit proposed by Steffen et al. (2015) and to be computable with the database selected for this report. The global limit in terms of releases of P from agriculture and wastewater is computed as follow. First, the proportion of the global P footprint due to releases from agriculture and wastewater is computed as the ratio of the P release computed from the database (for 2011) (1.8 Tg P) to the global footprint proposed by Steffen et al. (2015) (22 Tg P). Second, this ratio is applied to the limit proposed by Steffen et al. (2015) (11 Tg) to compute the global limit for the P releases from agriculture and wastewater. The European limit is then computed in the same way as for the other indicators.

For computing the footprint, the conversion from soil releases to water losses is based on the freshwater eutrophication characterization factors from the Life Cycle Impact Assessment methodology Recipe 2016 (Huijbregts et al., 2017).

Freshwater use (FU)

Steffen et al. (2015) consider two control variables in terms of freshwater use. One at the global level, in terms of the maximum amount of consumptive blue water use (in km^3 per year) (as in Rockström et al. (2009)), and another one at the basin level in terms of the blue water withdrawal as % of mean monthly river flows.

In this study, we consider the global level with an indicator in terms of the blue water consumption from socio-economic activities.

Land-system change - Land cover anthropisation (LC)

Steffen et al. (2015) consider two control variables in terms of forested area. One at the global level, in terms of the area of forested land as % of original forest cover, and another one at the biome level in terms of the area of forested land as % of potential forest cover. Rockström et al. (2009) propose an indicator in terms of the percentage of global land cover converted to cropland.

Dao et al. (2015) follow Rockström et al. (2009) and extend the type of land cover considered. They consider a control variable named "anthropised land area" which enables establishing a link with socio-economic activities 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.

In this study, we consider the global level following Dao et al. (2015).

Biosphere integrity (Genetic diversity)

Steffen et al. (2015) propose "a two-component approach, addressing two key roles of the biosphere in the Earth system." 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 propose "the (imperfectly) known extinction rate of well-studied organisms over the past several million years—about 1 per million species-years—and add a large uncertainty bound, raising the boundary to 10 per million species-years." 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 propose the Biodiversity Intactness Index (BII).

Steffen et al. (2015) clearly mention that these are interim control variables until a more appropriate one is developed.[16]

The biosphere integrity is not computed for Europe in this report but a case study on Switzerland is provided below.

5.3 Overview of performances

Current global production and consumptions patterns are not compatible with long-term limits for four Planetary Boundaries as shown in Table 6 (adapted from Dao et al. (2018). Current production and consumption patterns are considered as *a high risk* with respect to Climate change and Ocean acidification. They are considered as *an increasing risk* with respect to Nitrogen losses and Phosphorus losses. They are however considered as *safe* with respect to Freshwater use and Land cover anthropisation.

Such results are compatible with the ones proposed by Steffen et al. (2015). They differ however because the control variables differ, hence the limits. Steffen et al. (2015) use bio-physical control variables while we adopt a yearly perspective of current production and consumption patterns (PCP).

As a result, the overshoot is larger, in this report, for Climate change than in Steffen et al. (2015). In addition, Ocean acidification is also largely overshoot in this report while it is *safe* in Steffen et al. (2015). For both indicators, this is because current PCP produce a high level of emissions which is too

[16] « The risk is that, although the Earth system can tolerate a higher-than-background level of extinctions for a time, we do not know what levels of, or types of, biodiversity loss may possibly trigger nonlinear or irreversible changes to the Earth system."

high to stay within the long-term bio-physical limits set by Steffen et al. (2015). Nitrogen and Phosphorus overshoots are considered less critical in this report than in Steffen at al. (2015) since while they are clearly overshot they are however evolving slowly at global scale. The classification of Land-system change as *safe* differs from Steffen et al. (2015) because while the global footprint is close to the global limit, it is however evolving slowly at global scale. For Steffen et al. (2015), this PB is *an increasing risk.*

Performance	Planetary Boundary	Units	Limit	Footprint	Confidence	Trend
High risk						
	Climate Change	Gt CO2-eq	10.8 - 28.2	43.6	high	rapidly deteriorating
	Ocean Acidification	Gt CO2	7.7 - 20.1	33.1	high	rapidly deteriorating
Increasing risk						
	Nitrogen Losses	Tg	28.5	49.3	low	slow evolution
	Phosphorus Losses	Tg	0.9	1.8	low	slow evolution
Safe						
	Freshwater Use	km3	4'000	1'225	medium	rapid evolution
	Land Cover Anthropisation	10^6 km2	19.4	17.0	medium	slow evolution

Table 6. Global performance of current production and consumption patterns for 2011.

The global footprints computed in this project are compatible with the results generated by Dao et al. (2015, 2018) and in the blueDot project. The exact numbers are however different because they are computed with other databases and models, as well as because of methodological updates for Nitrogen and Phosphorus losses.

The quality of the results depends on:

- The uncertainties of the global bio-physical limits from Steffen et al. (2015) and/or from the global socio-economic limits from Dao et al. (2018). Knowing the uncertainties for a largely studied issue like climate change, one can easily imagine that uncertainties are even larger for the other bio-physical limits as well as when identifying control variables in terms of human activities.

- The quality of the modelling with global MRIO models. These models are mainly influenced by the data and models used as source and the need for providing a coherent picture at global scale (hence a balancing of the table). Further information is provided Appendix 4.

European performance

The European footprint for Nitrogen losses and Phosphorus losses are larger than the computed median limits for Europe (like the global situation) except when considering the Sovereignty principle based on grandfathering (#11) and economic throughput (#10), i.e. an allocation based on the current European share of global footprints or global GDP. The situation is the same for Land cover anthropisation except that the result differs from the global limit which is not overshot. The European footprint for global Freshwater use is, as in the global situation, the only one which is not overshot.

The size of the European under/overshot for 2011 is shown for each PB in Figure 8. In this table, the European limit based on the median of the median values (7.3%) is set to 1 and the numbers indicate size of the under/overshot (e.g. 3.5 times the European limit for Nitrogen).

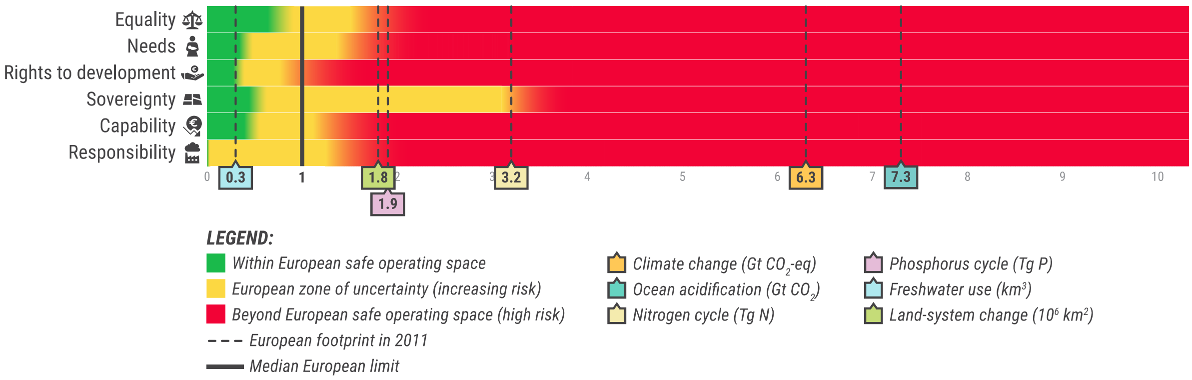

Figure 8 Overview of the European performance (2011).

Considering the latest available year for computing median limit values show a very similar picture except for Climate change and Ocean acidification, where the yearly European limit has been already reduced between 7% to 9%, respectively 8% to 12%, over the 2011 to 2015 period.

This means that European consumption and production patterns could not be scaled up to the globe without crossing planetary boundaries. Note that this evaluation does not consider regional boundaries but only global ones. Regional phosphorus and land use boundaries may thus be overshot. In addition, European consumption may be associated with regional freshwater overconsumption within or outside Europe. The regional patterns of the European land use, phosphorus and freshwater use footprints are however not analysed in this report.

Results and limitations are discussed in the following chapters per Planetary Boundary based on median values. Results for the global and the European limits, footprints, and performances are provided in Table 7. Per capita values are presented in Table 8. Minimum, average, median and maximum European limits are based on the shares proposed for 2011 in Table 3. In addition, median values have also been added for the latest available year (going from 2011 to 2017, more information in Appendix 3). Footprints have been computed for 2011 (see Appendix 4 for additional information).

Planetary Boundary		Global		EEA						
				Limit					Footprint	
Name	Indicator	Limit	Footprint	Min	Avg	Median	Median (latest)	Max		Date global limit
Nitrogen Losses	Loss of N to water from agriculture in Tg N	28,5	49,3	0,8	2,1	2,1	2,1	6,0	6,8	2010, 2013
Phosphorus Losses	Loss of P from fertilizers and waste in Tg P	0,92	1,84	0,03	0,06	0,07	0,07	0,19	0,13	2010, 2013
Freshwater Use	Blue water consumption in km^3	4 000	1 225	110	280	291	291	840	99,1	2009
Land Cover Anthropisation	Anthropised land in 10^6 km^2	19,4	17,0	0,5	1,4	1,4	1,4	4,1	2,5	2009

Footprints are for 2011.
The number of scenarios considered is 27 for all indicators.
The date for the most recent year varies according to the computation methods (2011 to 2017)

Table 7. Global and European limits and footprints (absolute values)

Planetary Boundary		Global		EEA							
				Limit					Footprint	
Name	Indicator	Limit	Footprint	Min	Avg	Median	Median (latest)	Max		Date global limit
Nitrogen Losses	Loss of N to water from agriculture in kg N	4,0	7,0	1,3	3,5	3,5	3,4	10,1	11,4	2010, 2013
Phosphorus Losses	Loss of P from fertilizers and waste in kg P	0,13	0,26	0,04	0,11	0,11	0,11	0,32	0,23	2010, 2013
Freshwater Use	Blue water consumption in m^3	568	174	185	471	488	482	1.411	166,6	2009
Land Cover Anthropisation	Anthropised land in m^2	2.749	2.413	894	2.385	2.364	2.332	6.832	4.150,1	2009

Footprints are for 2011.

The number of scenarios considered is 27 for all indicators.

The date for the most recent year varies according to the computation methods (2011 to 2017)

Table 8. Global and European limits and footprints (per capita)

5.4 Climate change

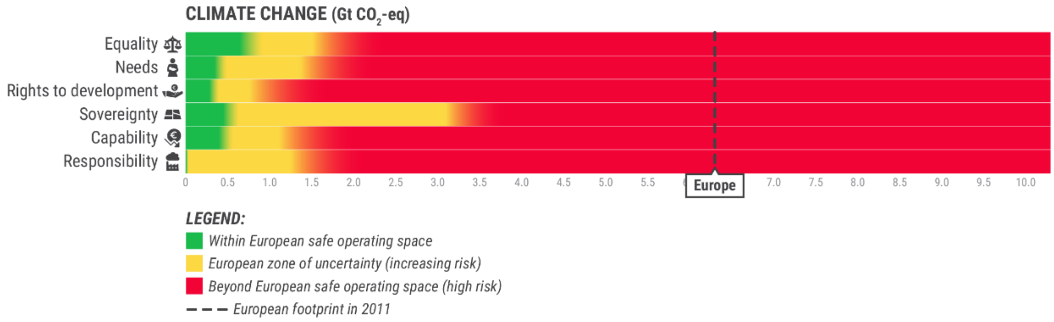

Figure 9 European performance (2011) for Climate change (in Gt CO_2-eq.)

Key messages

- The global and European yearly limits are overshot in all climate change scenarios.
- Applying a 2oC with p>66% climate change scenario and using the median value, Europe exceeds the limit by a factor 2.5 to 6.
- The trend of the European footprint over the period 1995-2011 is almost flat (+ 1.9%).

Analysis

At global scale, applying a 2°C with p>66% climate change scenario, the annual global limit in 2011 is between 10.8 and 28.2 Gt CO_2-eq (1.5 and 4.0 t CO_2-eq per capita respectively) (depending on the time horizon). At global scale, the footprint is equal to 43.6 Gt CO_2-eq (6.2 t CO_2-eq per capita). This is 1.5 to 4 larger than the limit.

Considering four additional global budgets corresponding to alternative climate change scenarios (described in Table 4 in Chapter 4), the annual global limit in 2011 ranges from 6.7 Gt CO_2-eq (0.9 t CO_2-eq per capita) for the strictest scenario (1.5°C with 66% confidence interval with zero emissions in 2100) to 31.3 Gt CO_2-eq (4.4 t CO_2-eq per capita) for the least strict considered scenario (2.0°C with 50% confidence interval with zero emissions in 2050). The yearly Climate change PB is overshot at global scale in all of these scenarios. This range of global budgets is larger than the range provided in this report for the computation of the European share (median values). Uncertainty is thus as much on the side of the policy objectives than on the application of the allocation principles to compute European shares.

At European scale, applying a 2°C with p>66% climate change scenario and considering the median value for the allocation of the global limit to Europe, the yearly European limit is between 1.0 and 2.3 Gt CO_2-eq (1.7 and 3.8 t CO_2-eq per capita respectively) (depending on the time horizon). The computed European footprint for 2011 is larger (6.3 Gt CO_2-eq or 10.5 t CO_2-eq per capita). This means that current European production and consumption patterns are not compatible with the global limit in the long run. This conclusion is valid for all allocation principles.

Considering the four additional global budgets corresponding to alternative climate change scenarios (described in Table 4 in Chapter 4), the annual European limit in 2011 ranges from 0.6 to 2.6 Gt CO_2-eq. (1 and 4.3 t CO_2-eq per capita respectively). The fact that the lower bound of the European limit is larger than the lower bound of the global limit (1 vs 0.9) is due to an increase in future global population which is larger than for the European population). The yearly European limit for Climate change is overshot in all of these scenarios.

The EU 2050 policy has for objective to reduce emissions by 80% in 2050. Assuming that the objectives are considered from a consumption perspective, i.e. considering also a reduction outside of Europe along the supply chains of the goods consumed in Europe, the European footprint would be 1.26 Gt CO_2-eq in 2050. This reduction would not enable respecting the limits (since with a 2050 horizon, emissions should stop at this date and since the limit is equal to 1 Gt CO_2-eq with a 2100 time horizon). In addition, this limit will be much lower in 2050 due to the currently too important yearly use of the remaining budget.

Since limits are based on budget over time, several options are possible to spend this budget. In order to get a better understanding of the size of the current EU budget, a simple evaluation of the number of years before depleting it is interesting. The European budget of GHG emissions (89.2 Gt CO2-eq, for the median scenario from IPCC (2°, p > 66% (IPCC, AR5) corresponds to (in 2011):

- 14 years of emissions (until 2025) at the 2011 European yearly emissions rate followed by zero emissions from 2026 on.
- Less than 27 years with an ongoing yearly reduction of 5% followed by zero emissions from 2038 on.
- Sustainable, i.e. in line with the Planetary Boundaries, with an ongoing yearly reduction of 7%.

Evolution over time (1995-2011)

Over the 1995-2011 period, yearly global GHG emissions have been increasing (+ 42% up to 43.6 Gt CO_2-eq in 2011) while the yearly European footprint has been only very slightly increasing (+ 1.9%) over this period (-8.2% lower than at its peak in 2007). The share of the European footprint in global GHG emissions has thus decreased from 20% in 1995 to 14.4% in 2011.

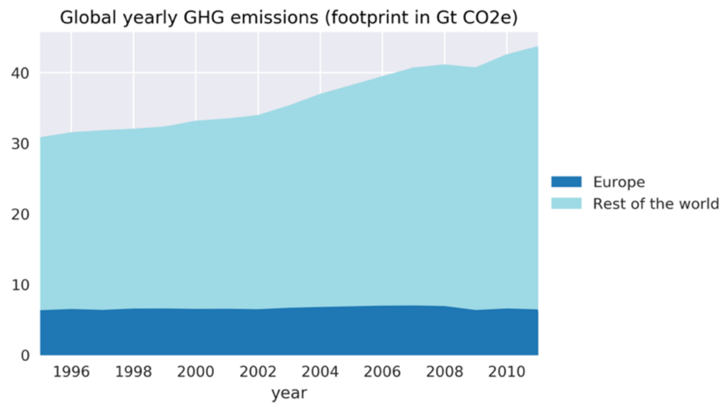

Figure 10 Global yearly GHG emissions from a footprint perspective (in Gt CO_2e)

Comparison with Steffen et al. (2015)

The global limit is different from Steffen et al. (2015) who consider a control variable in terms of atmospheric CO_2 concentration (in ppm). Considering a limit in terms of yearly global production and consumption patterns (PCP) show a larger overshoot than in Steffen et al. (2015) because current PCP produce a high level of emissions which is too high to stay within the long-term bio-physical limits set by Steffen et al. (2015).

Critical review

IPCC global estimates that 49 (+- 4.5) Gt CO_2-eq are emitted in the atmosphere in 2010 (IPCC, 2014). Due to an overall uncertainty equivalent to 10%, the range of possible emissions is thus between 44.5 and 53.5 Gt CO_2-eq. The global greenhouse gas footprint in this study is equal to 43.6 Gt CO_2-eq. (2011), i.e. in the low range of the IPCC emissions. Outside of difference in modelling assumptions, a key reason for this difference is that the database used for computing the footprint does not consider the absorption and releases from land use (LULUCF). In IPCC estimates, LULUCF represent 25% of the emissions, with an uncertainty estimated at 50%[17]. The emissions in this report are also 12% lower than the emissions considered by Dao et al. (2018) (50.8 Gt CO_2-eq), using a different MRIO model and assumptions for carbon modelling (WIOD release 2013[18]). They are also 5.3% lower than the emissions from EDGAR (46 Gt CO_2-eq for 2011) which does not either consider land-use change and forestry sector (Janssens-Maenhout et al., 2017).

The quality of the global results can thus be considered as satisfactory since they are compatible with the global uncertainty suggested by IPCC, while in the lower range. The global overshoot is thus confirmed when using data from IPCC.

The European footprint depends on additional assumptions linked to the use of a global MRIO model to allocate emissions from producing to consuming countries. The size of the error is however very likely smaller than the magnitude of the overshoot (2.5 to 6 time the limit). In addition, changing from a consumption to a territorial perspective (i.e. not considering a footprint) results in similar conclusions (the European footprint is 17% larger than the territorial European GHG emissions as computed in this project with Exiobase).

The evolution of the world and European footprints over the period 1995 to 2008 (+33.6% and +9.5% respectively), is similar to the evolution provided by Arto et al. (2012) computed with another MRIO model (WIOD) and for EU-27 rather than EEA-33 (+29% for the world and +11% for Europe). The absolute values are also very similar for Europe in 2008 (0.7% difference).

While adding emissions from LULUCF to current results would not be feasible easily, it is known that considering LULUCF would add to the European footprint since Europe is a carbon sink but this is not the case of its trading partners. This fact goes in the direction of confirming the overshoot at European level. The European footprint can therefore be considered a conservative estimate.

Difficulties for the integration of LULUCF in MRIO models are multiple. First, there is large variability between models considering the absorption and releases from land use. Second, carbon is sequestered in several components (biomass from forest (53%), dead wood and carbon in soil (39%)) which are not detailed per country nor can easily be allocated to production sectors. Third, changes in land use are difficult to evaluate on a sector based level. (see Appendix 4 for further information).

[17] IPCC also provide an uncertainty for CH_4, equal to 20% (representing 16% of the total GHG emissions).

[18] www.wiod.org

5.5 Ocean acidification

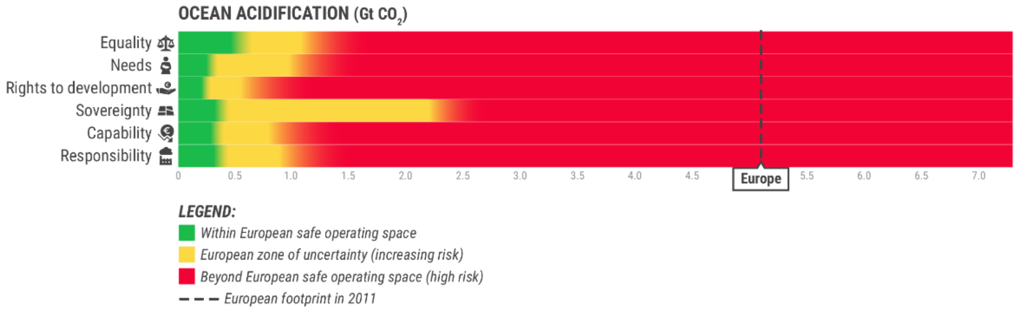

Figure 11 European performance (2011) for Ocean acidification (in Gt CO_2).

Key message

- The global and European limits are overshot.
- Using median values, Europe exceeds the limit by a factor between 3 to 7 depending on the time horizon.
- The trend of the European footprint over the period 1995-2011 is almost flat (+ 0.9%).

Analysis

The global yearly limit is between 7.7 and 20.1 Gt CO_2 (1.1 – 2.8 t CO_2 per capita), varying in function of the length of the period. The global footprint (2011) is equivalent to 33.1 Gt CO_2 (4.7 t CO_2 per capita) in this study. This is 1.7 to 4.3 larger than the limit.

The European yearly limit is between 0.7 and 1.7 Gt CO_2 using median values for the allocation (1.2 – 2.8 t CO_2 per capita). The European footprint (2011) is equivalent to 5.1 Gt CO_2 (8.5 t CO_2 per capita). This means that current European production and consumption patterns are not compatible with the global limit in the long run. This conclusion is valid for all allocation principles.

Since limits are based on budget over time, several options are possible to spend this budget. In order to get a better understanding of the size of the current EU budget, a simple evaluation of the number of years before depleting it is interesting. The European budget of CO_2 emissions (median value equivalent to 68.1 Gt CO_2) corresponds to (in 2011):

- 14 years of emissions (until 2025) at the 2011 European yearly emissions rate, followed by zero emissions from 2026 on.
- Less than 24 years with an ongoing yearly reduction of 5%, followed by zero emissions from 2035 on.
- Sustainable, i.e. in line with the Planetary Boundaries, with an ongoing yearly reduction of 7%.

Evolution over time (1995-2011)

As with GHG emissions over the 1995-2011 period, yearly global CO_2 emissions have been increasing up to 33.1 Gt CO_2 in 2011 (+ 46.5%) while the yearly European footprint have not changed much (+0.9%) (- 8.4% compared to its peak in 2007). The share of the European footprint in global CO_2 emissions has thus decreased from 22.2% in 1995 to 15.3% in 2011.

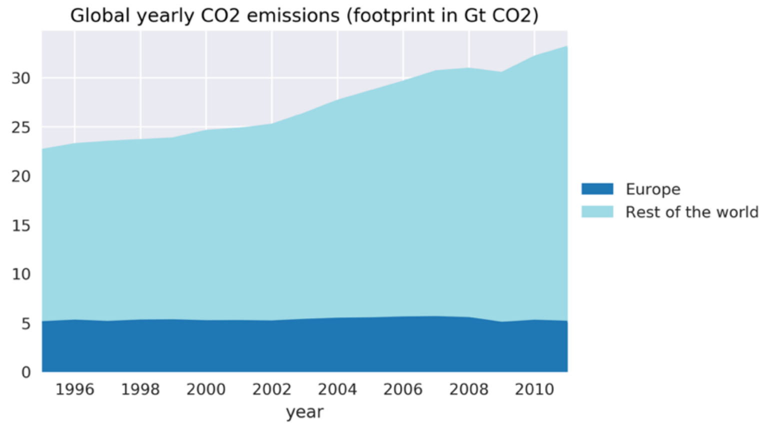

Figure 12 Global yearly CO_2 emissions from a footprint perspective (in Gt CO_2)

Comparison with Steffen et al. (2015)

The limit is different from Steffen et al. (2015) who consider a control variable in terms of carbonate ion concentration (average global surface ocean saturation state with respect to aragonite (Ω arag)). Considering a limit in terms of yearly global production and consumption patterns (PCP) show an overshoot not shown in Steffen et al. (2015) because current PCP produce a high level of emissions which is too high to stay within the long-term bio-physical limits set by Steffen et al. (2015).

Critical review

Like climate change, the Ocean acidification footprint does not consider emissions from land use (LULUCF). Global results are nevertheless estimated to be compatible with the global uncertainty suggested by IPCC (2014), while in the upper range. The computed emissions are also 14% lower than the emissions considered by Dao et al. (2018) (38.6 Gt CO_2-eq) and less than 5% lower than the emissions from EDGAR (33.6 Gt CO_2-eq for 2010 and 34.8 Gt CO_2-eq for 2012) which does not consider land-use change and forestry sector (Janssens-Maenhout et al., 2017).

The quality of the global results can thus be considered as satisfactory. The global overshoot is thus confirmed when using data from IPCC.

The European footprint depends on additional assumptions linked to the use of a global MRIO model to allocate emissions from producing to consuming countries. The size of the error is however very likely smaller than the magnitude of the overshoot (3 to 7 time the limit). In addition, changing from a consumption to a territorial perspective (i.e. not considering a footprint) results in similar conclusions (the European footprint is 11.8% larger than the territorial European CO_2 emissions as computed in this project with Exiobase).

The world and European footprints computed in this report for 2008 are very similar to the values provided by Arto et al. (2012) computed with another MRIO model (WIOD) and for EU-27 rather than EEA-33: a difference of +4.1% for the world and 1.8% for Europe.

5.6 Biogeochemical flows (Nitrogen) – Nitrogen losses

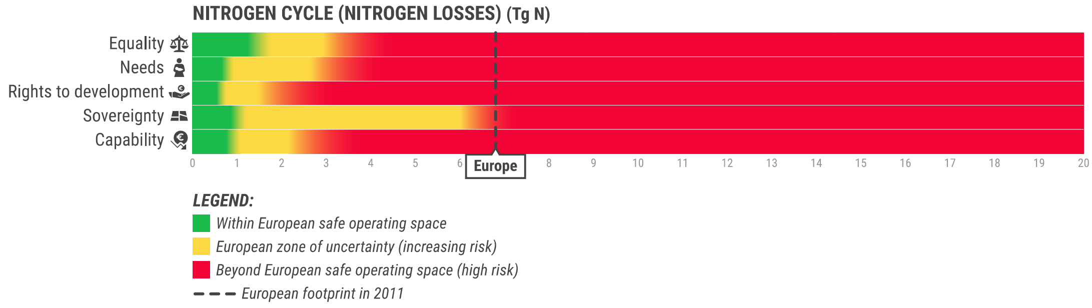

Figure 13 European performance (2011) for Nitrogen losses (in Tg N).

Key message

- The global and European limits are overshot.
- Using median values, Europe exceeds the limit by a factor 3.
- The trend of the European footprint over the period 1995-2011 is slightly positive (+ 4.3%).

Analysis

The global yearly limit in terms of N losses from agriculture is 28.5 Tg N (4 kg N per capita). The global yearly footprint is 49.3 Tg N for 2011 (7.0 kg N per capita) in this report. This is 1.7 time larger than the limit.

The yearly European limit (2011) is 2.1 Tg N using the median value for the allocation (3.5 kg N per capita). The European footprint (2011) is equivalent to 6.8 Tg N (11.4 kg N per capita). The European overshoot is thus proportionally larger than the global overshoot. This conclusion is valid for all allocation principles except for Sovereignty when considering an allocation to Europe based on grandfathering (#11) and economic throughput (#10), i.e. an allocation based on the current European share of global footprints or global GDP.

Evolution over time (1995-2011)

Over the 1995-2011 period, the yearly global nitrogen losses to water have increased by a third (+33.9%). The yearly European footprint has been increasing only slightly during this period (+4.3%) and in 2011, it is 2.7% lower than compared to its peak in 1998. The share of the European footprint in the yearly global nitrogen losses to water is thus decreasing over time, ranging from 13.7% to 18.1% over the period (13.7% in 2011).

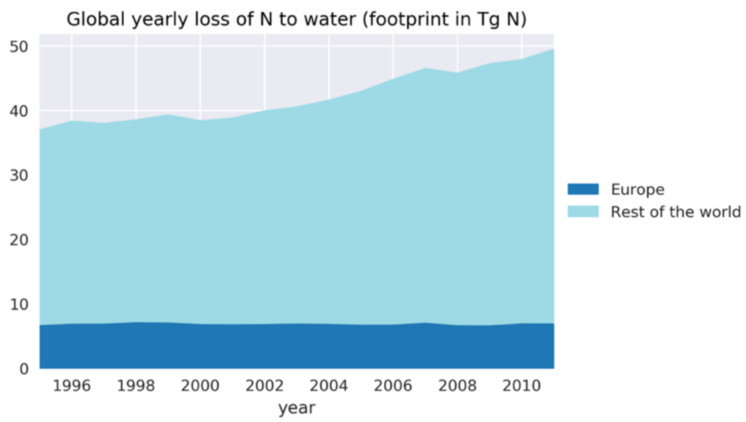

Figure 14 Global yearly losses of N to water from a footprint perspective (in Tg N)

Comparison with Steffen et al. (2015)

As mentioned in Chapter 5.3, the limit computed in this report differs from the limit computed by Steffen et al. (2015) but is completely compatible with it. The only difference is that is considers losses instead of N fixation. The limit differs however slightly from (Dao et al., 2018) (47.6 Tg) and is an improvement since it does not rely on additional assumptions. The resulting overshoot is comparatively smaller compared to the overshoot computed by Steffen et al. (2015).

Critical review

The global computed footprint is smaller than in Dao et al. (2018) (55.6 Tg N) which was taken from the literature (Bouwman et al., 2009 and 2013) rather than computed with Exiobase.

The N footprints generated with Exiobase are modelled with an approach based on a distribution of fertilizers to crops using specific nutrients requirements dependant on production and land use data as well as on a mass balance of N-inputs and outputs (crops and N emissions) following an IPCC procedure (Merciai and Schmidt, 2016). They have been accepted as valid by the scientific community through a publication in Nature sustainability (Hamilton et al., 2018).

Such differences are due to a lack of consensus about the size of Nitrogen releases from leaching and runoffs. This is due to the complexity of the modelling of the N cycle and its sensitivity to local behaviours and local soil conditions. Most of the computations are thus generic and do not include local considerations. This is for example the case of the conversion from applications to releases. Global estimates vary thus considerably. Exiobase includes, for example, N emissions from leaching and runoff that are 50% larger than a global model of reference (Bouwman et al., 2009) (61 vs 41 million tons per year) (Hamilton et al., 2018).

The European footprint depends on additional assumptions linked to the use of a global MRIO model to allocate emissions from producing to consuming countries. The size of the error is however very likely smaller than the magnitude of the overshoot (1.7 time the limit).

In addition, changing from a consumption to a territorial perspective (i.e. not considering a footprint) results in similar conclusions (the European footprint is 18.9% larger than the territorial European releases (5.5 Tg N) as computed in this project with Exiobase). De Vries et al. (2011) compare land nitrogen budgets for territorial European agriculture by various modelling approaches. N loss by leaching and runoff in EU-27 is calculated to be about 2.7 to 6.6 Tg N according to the different models to which NH_3 air releases to water would add 0.3 Tg N. The results from Exiobase are thus in the high range. Assuming Exiobase is wrong by a factor of two, the limit would nevertheless be overshoot.

The quality of the global results can thus be considered as satisfactory considering the level of uncertainty of the N cycle on a global scale.

5.7 Biogeochemical flows (Phosphorus) – Phosphorus losses

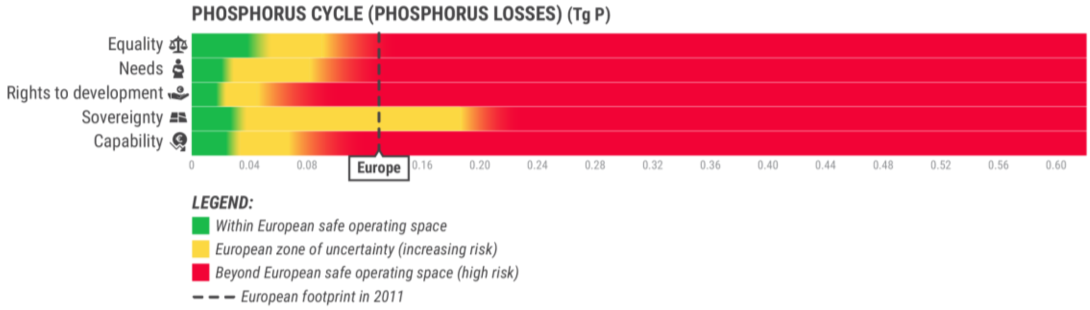

Figure 15 European performance (2011) for Phosphorus losses (in Tg P).

Key message

- The global and European limits are overshot.
- Using median values, Europe exceeds the limit by a factor 2.
- The trend of the European footprint over the period 1995-2011 is negative (- 15.4%).

Analysis

The global yearly limit (2011) for phosphorus losses from agriculture and waste is 0.9 Tg P (0.13 kg P per capita) and the global yearly footprint is equal to 1.8 Tg P (0.26 kg P per capita).

The yearly European limit (2011) is 0.07 Tg based on the median value for the allocation (0.11 kg P per capita) and the European footprint is equal to 0.13 Tg P (0.23 kg P per capita).

The European overshoot is thus very similar to the global overshoot. This conclusion is valid for all allocation principles except for Sovereignty when considering an allocation to Europe based on economic throughput (#10), i.e. an allocation based on the current European share of global GDP. The current footprint is just equal to a limit set based on grandfathering (#11), i.e. an allocation based on the current European share of global footprints.

Evolution over time (1995-2011)

Over the 1995-2011 period, the yearly global phosphorus losses to water have increased (+17.6%) and are equivalent to 1.8 Tg P in 2011. On the contrary, the yearly European footprint has been decreasing during this period (-15.4%), i.e. a 15.7% reduction compared to its peak in 1998. The share of the European footprint in the yearly global phosphorus losses to water is decreasing over time: 7.3% in 2011 and ranging from 7.3% to 10.2% over the period.

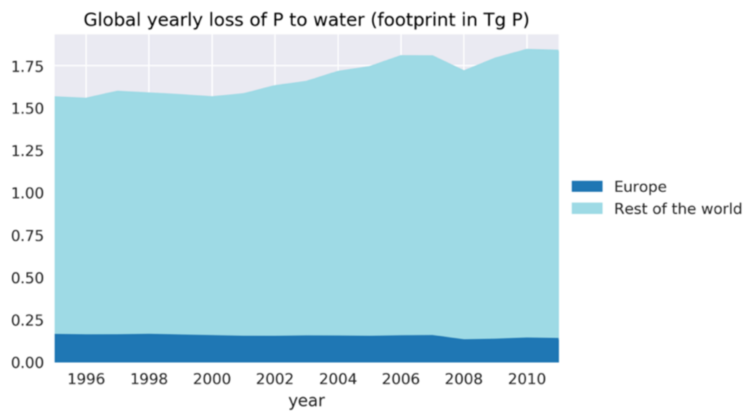

Figure 16 Global yearly losses of P to water from a footprint perspective (in Tg P)

Comparison with Steffen et al. (2015)

The limit applied in this report differs from the limit computed by Steffen et al. (2015) (the quantity of P flowing into the oceans) and from the limit computed in Dao et al. (2018) (the use of P- fertilisers).

In this study, as in Dao et al. (2018), the performance is computed by considering only the P releases from agricultural activities. Their approach is however adapted in order to be compatible with the global limit proposed by Steffen et al. (2015) and to be computable with the database selected for this report. The focus on the P releases from the application of fertilisers and manure in agriculture only means that only 10% of the limit proposed by Steffen et al. (2015) is here considered, hence a limit 10 times lower. The overshot is however, proportionally similar to Steffen et al. (2015) by definition. It contrasts with the results from Dao et al. (2018), who did not consider there is an overshoot.

Why a custom limit? According to Carpenter and Benett (2011), P inputs to oceans are coming from dust air transport (1 Tg) and transport by rivers (22 Tg). This P originate from mining (96% being for fertilisers), human-induced weathering (by land surface disturbance) and natural weathering. The global natural weathering from P-bearing rocks is around 10 Tg per year (pre-industrial flows are estimated around 8 Tg P per year) and releases of P to surface soil due to weathering ranges between 15 and 20 Tg per year. The size of P weathering depends of the current stock of P in erodible soil (50’000 Tg). The annual increase of P in soil from applied mined fertilisers (7 to 10 Tg) is thus very small compared to this stock. Since Exiobase considers only P in terms of yearly inputs of fertilisers, only this incremental part can be captured with the model and not all the weathering of P. These releases are nevertheless important because according to Bouwman et al. (2009 and 2013) they will largely evolve in the future while most of the other P emissions and releases will remain almost constant.

The proposed limit captures thus around 10% of the limit from Steffen et al. (2015) but the considered footprint is equivalent to around 15% of the human induced weathering and considering all the yearly additional inputs to the P stock.

Critical review

The limit proposed in this report is a positive improvement compared to the limit proposed in Dao et al. (2018) because it is more robust and relies on less assumptions.

The limit (11 Tg P) proposed by Steffen et al. (2011) should be considered with caution because the mentioned range of uncertainty is very large (from 11 Tg to 100 Tg). The global computed overshoot (22 Tg global footprint) is thus only valid when considering the lower part of the range.

In addition, the global footprint (P flows to the ocean) proposed by Steffen et al. (2015) is a value which is the most plausible estimate as accepted by several authors from the literature (Carpenter and Benett, 2011). The range of published estimates vary however more than threefold: While Bennett et al. (2001) report a published range of 17–32 Tg per year, Carpenter and Benett (2011) also mention that the most recent estimate, based on the global model NEWS and a better approach (according to their author (Seitzinger et al 2010)) is equal to 8.6 Tg per year.

The P releases computed with Exiobase are modelled with a similar approach than the N releases (Merciai and Schmidt, 2016). The footprints generated with Exiobase have been accepted as valid by the scientific community through a publication in Nature sustainability (Hamilton et al., 2018). There is however a lack of consensus about the size of Phosphorus releases from leaching and runoffs. This is due to the complexity of the modelling of the P cycle and its sensitivity to local behaviours and local soil conditions. Global estimates vary thus considerably.

The footprint in this report has been computed with global characterisation factors from Recipe 2016 (Huijbregts et al., 2017). It is thus an approximation of the footprint in (Hamilton et al., 2018) who applied country-specific characterisation factors also provided by Recipe 2016. Both are however very close since their global footprint is equal to 1.82 Tg P and the European footprint is equal to 0.133 Tg P, i.e. less than 1% of difference compared to the results in this report. This small difference did not justify the additional work of using country-specific characterisation factors.

Mekonnen and Hoekstra (2018) estimate that the global anthropogenic P load to freshwater systems (not to ocean) is estimated at 1.5 Tg per year. These results are in the same order of magnitude than the footprint computed in this report (around 15% lower). Differences are due to variations in modeling assumptions, e.g. a global average of 2.4% for the total P input in the form of mineral fertilizer and manure entering the freshwater through erosion, runoff or leaching while 2.9% is used as single global transfer rate in Exiobase.

It should be noted that while the P run-off from agriculture are 10 times larger than P from urban wastewater, adding urban wastewater to consider P in detergents allow for building a more complete picture and increase considerably the part of the total footprint considered in Steffen et al. (2011). Drecht et al. (2009) estimate the P content of wastewater releases to freshwater to be 1.3 Tg in 2000 and projections of 2.4-3.1 Tg in 2050.

The European footprint depends on additional assumptions linked to the use of a global MRIO model to allocate emissions from producing to consuming countries. The size of the error is however very likely smaller than the magnitude of the overshoot (2 time the limit). In addition, changing from a consumption to a territorial perspective (i.e. not considering a footprint) results in similar conclusions (the European footprint is 43.6% larger than the territorial European P releases as computed in this project with Exiobase) but with less certainty.

The quality of the global results can thus be considered as satisfactory considering the level of uncertainty of the P cycle on a global scale. Mekonnen and Hoekstra (2018) mention however that due to the large range of existing results, “an extensive literature review and further field studies will be needed to come up with better estimates”.

5.8 Freshwater use

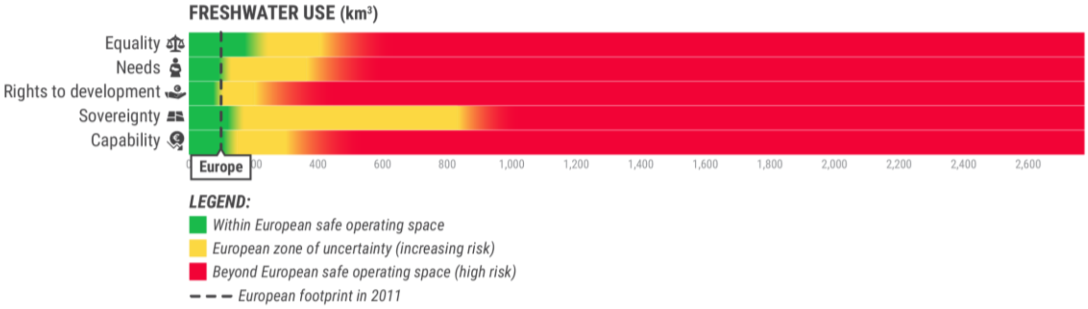

Figure 17 European performance (2011) for Freshwater use (in Tg P).

Key message

- The global and European limits are not overshot.
- Using median values, Europe is a factor 3 below the limit.
- The trend of the European footprint over the period 1995-2011 is largely positive (+25.3%).

Analysis

The global yearly limit (2011) is 4'000 km^3 (Steffen et al. (2015)), i.e. 568 m^3 per capita. The global footprint is equal to 1'225 km^3 (174 m^3 per capita) in this study for 2011.

The yearly limit for Europe (2011) is 291 km^3 (488 m^3 per capita) using the median value for the allocation. The European footprint (2011) is equivalent to 99.1 km^3 (166.6 m^3 per capita). The European situation is thus very similar to the global situation (almost three times under the limit).

This conclusion is valid for all allocation principles.

The fact that the global PB is not overshoot does not mean that freshwater use is not a critical issue in multiple regions.

Evolution over time (1995-2011)

Over the 1995-2011 period, the yearly global blue water consumption has increased by a third (+32.1%). The yearly European footprint has been increasing slightly less during this period (+25.3%). In 2011, it is 4.4% lower compared to its peak in 2008. The share of the European footprint in the global blue water consumption is very stable over time, from 7.9% to 9.5% (8.1% in 2011).

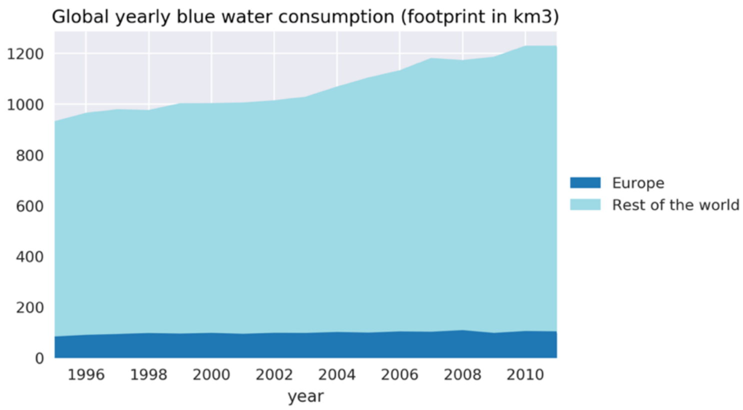

Figure 18 Global yearly blue water consumption from a footprint perspective (in km^3)

Comparison with Steffen et al. (2015)

The limit in this report is similar than in Steffen et al. (2015). The global footprint is however two times lower in this study (1'225 km^3 instead of 2'600 km^3). The footprint from Steffen et al. (2015) is taken from Shiklomanov (1999) cited in (World Water Council, 2000) which assumes that blue water consumption in 1995 is equal to around 5% of the 40'000 km^3 blue water available. Shiklomanov (1999) is also the source of the FAO-Aquastat database for water withdrawal in 1995 (10% of the blue water available). Explanations are given below on the source of the 1'225 km^3.

Critical review

According to Exiobase supplementary information for water accounts (Brucker and al., 2016), the water dataset is "strictly aligned with the UN-SEEA Water (United Nations 2012a), the UN International Recommendations for Water Statistics (United Nations 2012b) and the recent water accounting framework set up by members of the project team for Eurostat. However since data on "water withdrawal and consumption are scarce – especially on the international level" modelled data is used using two main sources: the Water Footprint dataset (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. Data has 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. The WaterGap model has been recognised as a valid model and its results "have contributed to international assessment of the global environmental situation including the UN World Water Development Reports, the Millennium Ecosystem Assessment, the UN Global Environmental Outlooks as well as to reports of the Intergovernmental Panel on Climate change"[19]. The Water Footprint dataset is one of the reference datasets on water footprint (Hoekstra and Mekonnen, 2012).

Hoekstra and Mekonnen (2012) global blue water footprint is between 943 and 1'025 km^3 (for the 1996-2005 period). This is closer (around 20% lower) to the results from Exiobase computed for 2011 than from the values in Steffen et al. (2015). Their methodology is different from FAO-Aquastat for the water use for agriculture and FAO-Aquastat is used for the water withdrawal related to industrial production and domestic water supply with a consumptive share of 10%. Due to the facts that a) FAO-Aquastat only proposes data for water withdrawal but not consumption, b) the Water Footprint dataset is more specialised than the FAO-Aquastat for agriculture, and c) the consumption of blue water by agriculture is close to 85% of total blue water consumption, we assume here that the results for global water consumption are more correct than the estimate in Steffen et al. (2015).

The European footprint depends on additional assumptions linked to the use of a global MRIO model to allocate emissions from producing to consuming countries. The size of the error is however very likely smaller than the magnitude of the undershot (a third of the limit). In addition, changing from a consumption to a territorial perspective (i.e. not considering a footprint) results in similar conclusions (the European footprint is 53% larger than the territorial European blue water consumption as computed in this project with Exiobase). Hoekstra and Mekonnen (2012) also compute country footprints (not using Exiobase) which result in a European blue water footprint of 84 km^3, i.e. 15% lower than with Exiobase.

The evolution of the world and European footprints over the period 1995 to 2008 (+26% and +31% respectively), is different (but showing a similar trend) from the evolution provided by Arto et al. (2012) computed with another MRIO model (WIOD) and for EU-27 rather than EEA-33: +37% for the world and +34% for Europe. The absolute values are even more different and are somewhere in between the values in this report and in Steffen et al. (2015) for global freshwater use: 1'968 km^3 while the European blue water consumption is estimated at 222 km^3 for EU27. The same conclusion can however be made.

The quality of the global and European results can thus be considered as satisfactory.

[19] Wikipedia, https://en.wikipedia.org/wiki/WaterGAP, 06.09.18.

5.9 Land-system change - Land cover anthropisation

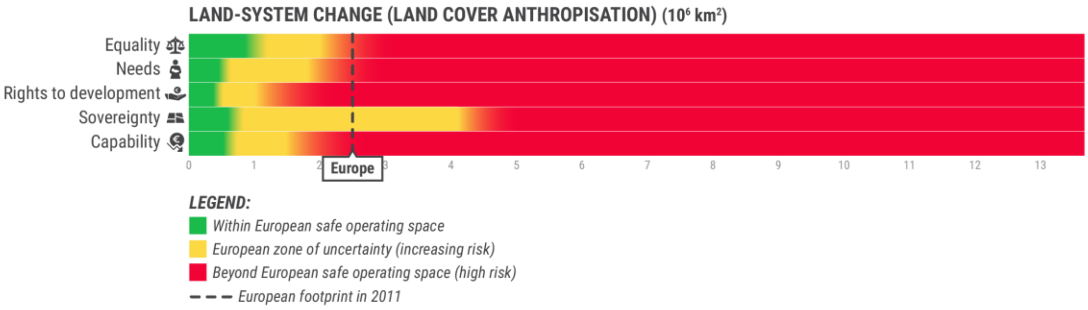

Figure 19 European performance (2011) for Land cover anthropisation (in 10^6 km^2).

Key message

- The global limit is not overshot but the European limit is overshot.
- Using median values, Europe exceeds the limit by a factor 1.8.
- The trend of the European footprint over the period 1995-2011 is almost flat (+ 1.3%).

Analysis

The global yearly limit considering cropland and infrastructure land is 19.4 10^6 km^2 for 2011 (Dao et al. (2018)), i.e. 2'749 m^2 per capita. The global footprint is equal to 17 10^6 km^2 in this study (2'413 m^2 per capita) for 2011.

The European yearly limit is 1.4 10^6 km^2 (2'364 m^2 per capita) using the median value for the allocation. The European footprint (2011) is equivalent to 2.5 10^6 km^2 (4'150 m^2 per capita). The European situation is thus totally different from the global situation since there is an overshoot.

This conclusion is valid for all allocation principles except for Sovereignty when considering an allocation to Europe based on grandfathering (#11) and economic throughput (#10), i.e. an allocation based on the current European share of global footprints or global GDP.

Evolution over time (1995-2011)

Over the 1995-2011 period, the yearly global surface of anthropised land is stable (+3.2%). The yearly European footprint has been similarly stable (+1.3%) over this period. In 2011, it is 4.3% lower than at its peak in 1998. The share of the European footprint in the global anthropised surface is very stable over time, from 14% to 15.7% (14.5% in 2011).

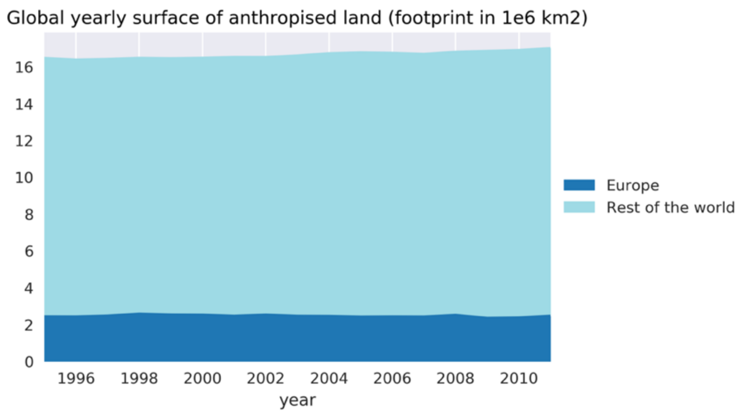

Figure 20 Global yearly surface of anthropised land from a footprint perspective (in 10^6 km^2)

Comparison with Steffen et al. (2015)

The limit applied in this report differs from the limit computed by Steffen et al. (2015), i.e. the area of forested land as % of original forest cover (limit = 75% – 54%). It is similar to the limit in Dao et al. (2018) who set a limit following Rockström et al. (2009), i.e. the surface of land cover converted to cropland (limit = 15%), but extending it to consider urbanised (sealed) land in addition to agricultural land (arable land and permanent crops) only as percentage of ice-free land excluding water bodies.

According to Dao et al. (2018), a logic similar to Rockström et al. (2009) is applied to compute a custom limit accounting for the types of land considered: "starting from the current situation, maximum desirable changes are set. The limit is set based on two policy objectives: (a) a stable surface of urban area per capita until 2050, resulting in an estimated additional share of urban area of 0.8% (from 1% to 1.8% of the global area) by 2050, and (b) a respect of the call published by UNEP (Trumper et al., 2009) to cut the current global deforestation rate by two until 2050 and to stabilise beyond, resulting in a maximum additional loss of forest cover of 1% by 2050."

While considering a different indicator than in Steffen et al. (2015), the distance to the current limit is similar (slightly stricter): it is 14% above the global footprint while it is 22% above in Rockström et al. (2009) and 17% above in Steffen et al. (2015).

Critical review

The Planetary Boundary Land System Change is focussing on "the biogeo-physical processes in land systems that directly regulate climate—exchange of energy, water, and momentum between the land surface and the atmosphere." (Steffen et al., 2015). As a result, it does not consider the other essential roles played by land on Earth (to humans, e.g. ecosystem services, and animal communities). The fact that the global PB is not overshoot does not mean that land use is not a critical issue in multiple regions.

In Exiobase, land use data is modeled based on reference data from the FAO database and additional assumptions (Theurl et al., 2016). The global footprint is thus similar (2% smaller) to results in Dao et al. (2018) which use the same source but other assumptions.

The European footprint depends on additional assumptions linked to the use of a global MRIO model to allocate emissions from producing to consuming countries. The size of the error is however very likely smaller than the magnitude of the overshoot (1.8 time the limit). In addition, changing from a consumption to a territorial perspective (i.e. not considering a footprint) results in similar conclusions (the European footprint is 42.7% than the territorial European land cover anthropisation as computed in this project with Exiobase) but with less certainty.

The evolution of the world and European footprints over the period 1995 to 2008 (+2% and +3.1% respectively), is close to the evolution provided by Arto et al. (2012) computed with another MRIO model (WIOD) and for EU-27 rather than EEA-33 (+2% for the world and +4% for Europe). The absolute values are however different and higher in this study for Europe (+26.8%) and for the world (+9%).

It should be noted that the modelling of infrastructure land, while small on a global scale (smaller than 5% of global land) could be an issue for some highly-built countries for two reasons. First, because of the low quality of the global datasets existing on this topic. Second, because the allocation of build land to sectors is problematic. In Exiobase, built land is allocated to final demand, i.e. it is not distributed through trade. Other solutions could be set in place (e.g. proportionally to value-added to consider the services provided by build land to economic sectors).

In addition, the limit and footprint in this report does not consider permanent pastures because it is not clear which share have been deforested in each country. Including them could be an added-value in the future.

5.10 Change in biosphere integrity (genetic diversity)

Steffen et al. (2015) propose an interim control variable in terms of the global extinction rate to consider 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.”

Biosphere integrity as genetic diversity has not been evaluated in this report. While several publications exist to compute footprints at global scale, the authors of this report do not believe that such a complex issue is adequately dealt with in such models yet. This is due to the complexity of the issue, its highly local and regional nature and the lack of appropriate data.

New innovative approaches are however developed and could be applied in the future assuming they are proved as robust enough or accepted as an adequate accounting approach. Switzerland recently (in September 2018) released a new report applying one of these new approaches. It is presented here as an example of the current State of the Art.

The biodiversity footprint presented here is necessarily a gross simplification of the complex issue of biosphere integrity. However, it gives an indication of where in the world the consumption of a country is likely to affect biodiversity most. There is an ongoing discussion on the operationalisation of biodiversity in national footprints, see e.g. Mace et al. (2014), and Sala et al. (2016). Chaudhary and Brooks (2017) applied a similar approach on biodiversity impacts of national consumption and world trade and critically discuss its merits and shortcomings. Chaudhary and Brooks (2018) derived updated characterization factors for projecting potential species losses.

The biodiversity footprint of Switzerland

The biodiversity footprint for Switzerland was calculated based on the interim recommendations of the UN-hosted Life Cycle Initiative[20], and is also recommended by Meyer and Newman (2018, forthcoming). The indicator is a further development of a similar indicator implemented in Frischknecht et al. (2014) and Dao et al. (2018). It has recently been updated and extended (Chaudhary & 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 a specific land use (such as agriculture or settlements) compared to an untouched, natural reference state. It takes the vulnerability of species into consideration and converts the regional decline of widespread species and the global extinction of endemic species into “completely globally extinct species”. The equivalents of potentially globally extinct species are integrated over the years and quantified per million species (micro-PDF·a) or per billion species (pico-PDF·a).[21] Using comparisons to a natural state, the indicator describes the likelihood that species will become irreversibly extinct due to the 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 or habitat fragmentation are not addressed.

In order to calculate Switzerland’s biodiversity footprint a combination of data was used: domestic emissions inventories, trade data, and life cycle assessment data (TRAIL method)[22]. Given that biodiversity impacts of land use are highly location-specific, the latter were regionalised on a country

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[20] The Life Cycle Initiative is a programme hosted by the United Nations Environment Programme (UNEP) with global outreach, see www.lifecycleinitiative.org/applying-lca/lcia-cf/, see also see Chaudhary et al. (2015), Chaudhary et al. (2016) and Frischknecht & Jolliet (2017)

[21] 1 pico-PDF ·a = 10^{-12} PDF ·a (i.e. a trillionth PDF ·a); PDF = potentially disappeared fraction of species; the term “species-years” refers to this integration over time.

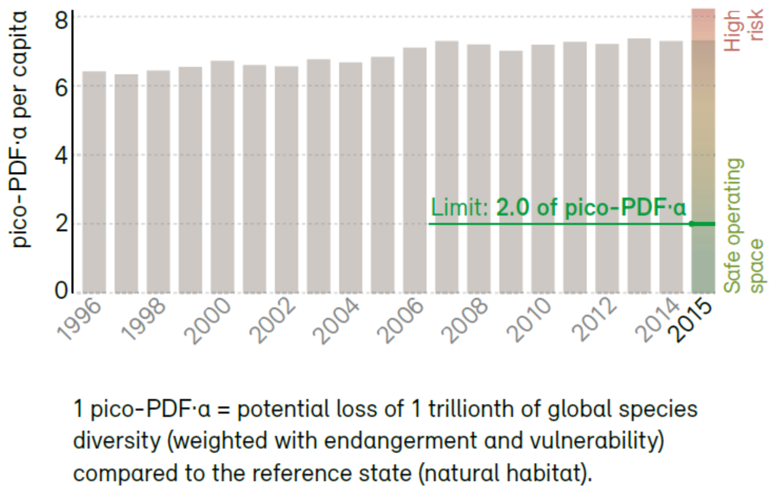
[22] TRAIL stands for trade information and LCA (life cycle assessment) in reference to the fact that trade and life cycle assessment data are used.

scale, based on the World Food Life Cycle Database WFLDB (Nemecek et al. 2015), KBOB et al. (2016), FAOSTAT (2017), and Pfister et al. (2011).

Switzerland's biodiversity footprint was compared to the boundary for biosphere integrity proposed by Steffen et al. (2015). They propose to use the global yearly extinction rate as an interim control variable with a boundary value of yearly ≤ 10 extinctions per million species-years (E/MSY). As a second control variable, Steffen et al. propose the Biodiversity Intactness Index (BII).[23] The former control variable has been used and operationalised as follows.

The first large-scale human influence on biodiversity was caused by man-made deforestations, 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. A yearly extinction rate of 10 species per million species and year over the last 1,500 years - 15,000 species per million species was assumed as threshold value. Applying an equal share per capita approach, a yearly footprint limit of 2.0 Pico PDF·a per capita was deduced.

The Swiss biodiversity footprint per capita from 1996 to 2015 increased by around 14%. It totalled 7.5 pico-PDF·a in 2015 (cf. **Erreur ! Source du renvoi introuvable.**). In absolute terms, it totalled nearly 62 species-years per million species (micro-PDF·a). The planetary boundary level (threshold value) is 73% and the natural extinction rate is even 97% below that value.[24]



Development of consumption-based pressure on biodiversity due to land use in pico-PDF·a per capita, divided into the consumption-based impact caused in Switzerland and abroad. Other influential factors on biodiversity such as pollutant loads or fragmentation effects are not taken into account.

Figure 21 Development of Switzerland's consumption-based biodiversity footprint per capita. Source: Calculations treeze and Rütter Soceco.

[23] It must be kept in mind that Steffen et al. (2015) proposed the extinction rate as an interim control variable only, as long as global data for Phylogenetic Species Variability are not yet available.

[24] In other words: The Swiss biodiversity footprint exceeds the planetary boundary level (threshold value) by 270% and the natural extinction level by more than 3'000%.

6 Regional boundaries and data

Regional information is interesting for three reasons. First to consider how regional transgressions of limits can contribute to a global overshoot. Second, to improve the quality of assessments dealing with environmental phenomena having an environmental impact at regional scale, for example water scarcity, and to better understand where environmental loads and impacts are occurring to enable action, for example for reducing GHG emissions. Third, to increase the correspondence with EEA data, and thus increase the coherence with current reporting and policies by giving the possibility to go to the regional level.

6.1 Regional boundaries in Steffen et al. (2015)

In addition to the global limits, Steffen et al. (2015) propose sub-global limits for five PB. These limits are compatible with the global limits and their objective is to better consider the fact that the overshot of sub-global boundaries contribute negatively to the aggregated outcome at planetary-level: only the global aggregated outcome is, by definition, of importance in the Planetary Boundaries framework. Steffen et al. (2015) clearly state that “The PB framework is therefore meant to complement, not replace or supersede, efforts to address local and regional environmental issues.”

Among these five limits, three are considered in this report: Biogeochemical flows (Phosphorus and Nitrogen), Land-system change and Freshwater use.

For Biogeochemical flows (Phosphorus), Steffen et al. (2015) consider a control variable in terms of the P from fertilizers applied to erodible soil. While the objective of the global limit is to avoid a large-scale ocean anoxic event, the objective of the regional limit is to avoid a widespread eutrophication of freshwater systems. The focus is thus here on fertilizers in cropland.

According to Steffen et al. (2015), the current transgression of the boundary (14.2 Tg P per year for a limit set at 6.2 Tg P per year) comes from a “a few agricultural regions of very high P application rates”. These regions are mainly in the USA, Europe, the north of India and in China.

Similarly, according to Steffen et al. (2015), a few agricultural regions with a very high rate of application of N are the main contributors to this boundary. These are the roughly the same responsible of the P footprint.

For Land-system change, Steffen et al. (2015) consider a control at the biome level in terms of the area of forested land as % of potential forest cover. Three major forest biomes for climate regulation are considered (tropical, temperate and boreal) with specific limit values (85%, 50% and 85% respectively vs 75% for the global forest limit). According to Steffen et al. (2015), the temperate and boreal forests are in the zone of uncertainty while the tropical forest is beyond the zone of uncertainty (high risk) in Asia and Africa but safe in North and South America.

For Freshwater use, Steffen et al. (2015) consider a control variable at the basin level in terms of the blue water withdrawal as % of mean monthly river flows. According to Steffen et al. (2015), the main area beyond the zone of uncertainty (high risk) are on the west coast of North and Central America, the coast of North Africa, and on a band going from the south of Europe to India and the north of China.

6.2 Considering sub-national data in footprints

The computation of the footprints is based on an internationally harmonised database (Exiobase 3.4). While this database has been designed in order to be compatible with national accounts, many internationally coherent datasets, and models, have been used rather than datasets published by the EEA or official EU datasets. Several aspects can be considered in order to understand the possibilities and limitations of linking such a global model with sub-national datasets.

First, the availability of data for the same indicator both in the MRIO model and in regional datasets. Due to a lack of data in many developing economies, adding more precision evenly based on regional data is probably not possible for all countries in the world. From an environmental perspective, increasing the level of details in EEA countries only makes sense if a large share of the impacts is occurring domestically and not in trade partner's territories. Existing studies show however that a large share (the majority in some cases) of the impacts are occurring outside of developed economies through trade linkages.

Second, the possibility/validity of mixing global and regional datasets in a coherent way knowing that the whole world will not be modelled similarly and with the same level of details in both cases. While some of the indicators are both available in the MRIO model and in Eurostat/EEA databases at sub-national scale, the very nature of MRIO models make the inclusion of regional datasets difficult and the quality of the result can be questioned:

- Global models are a coherent representation of the world. This process requires calibration to make all parts coherent between them. Each individual component is modified during the process, some more than others. The exact match with original detailed data is thus not possible.
- The compatibility of the data generated by official bodies from different countries in the world cannot be guaranteed. In addition, a large part of the information in the MRIO is not generated by statistical offices but is modelled. The difference with the official data sets is unavoidable if different models and assumptions are used. This is particularly true for developing economies since most of the models are generated in developed economies. This is an issue since a growing (the majority for key environmental issues) part of the impacts are induced in developing economies.
- The computation of footprints requires square country tables (i.e. with a similar number of producing and buying sectors). The raw data generated by statistical offices or modelled is however not built using square tables but rather with tables representing the supply or the use of the goods by sectors (each sector can produce one or several goods). The generation of footprints requires thus additional assumptions regarding technology to generate square tables, hence the introduction of an additional difference with raw data and possibly regional data.
- Generating sub-national information induce additional uncertainties due to the fact that the MRIO model is at national scale. In these models, there is no information on the location of production activities, nor if these activities are for domestic consumption or exported to a specific trade partner. Extrapolation are usually based on the location of population or GDP as proxy.
- The information to allocate environmental information to each one of the economic sectors of the MRIO model (required to enable computing impacts over global value chains) is often missing at regional scale.
- The quality of the assumptions, which is enough when modelling at country and global scale (i.e. they are average values), are however usually not enough to model the specificities at regional scale.

The inclusion in the model of information at sub-national scale in order to increase its quality seems thus a difficult objective. We believe however that information at sub-national scale is of high interest in order to better understand the location and sources of impacts in an iterative process. For a specific problem, the following steps can be followed:

- With the MRIO model: Identification of the country and sectors responsible of the impact (in terms of consumption and production).
- With additional data sets from Eurostat or EEA: Identification of the region responsible of the impact either by using existing indicators or based on proxies, e.g. population or GDP or spatial land use data sets.

7 Conclusion and suggestions

Allocating the global limits of the Planetary Boundaries framework between countries means sharing resources between them. Many different allocation principles and computation methods have been designed in this aim, particularly since the discussions related to climate change. We provide in this report the first systematic exploration of the allocation approaches with respect to the Planetary Boundaries framework, both from a theoretical and quantitative perspective.

The computed range of European shares can be seen as large (from 0.2% to 21%) at first sight. It is however influenced by extreme cases: Considering all principles results in a median European share of 7.3% while it is slightly lower when not including the principle of responsibility (6.8%).

Considering the Equality principle as starting point, the application of all other principles reduces the European share except when applying the principle of Sovereignty. Considering an equal share per capita approach results in the second highest share for Europe.

Several options are possible to set the reference European share. The median European share (7.3% with the Responsibility principle or 6.8% without it) could be applied. Another possibility would be to set the reference European share equivalent to the average of the range based on median values. It happens that this value represents the value computed for the Equality principle (8.1%). Setting a 50% larger value would result in the maximum median value, Sovereignty (12.5%) while setting a 50% lower value would result in the minimum median value, Rights to development (4.1%). This proposal seems adequate to account for the uncertainty with respect to the range of shares. It should be noted that since this uncertainty is much lower than the uncertainty with respect to the evaluation of the limits of the Planetary Boundaries by Steffen et al. (2015). The main messages related to the choice of a reference share are thus of ethical and policy nature.

The current global footprints using Exiobase yield results compatible with the previous studies by Dao et al. (2015 and 2018) and in the blueDot project. Differences can be explained by the use of another dataset or the inclusion of better data and knowledge to compute the global limits. While not all environmental aspects are considered within Exiobase (e.g. no consideration of land use changes for climate change), we believe that the provided results are robust enough to be used. They enable showing the interest of considering global issues beyond climate change and the role of Europe in terms of impacts in the rest of the world. The overall finding is in line with a recent assessment by Häyhä et al. (2018) that “based on equal-per capita allocation of the global safe operating space, the EU does not appear to be “living within the limits of our planet” for most of the boundaries analysed, and that from a consumption-based (footprint) perspective, Europe’s per-capita contribution to the different PBs is significantly higher than the global average.

While approximations had to be performed to generate limits and footprints (related to socio-economic activities), they are in line with current practices in this field and in accordance with the current status of scientific developments in this area. These approximations show however that further research is needed. Further work is particularly needed to generate results for Biodiversity and to improve the evaluation of Phosphorus losses.

The European performance is influenced by the choice of an allocation method. Based on median values computed in this report, Climate change, Ocean acidification, Nitrogen losses and Phosphorus losses are overshot in 2011 at global scale and for Europe. Land cover anthropisation is overshot for Europe but not for the world. Freshwater use is not overshot.

Conclusions regarding the need for action

The Planetary Boundaries framework has come to light for a reason: the extent of human activities and their impacts on the environment are increasing faster than ever due to the large increases in global population and global wealth of the last decades.

The Planetary Boundaries framework and this report confirm some common knowledge with respect to climate change: it is a key issue and should be tackled in priority. In addition, this report shows (as in

Dao et al. (2018)) that ocean acidification is also a critical issue that should be tackled in priority since this limit is at risk of being overshot even more rapidly than climate change. Furthermore, there is an increasing need for action on nitrogen and phosphorus footprints.

In order to contribute to staying within a safe operating space, the European footprint should thus be reduced, in priority, by a factor 3 to 6 for Climate change and 3 to 7 for Ocean acidification. Then, as a second priority (because the evolution is less rapid at global scale), the European footprint should be reduced by a factor 3 for Nitrogen losses and 2 for Phosphorus losses. A reduction by almost 2 would also be needed for Land cover anthropisation but it is less of a priority since there is not global overshoot. Based on the Planetary Boundaries framework, there is no reduction needed for Freshwater Use. These results consider however only global issues and do not preclude that there are not regional issues which should be also considered.

The magnitude of the need for action is huge. Postponing action would be a risky option. The longer we wait, the smaller the remaining budget. Furthermore, given that transitions take time, and that future possibilities depend on paths taken in the past, even small steps in an early stage may be crucial for achieving ambitious goals.

In order to transform current unsustainable consumption and production patterns to patterns that are in line with planetary boundaries, a combined effort of companies, governments, research and civil society is necessary (see e.g. Sabag Muñoz, Gladek (2017)). Such transformation processes are complex and should be simultaneously addressed at multiple levels, using various governance styles at different stages (see e.g. EEA (2017)).

In the light of the heterogeneity of possible allocation approaches we see the need for a public dialogue both within countries and between countries on how to share burdens, roles and responsibilities in implementing the UN Agenda 2030. In addition to the public dialogue a dialogue among experts is needed as well. In addition to quantitative aspects, the latter should also deal with normative (ethical and juristic) aspects of the allocation principles and what they mean for implementation. While such decisions are in the end political, clarifications on their normative foundations would, indeed, clarify the debate.

8 Appendix 1. Computation methods

This appendix lists additional information per computation method. Detailed computations are provided in the Excel document provided with the report.

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

All data for computing min, avg, median and max European shares is for 2011 (or earlier years when relevant) except for bio-capacity (2017). The values for the most recent year have been updated for population and population per age group (2015), HDI (2015), GDP PPP (2015) as well as for the footprints considered for computing methods #14 and #15 using extrapolations of Exiobase for the years 2012-215 computed by NTNU specifically for the EEA.

8.1 Allocation principle A: Equality

Computation method 1: Equal share per capita

- Allocation key: total population
- Unit: persons
- Source: UN Population Division, World Population Prospects 2017 https://esa.un.org/unpd/wpp/
- Scenarios: Three scenarios are built by varying the considered year: 1990, 2000, 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

- Allocation key: total population (cumulated)
- 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, 2011) and end year (2050, 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 period.

8.2 Allocation principle B: Needs

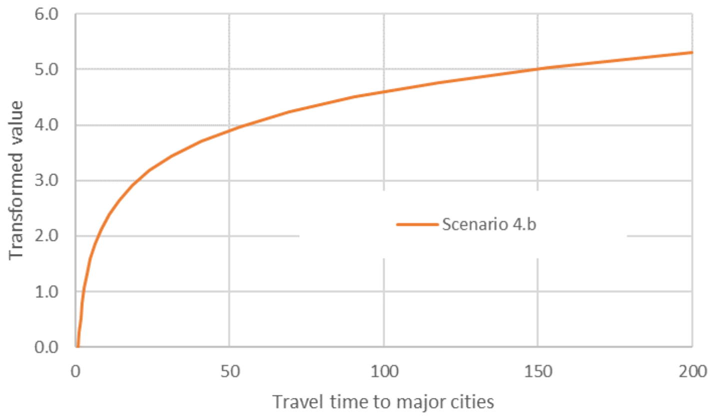
Computation method 3: Equivalence between children and adults

- Allocation key: population, share of ages 0-14, OECD equivalence scale
- Unit: % 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

- Allocation key: travel time to major cities
- Unit: minutes per capita
- Source: Own calculations based on the dataset "Travel time to major cities: A global map of Accessibility" accessible from JRC http://forobs.jrc.ec.europa.eu/products/gam/
Background paper: (Uchida et al., 2008).
- Scenarios:
  - Scenario 1: no transformation
  - Scenario 2: logarithm of the 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 1km spatial resolution) divided by the world population weighted by the average the per capita travel time (as for the European population).



Computation method 5: Nutrition

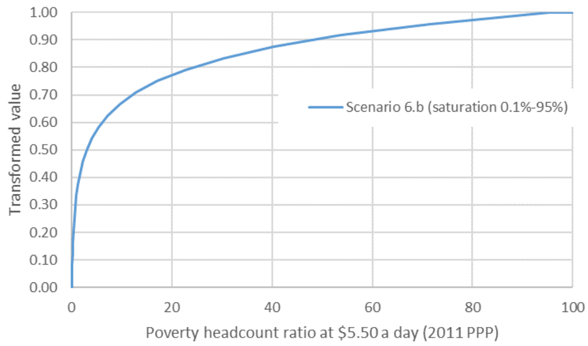
- Allocation key: Food Nutrient Adequacy
- Unit: 0-100 scale
- Source: (Chaudhary et al., 2018)
- Function: The European share is equal to the European population weighted by the distance to the theoretical maximum Food Nutrient Adequacy score of 100, divided by the world population weighted by the distance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

8.3 Allocation principle C: Rights to development

Computation method 6: Poverty line

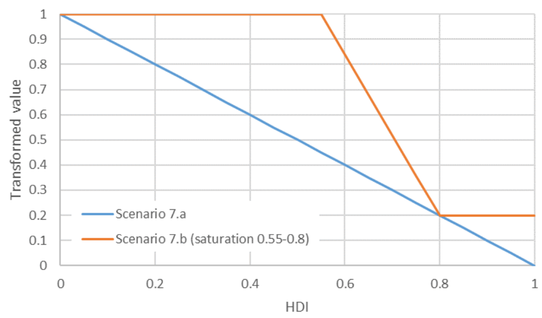
- Allocation key: Poverty headcount ratio at $5.50 a day (2011 PPP)
- Unit: % of population

- Source: World Bank, World Development Indicators https://data.worldbank.org/indicator/SI.POV.UMIC
- Scenarios:
    - Scenario 1: logarithm of the % of population
- Function: The European share is equal to the European population weighted by the percentage of people at $5.50 a day (2011 PPP) divided by the world population weighted by the percentage of people at $5.50 a day (2011 PPP) (as for the European population).



Computation method 7: Development level

- Allocation key: Human Development Index (HDI)
- Unit: unitless
- Source: HDR (2015)
- 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).

8.4 Allocation principle D: Sovereignty

Computation method 8: Land

- Allocation key: land area
- Unit: ha

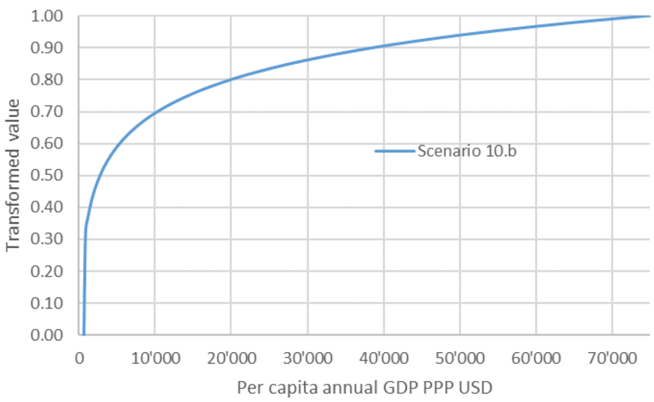
- Source: FAO, Land Use data http://www.fao.org/faostat/en/#data/RL
- Function: The European share is equal to the European land area divided by the world land area.

Computation method 9: Bio-capacity

- Allocation key: bio-capacity
- Unit: global hectares (gha) per person
- Source: Global Footprint Network, 2017 Edition National Footprint Accounts: Ecological Footprint And Biocapacity (Data Year 2013) http://data.footprintnetwork.org.
- Function: The European share is equal to the European bio-capacity (i.e. the European population multiplied by the European average per capita bio-capacity) divided by the world bio-capacity (calculated the same way as for the European population).

Computation method 10: Economic throughput

- Allocation key: GDP PPP
- Unit: constant 2010 USD 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 in the approach applied in (HDP, 2015), the index is a normalised version of the natural log: ln(value) – ln(min) / ln(max) – ln(min)



- 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

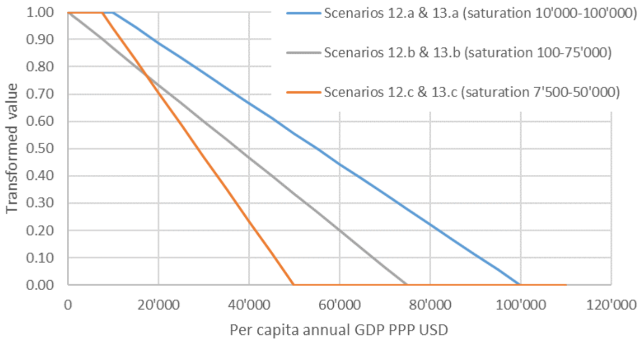
- Allocation key: footprints computed in this report
- Unit: various units (different for each Planetary Boundary)
- Source: Exiobase 3.4, http://www.Exiobase.eu/

- 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.

8.5 Allocation principle E: Capability

Computation method 12: Income

- Allocation key: GDP PPP
- Unit: constant 2010 USD per capita
- Source: World Bank, World Development Indicators https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD
- Scenarios:
  - Scenario 1: saturation points of GDP per capita values set at 10'000 and 100'000 USD (empirical observation of values in the Maddison Project Database[25]).
  - Scenario 2: saturation points of GDP per capita values set at 100 and 75'000 (the min. & max. values used for the standardisation of the income component of the Human Development Indicator).
  - Scenario 3: saturation points of GDP per capita values set at 7’500 and 50'000 USD (the min. & max. values proposed in the CERP Responsibility & Capability calculator https://calculator.climateequityreference.org/).



- 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

- Allocation key: cumulative GDP PPP (since 1990)
- Unit: constant 2010 USD per capita
- Source: World Bank, World Development Indicators https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD
- Scenarios: similar to the allocation method 10.

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[25] https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018

- Function: Similar to 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).

8.6 Allocation principle F: Responsibility

Methods 14 and 15 apply only to climate change and to ocean acidification since they are the only budgets over time.

Computation method 14: past emissions

- Allocation key: past emissions
- Unit: CO_2-eq emissions (Climate change), CO_2 emissions (Ocean acidification)
- Source: UN Population Division, World Population Prospects 2017 https://esa.un.org/unpd/wpp/, footprints computed in this report for emissions
- Scenarios: As in method 2 and in accordance with Dao et al. (2018), six scenarios are built for Climate change by varying the start year (1990, 2000, 2011) and end year (2050, 2100). Three scenarios are built for Ocean acidification (only two starting dates 2005, 2011).
- Function: A six-step calculation:
    - The demographic share of Europe in the world at a start year in the past (e.g. 1990) is the European population at start year divided by the world population at start year.
    - The European budget (over time) at start year is the world budget (over time) at start year multiplied by the demographic share of Europe at start year.
    - The budget remaining over time at present time (European and world) is the budget at start year minus the cumulative emissions from start year to present year.
    - The per capita yearly budget (from present to 2050 or 2100) is the remaining budget at present year divided by the cumulative population from present until 2050 or 2100.
    - The yearly budget of the present year is the per capita yearly budget multiplied by the population of the present year.
    - The present European share is the present European yearly budget divided by the present world budget.

Computation method 15: past emissions and population over time

- Allocation key: total population and past emissions
- Unit: CO_2-eq emissions (Climate change), CO_2 emissions (Ocean acidification)
- Source: UN Population Division, World Population Prospects 2017 https://esa.un.org/unpd/wpp/, footprints computed in this report for emissions
- Function: similar to method 14, except for step1 in which the demographic share of Europe in the world is calculated based on cumulative population over a given period instead of population at start year. Consequently, in method 15 this demographic share is the European cumulative population from start year (e.g. 1990) until 2050 or 2010, divided by the world cumulative population of the same period. Steps 2 to 6 are the same as in method 14.

9 Appendix 2. Control variables from Steffen et al. (2015) & in this report

This study			Steffen et al. 2015, R2009 = Rockström et al. (2009)	
PB acronym	**PB name**	**Indicator**	**Earth system process**	**Control variable(s)**
CC	Climate change	GHG emissions	Climate change (R2009: same)	Atmospheric CO_2 concentration, ppm Energy imbalance at top- of-atmosphere, W m^{-2}
OA	Ocean acidification	Carbon dioxide emissions	Ocean acidification (R2009: same)	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ωarag)
NL	Nitrogen losses	Loss of Nitrogen from agriculture	Biogeochemical flows: (P and N cycles) [R2009: Biogeochemical flows: (interference with P and N cycles)]	*N cycle:* Global: Industrial and intentional biological fixation of N
PL	Phosphorus losses	Loss of Phosphorus from agriculture and wastewater		*P cycle:* Global: P flow from freshwater systems into the ocean Regional: P flow from fertilizers to erodible soils
FU	Freshwater use	Blue water consumption	Freshwater use (R2009: Global freshwater use)	Global: Maximum amount of consumptive blue water use (km3 yr-1) Basin: Blue water withdrawal as % of mean monthly river flow
LA	Land cover anthropisation	Anthropised land	Land-system change (R2009: same)	Global: Area of forested land as % of original forest cover Biome: Area of forested land as % of potential forest cover
-	-	-	Change in biosphere integrity (R2009: Rate of biodiversity loss)	Genetic diversity: Extinction rate Functional diversity: Biodiversity Intactness Index (BII) *Note: These are interim control variables until more appropriate ones are developed.*
-	-	-	Stratospheric ozone depletion (R2009: same)	Stratospheric O3 concentration, DU
-	-	-	Atmospheric aerosol loading (R2009s: same)	Global: Aerosol Optical Depth (AOD), but much regional variation Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study
-	-	-	Introduction of novel entities (R2009: Chemical pollution)	*Note: no control variable defined yet*

10 Appendix 3. Limits and footprints for EU28

Planetary Boundary		Global		EU						
				Limit				Footprint	
Name	Indicator	Limit	Footprint	Min	Avg	Median	Max		Date global limit
Nitrogen Losses	Loss of N to water from agriculture in Tg N	28,5	49,3	0,7	1,8	1,8	5,3	5,9	2010, 2013
Phosphorus Losses	Loss of P from fertilizers and waste in Tg P	0,92	1,84	0,02	0,05	0,06	0,17	0,11	2010, 2013
Freshwater Use	Blue water consumption in km^3	4 000	1 225	94	235	249	746	75,8	2009
Land Cover Anthropisation	Anthropised land in 10^6 km^2	19,4	17,0	0,5	1,2	1,2	3,6	2,0	2009

Footprints are for 2011.

The number of scenarios considered is 27 all indicators.

11 Appendix 4. Additional information on the computed footprints.

This appendix provides additional information on the computed footprints. Starting from a brief explanation of Input-Output Analysis (IOA), a critical review of Exiobase 3.4 (Wood et al., 2015) is then provided. Time series, data sources, assumptions and limitations are then described for each of the PB.

11.1 Environmentally Extended Input-Output (EE-IO) models

Environmentally Extended Input-Output (EE-IO) models are economic-environmental models at country scale providing economic and environmental information at country, industry and generic product level. They are built by combining economic information from the national accounts (input-output tables) (Eurostat, 2008) with environmental information per industry. They provide thus a coherent vision of the total environmental load of a country and of the average direct environmental load its industries. Such country models can be extended to build global models: Environmentally Extended Multi-Regional-Input-Output (MRIO) models are economic-environmental models describing inter-industrial relationships on a world scale. They integrate the full production, trade and consumption linkages between industries and countries, following the IRIO (Interregional Input-Output) philosophy (Miller and Blair, 1985).

EE-IO models can be applied to generate environmental footprints according to a Life Cycle perspective on a global scale: any emission or resource use within the global economic system can be re-allocated along global production chains to the goods and services consumed by the final demand (i.e. consumption by households, and public expenditure) in a specific country (Friot, 2009).

11.2 Critical review of Exiobase 3.4

Exiobase can be considered as the state of the art of Multi Regional Input-Output (MRIO) models. Like any model, it is however only a representation of the reality and not the reality per se. To achieve a global coherence, compromises have to be made: in Exiobase 3.4 the coherence over time (time series) has been privileged over the strict compatibility with reported national data. The economic part of the model is however in line with macro data from the UN. To achieve a high level of details (sectors and environmental extensions), assumptions are needed to extend existing dataset at a lower level of resolution, e.g. to split the few agricultural sectors of IO tables into multiple crop producing sectors based on FAO data. In addition, to cover the whole world, data available for some countries have to be extrapolated to other counties. While the number of environmental extensions is larger in Exiobase than in any other MRIO, it is however not as complete as in bottom-up LCA databases: emissions of chemicals and metals are, for example, missing. Food related extensions, (e.g. P and N releases to air and water) are based on bottom-up models and their totals differ thus from other top-down models. Some others are based on IPCC recommendations, i.e. carbon emissions. Some other are more rough and experimental (e.g. land grazing).

Comparison with other models

Since any model is based on specific assumptions, the computed environmental footprints differ between models. Any comparison between these models should thus consider the underlying assumptions (number of sectors, number of countries, aspects considered in the building of the environmental factors, etc.) to better understand the strengths and the limitations of each of them.

The EEA IOA expert meeting (26 June 2018) enabled making clearer the strengths and weaknesses of Exiobase. The JRC study on consumption (Sala et al., 2018), for example, shows that, for a large part of the environmental aspects, Exiobase results are compatible with results from bottom-up studies except for toxicity and eco-toxicity (not considered in this report). The JRC report on consumption will thus include results based on Exiobase. Eurostat explained that years would be needed before having an official MRIO model providing similar added-value as Exiobase. The currently built model will, in addition, not be detailed enough in terms of the number of economic sectors to allow for environmental analyses. For the time being, and for the years to come, the models originating from research like Exiobase, are thus the only way to go.

Ensuring results of quality

Exiobase 3.4 is considered a valid model for global and country/region analysis. While this is not the objective of this study, it should be noted that it is however much less reliable for evaluating specific sectors and products.

In this report, we have only considered the environmental extensions we considered as sufficiently robust either because they are in accordance with other global datasets or have been accepted as scientifically valid in renown peer-reviewed journals (e.g. data on N and P).

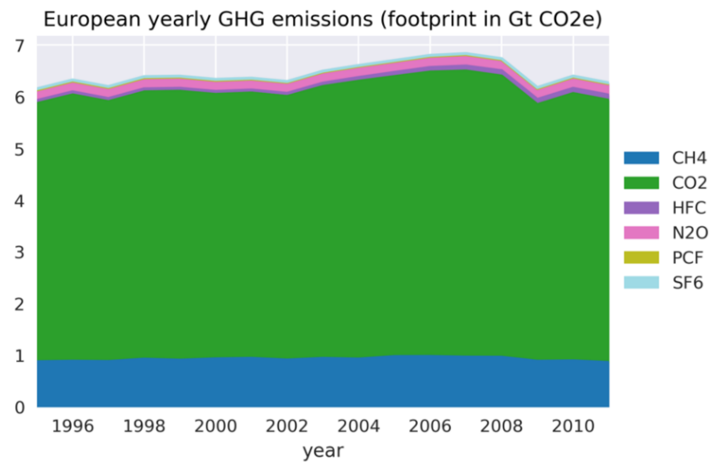
While the database provided by NTNU covers the years 1995-2015, only the years 1995-2011 have been considered in this report. The years 2012-2015 were not part of the EU DESIRE project and have been roughly estimated by NTNU. Our first analyses showed that results for these years show decreasing footprints which are not compatible with the previous years.

11.3 Climate change

Decomposition of the footprint over time (1995-2011)

The European footprint is mainly generated by economic activities (between 84.3% and 86.8% over the period 1995-2011) while 13.2% to 15.7% is resulting from emissions by households.

The main gases contributing to the European footprint are CO_2 emissions (around 81%), CH_4 (around 14%) and N_2O (around 3.2%). Their respective share is stable over the period. The other GHG have a marginal contribution. In the rest of the world, the contribution of CO_2 is smaller (between 71% and 76%) while CH_4 (18% to 22%) and N_2O emissions (4% to 5%) are larger.

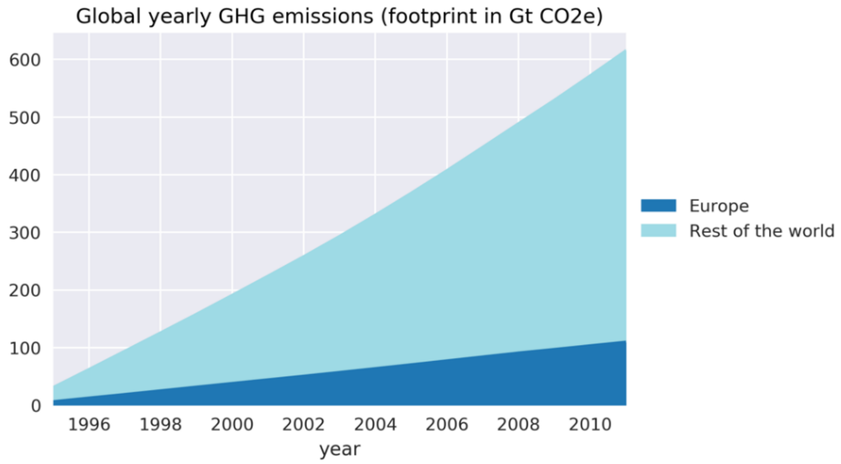


Evolution of cumulative emissions over time (1995-2011)

Due to the decreasing share of the European footprint with respect to global GHG emissions, the European cumulative share is regularly decreasing between 1995 (20%) and 2011 (17.7%). As a result, adopting a later year for starting counting cumulative emissions result in a lower share of cumulative emissions for Europe in 2011:

- Start in 2000: 17%
- Start in 2005: 16.1%

- Start in 2010: from 14.7%



Data source and assumptions

Exiobase 3.4 (Wood et al., 2015) contains the following GHG emissions: CO_2 (combustion, non-combustion, agriculture from peat decay, waste – fossil and biogenic), CH_4 (combustion, non-combustion, agriculture, waste), N_2O (combustion, agriculture), SF_6, PCF and HFC. The indicator considers all emissions.

Characterisations factors from IPCC 2013 have been applied to convert emissions to the climate change indicator in CO_2 equivalent (except for PCF and HFC for which values are already provided in CO_2 equivalent.

Emissions from land use change (LULUCF) are not considered in the computation since they are not provided in Exiobase. The extrapolation for the years 1990 to 1994 is a simple scaling with respect to world emissions (using data from EDGAR). This means that the European share is assumed constant over this period.

11.4 Ocean acidification

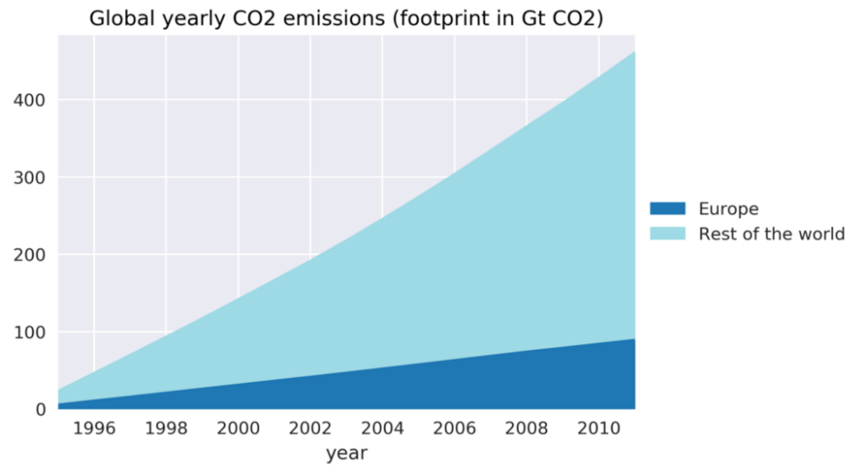
Decomposition of the footprint over time (1995-2011)

The European footprint is mainly generated by economic activities (between 15.7% and 18.5% over the period 1995-2011) while 81.4% to 84.2% is resulting from emissions by households. The footprint only consists in CO_2 emissions.

Evolution of cumulative emissions over time (1995-2011)

Like the GHG footprint, the European cumulative share is regularly decreasing between 1995 (22.2%) and 2011 (19.2%) due to the decreasing share of the European footprint with respect to global CO_2 emissions. As a result, adopting a later year for starting counting cumulative emissions result in a lower share of cumulative emissions for Europe:

- Start in 2000: 18.3%
- Start in 2005: 17.2%
- Start in 2010: 15.7%



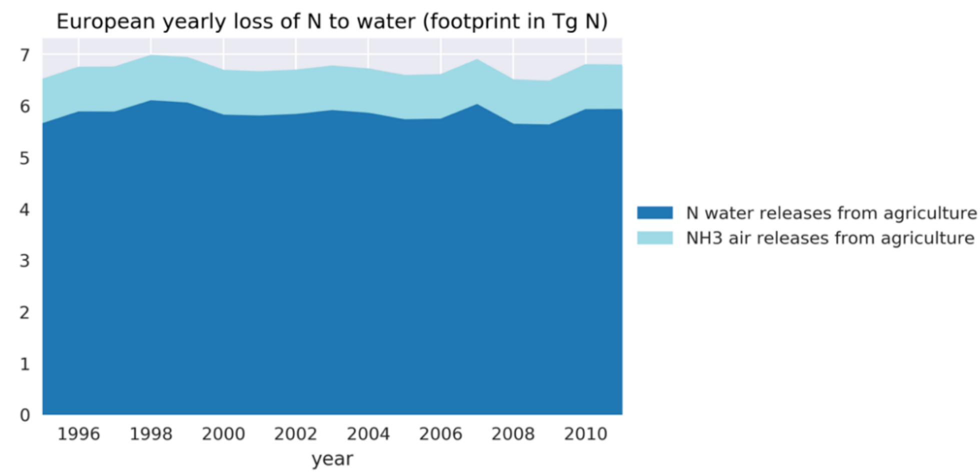
Data source and assumptions

Exiobase 3.4 (Wood et al., 2015) contains the following CO_2 emissions: combustion, non-combustion, agriculture from peat decay, waste - fossil and biogenic. The indicator considers all emissions. Emissions from land use change (LULUCF) are not considered in the computation since they are not provided in Exiobase.

11.5 Nitrogen losses

Decomposition of the footprint over time (1995-2011)

The European footprint is, by definition, only generated by agricultural activities. The main releases are from direct N releases to water (86.7% to 87.3%). The remaining releases are from indirect air releases (NH_3).



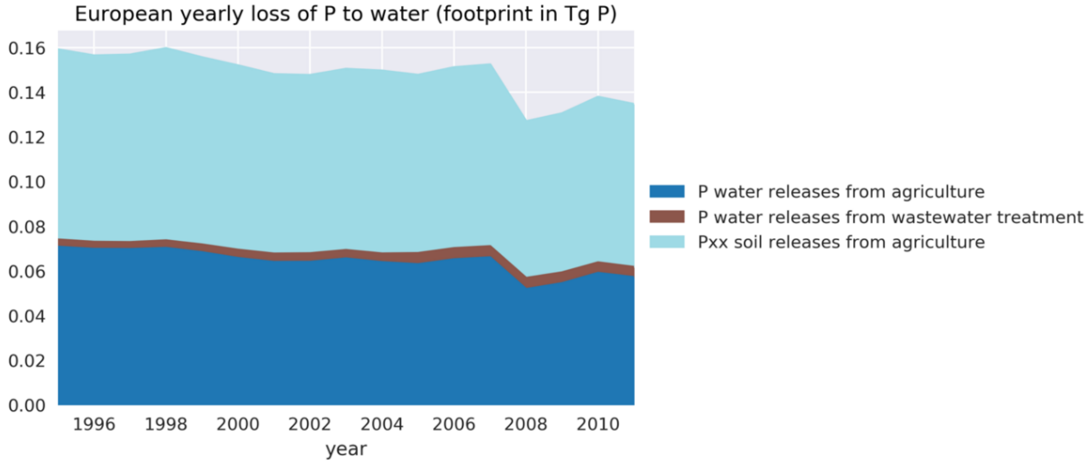
Data source and assumptions

Exiobase 3.4 (Wood et al., 2015) contains the following type of nitrogen releases: NO_x from combustion and non-combustion to air, N_2O from combustion to air, NH_3 from combustion to air, N from agriculture to water, N_2O from agriculture to air, NH_3 from agriculture to air, NO_x from agriculture to air N from waste to water, NH_3 from waste to air, NO_x from waste to air. The indicator considers only, by definition, N releases from agriculture to water and NH_3 releases from agriculture to air. Characterization factors to convert NH_3 releases to air into losses to water are taken from Recipe 2016 (Huijbregts et al. 2017) (0.1 for NH_3).

11.6 Phosphorus losses

Decomposition of the footprint over time (1995-2011)

The European footprint is, by definition, only generated by agricultural and wastewater activities. The main releases are from indirect Pxx releases to water (from soil) (54.2% in 2011). Then from direct releases to water from agriculture (42.4% in 2011). Waste water releases amount to 3.4%.



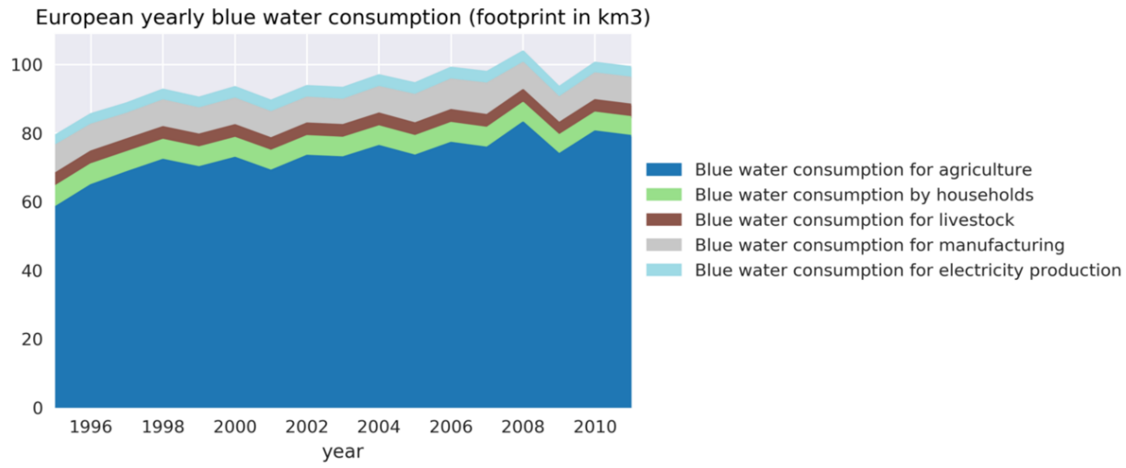
Data source and assumptions

Exiobase 3.4 (Wood et al., 2015) contains the following type of phosphorus releases: Pxx from agriculture to soil, P from agriculture to water and P from waste to water. The indicator considers all of them. Characterization factors are taken from Recipe 2016 (Huijbregts et al. 2017) (1 for P agriculture to water and P waste to water, 0.033 for Pxx).

11.7 Freshwater use

Decomposition of the footprint over time (1995-2011)

The European footprint is mainly generated by economic activities (between 92.3% and 94.5% over the period 1995-2011) while 5.5% to 7.7% are directly due to households. The main consumption is for agriculture (73.6% to 80%) then for manufacturing (from 7.7% to 10.3%) followed by livestock (3.6% to 4.7%).



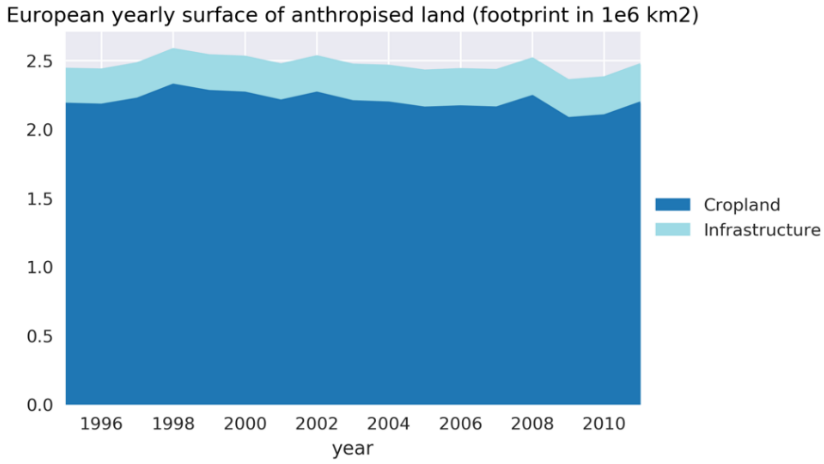
Data source and assumptions

Exiobase 3.4 (Wood et al., 2015) contains the following type of blue water consumption: agriculture, livestock, manufacturing, electricity tower, electricity once-through. The indicator considers all types of blue water consumptions.

11.8 Land cover anthropisation

Decomposition of the footprint over time (1995-2011)

Cropland contributes to the majority of the European footprint (88.7% in 2011), the rest being due to infrastructure land. Cropland is used by economic activities while all infrastructure land is allocated to households (by definition in Exiobase), i.e. it is not allocated internationally through trade.



Data source and assumptions

Exiobase 3.4 (Wood et al., 2015) 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, infrastructure land.

The indicator includes cropland and infrastructure land only. Permanent pastures could have been included but the quality of the data is not high enough (it is based on raw assumptions according to the documentation of Exiobase).

12 Appendix 5: Exploration of visualisation options

12.1 Objectives

This appendix provides additional examples for visualising the results. Like any other aspects of the Planetary Boundaries framework, the inherent nature of this set of indicators set new challenges compared to current practices.

The values in the visualisations are for illustration only and do not correspond to real values.

12.2 Selected visualisation

The selected visualisations are an extended version of the second round of proposals. Colours (green, yellow, red) represent respectively a *safe* zone (below the lower bound of the European shares, a zone of *increasing risk* (between the lower and upper European share) and a zone of *high risk*. While the colours are the same as in Steffen et al. (2015), the meaning of the yellow zone is different since in Steffen et al. (2015) it represents a zone between the possible lower and upper boundaries while it is here the zone between the computed lower and upper European shares.

Three charts are proposed:

1. An aggregated version per PB (on the cover page). Lower and upper values of the yellow zone correspond respectively to the average of the minimum values (one minimum value per principle in Table 3) and the average of the maximum values (one maximum value per principle in Table 3).

2. A detailed version showing each principle per PB (in Chapter 5.4 to 5.9). Lower and upper values of the yellow zone for each of the principle correspond respectively to the minimum, respectively to the maximum, value per principle in Table 3 (e.g. 6.2% * global budget for the minimum value for the Equality principle).

3. A summary chart showing the size of the overshot per PB and all allocation principles (in Chapter 5.3). The chart is an approximation only since the considered median limit is not the same for all PB (see the two last rows of Table 3). Except for climate change and ocean acidification, the median is 7.3% and the overshot is computed as the footprint/median limit in 2011. For the two budgets overtime, the median is 6.8% and the limit is computed as follow: (1) European budget over time = 6.8% * the global budget over time, (2) European per capita budget over time = European budget overtime / Sum(peoplePerYearDuringThePeriod), and (3) Yearly European budget = European Per capita budget over time * peopleAtSpecificYear. Every European get thus the same per capita budget over time but the yearly European budget depends on the number of people living during a certain year (2011 in the chart.)

12.3 Second round of proposals

The representation selected in the last round of proposals includes several key aspects. First, the bio-physical limits proposed by Rockström et al. (2009) and Steffen et al. (2015) have a large range of uncertainty (e.g. a factor 10 for Phosphorus). As a result, they cannot be considered as absolute numbers but should rather be interpreted in terms of risks, in conformity to the precautionary principle. We selected here a range of colours to represent this risk.

Second, setting a limit for Europe or any other region is a normative choice. The current performance of Europe will thus strongly depend on this choice. The range of possible European limits are thus clearly stated in the chart.

Third, the relevance of an overshoot at European scale depends of the global situation. In the case of a PB which is not overshot at global scale, the global risk is low. The global performance is thus also provided.

Eventually, due to the fact that Planetary Boundaries can be allocated at various scales, it is also important to provide absolute numbers that could be used by others for comparison or as a starting point for defining allocations at smaller scales (regions, companies).

Considering these four aspects leads thus to proposing a simple representation using different levels of risks of overshoot (Figure 22).

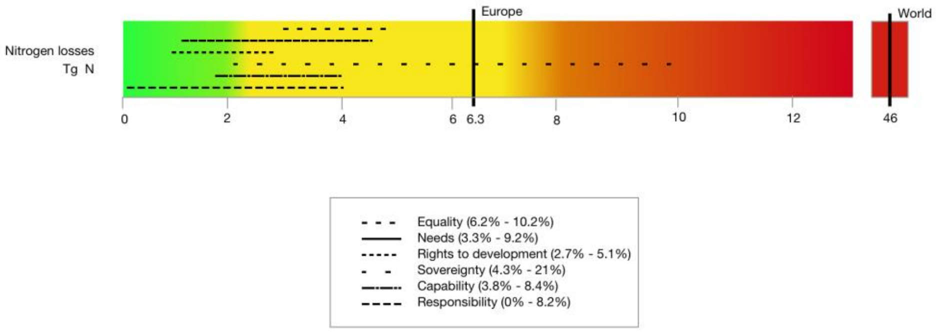


Figure 22. Synthetic representation of performances including the range of shares per principle (for illustration only).

12.4 First round of proposals

The first visualisations are purposely different from the choropleths radar representations proposed in Rockström et al. (2009) and Steffen et al. (2015). They aim at better representing proportionalities (areas of symbols truly proportional to scores) and at providing a higher number of information.

Additional representation for the general public

The graphic design for communicating to the public is based on a very straightforward infographic. The graphic design of energy classes in environmental labelling has been recognised as one of the best approaches for this purpose.

We propose (Figure 23) a representation replicating the design of energy classes with four colours from green, light green, orange and red. A grey colour indicates an unknown status.

The ratio of the footprint over the limit gives the score. This information is provided for Europe (in white) and for the World (in black). In this way, it is possible to compare the magnitude of an issue between Europe and in the World.

The four colours from green, light green, orange and red that depict the classes from clearly safe, safe, unsafe, clearly unsafe as defined in Dao et al. (2015).

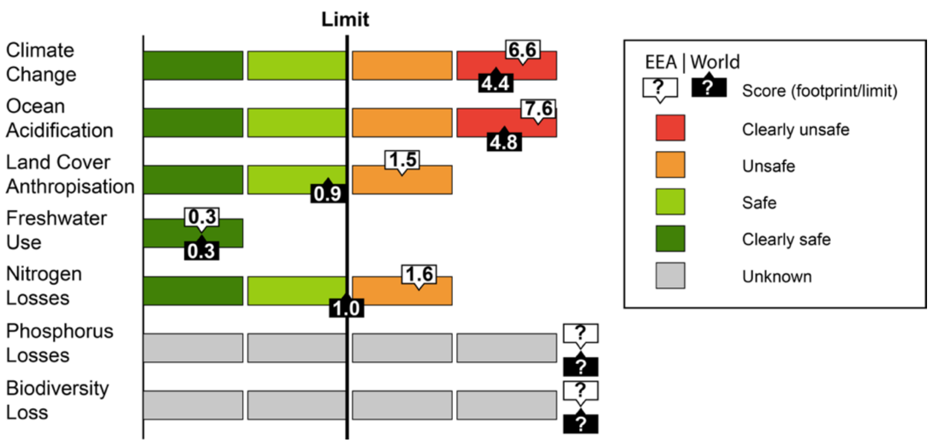


Figure 23. Synthetic representation of performances for the general public (for illustration only).

Scientific representation

A graphic design intended for readers familiar with the Planetary Boundaries framework is presented in Figure 24. It provides more information than the public infographic. This design is included in Dao et al. (2018).

The limit is standardized for all Planetary Boundaries to allow a comparison between Planetary Boundaries. It is symbolized by a line. The values of the limits are provided for each planetary boundary for Europe, the Rest of the World and for the World. The performance is the ratio between the footprint and the limit, allowing to easily see if the limit is respected (ratio smaller or equal to 1) or if the limit is exceeded (ratio > 1). The footprint values are provided in numbers. The share of the world footprint (the relative contribution to the global impacts) between Europe and the Rest of the world is computed and provided as a percentage. Finally, the trend for the last 5 years of the footprint are provided by arrows. Limit (1L), (2L), etc. represent the size of the overshoot.

This approach is however not adequate to represent the different possible shares as computed in Chapter 4.

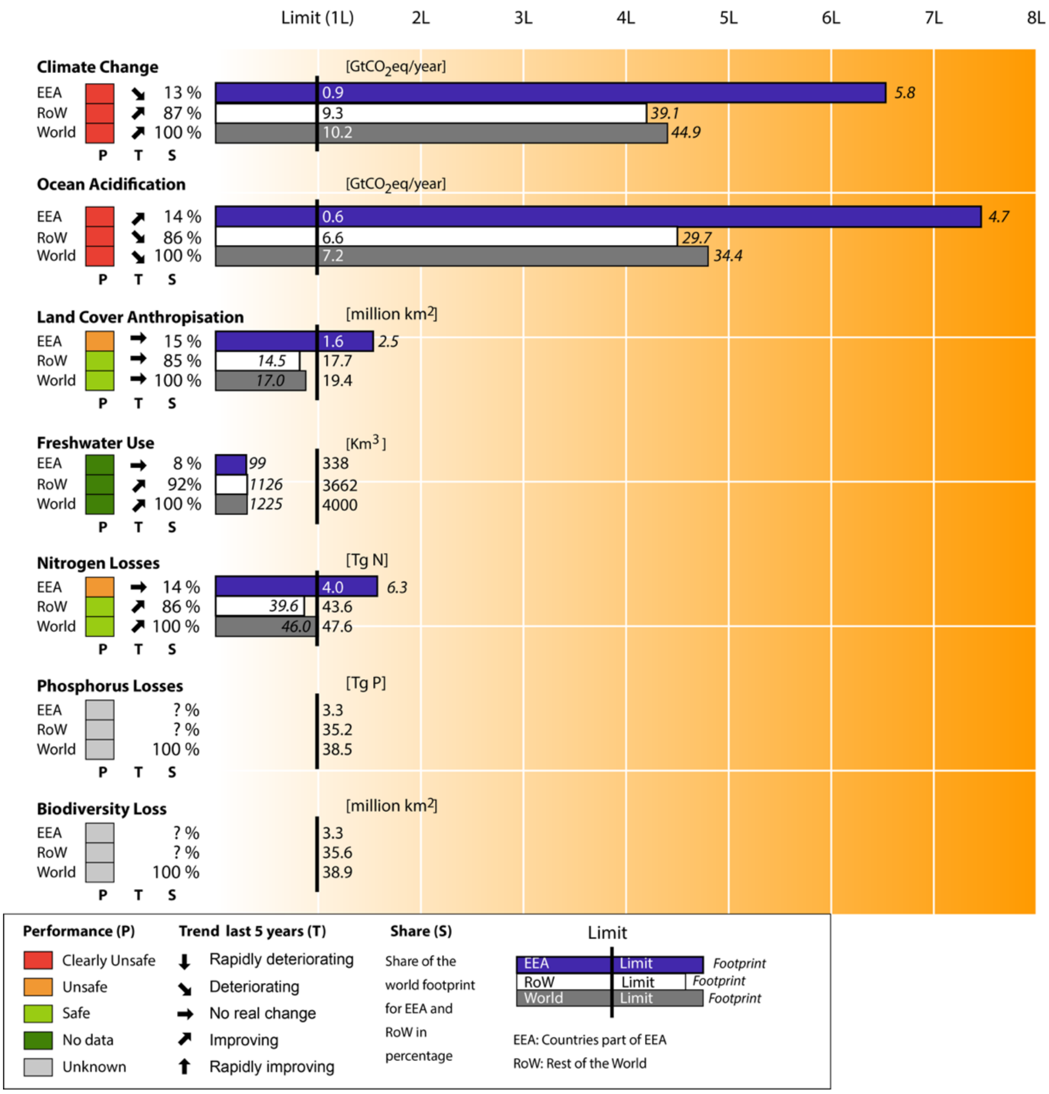


Figure 24. Synthetic representation of performances for the scientific community (for illustration only).

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