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National environmental limits and footprints based on the Planetary Boundaries framework: the case of Switzerland.

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Highlights

- Planetary Boundaries: going from bio-physical to related socio-economic indicators
- Setting limits at country level considering the role of countries and people needs
- Limits and footprints are computed for the world and for a case study: Switzerland
- Global priorities: Climate Change, Ocean Acidification, Biodiversity, Nitrogen Loss

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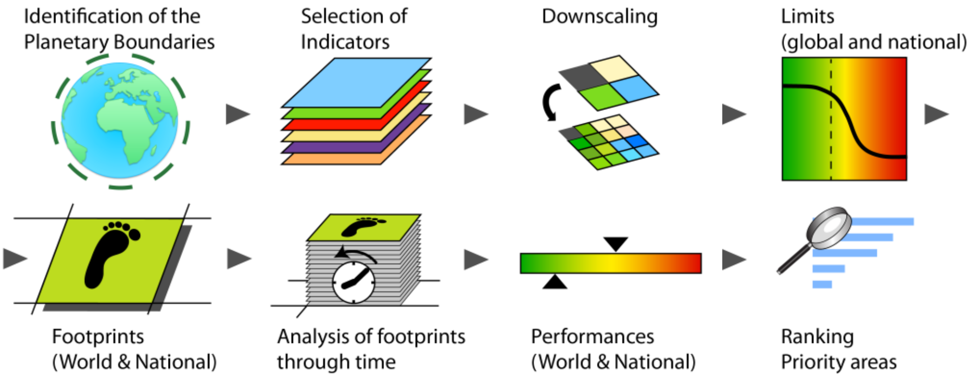
Abstract

The Planetary Boundaries concept is a recent scientific framework, which identifies 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. Crossing the suggested limits would lead to drastic changes in human society by disrupting some of the ecological bases that underlie the current socio-economic system. As a contribution to the international discussion, and using the case of Switzerland, this study proposes a methodology to apply the Planetary Boundaries concept on the national level. Taking such an approach allows to assess the environmental sustainability of the socio-economic activities (e.g. consumption) by the inhabitants of a country in a long-term global perspective, assuming that past, current and future populations on Earth have similar "rights" to natural resources. The performance of countries is evaluated by comparing the country limits with their environmental footprints according to a consumption-based perspective. An approach was developed to: i) better characterise the Planetary Boundaries and understand which limits can effectively be currently quantified; ii) identify related socio-economic indicators for which both country limits and footprints can be computed; iii) compute values for limits, footprints and performances (at global and country level); and iv) suggest priorities for action based on the assessment of global and national performances. It was found that Switzerland should, as a priority, act on its footprints related to Climate Change, Ocean Acidification, Biodiversity Loss and Nitrogen Loss. The methodology developed herein can be applied to the analysis of other countries or territories, as well as extended to analyse specific economic sectors.

Graphical abstract



Keywords

Planetary Boundaries, Green Economy, national footprints, Switzerland

1. Introduction

Since the 1950s, the extraction of natural resources and related environmental impacts have greatly accelerated worldwide (Steffen et al., 2015a). Human activities now generate ever-more significant pressures on the global environment: climate change, deforestation, biodiversity losses, and decline in air and water quality have been recognised as important issues which need to be addressed (UNEP, 2012).

The concept of Planetary Boundaries (PBs) is a fairly recent one (Rockström et al., 2009). The PBs are a set of nine physical and biological limits of the global Earth system that should be respected in order not to leave a “Safe Operating Space” that would put the planet’s human-friendly living conditions in peril. The most known PB is Climate Change, but other global limits have been identified: Stratospheric ozone depletion, Atmospheric aerosol loading, Land system change, Biodiversity loss, Nitrogen and phosphorus inputs to the biosphere and oceans, Global freshwater use and Chemical pollution. The PBs are the most recent scientific framework to consider global environmental limits; the concept was updated in 2015 (Steffen et al., 2015b).

The PB framework has a strong potential for guiding the environmental policy discussion. To play such a role, the global biophysical information provided by the PBs has to be converted to information related to human activities at the national level. This is essential due to the fact that, while there exists an international environmental governance regime with more than 500 multilateral agreements, actions are led by national governments.

The relevance of PBs to national policies was highlighted in April 2017 during the conference “Making the Planetary Boundaries Concept Work” in Berlin (Keppner, 2017), following international workshops in Geneva (2013) and Brussels (2015) with an increasing number of attendees from political institutions, academia and the private sector, showing the growing interest in this concept.

Many environmental indicators are already produced by countries as part of their reporting obligations to international agreements. These indicators at national scale are in their vast majority examining the environment from a territorial perspective; e.g., reporting on domestic greenhouse gas emissions under the Kyoto Protocol. Footprints, or consumption-based indicators applying a

Life Cycle Perspective, provide a complementary approach to the Sustainable Development Goals and other sustainability monitoring particularly relevant for the evaluation of the performance of countries with respect to global issues.

Such a perspective (Figure 1) is increasingly relevant in our interlinked global economy (Friot, 2009) since an increasing part of the impacts within a given country or territory is generated to satisfy consumers in other countries.

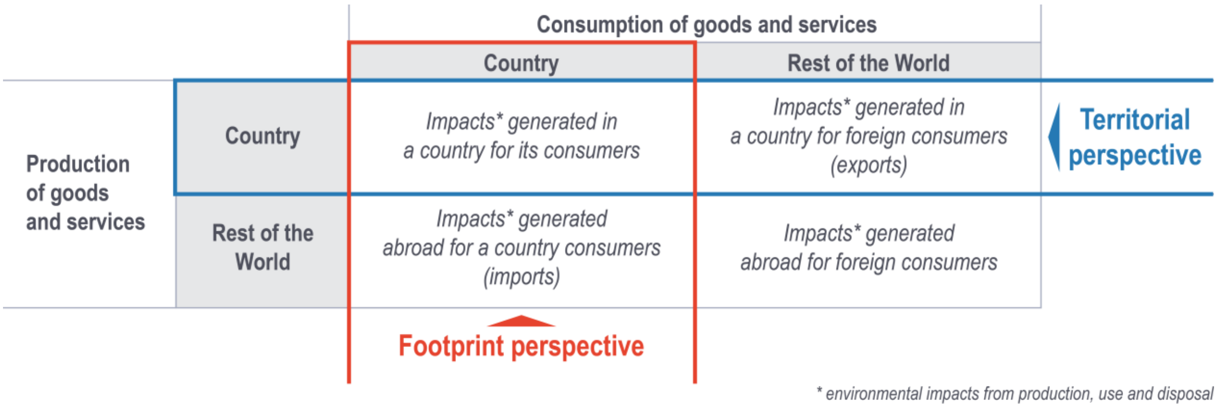


Figure 1. Territorial versus Footprint (or consumption) approach

This is especially the case for small, open and service-oriented economies such as Switzerland. More than half of the environmental impacts induced by the consumption of Swiss residents occur abroad (Jungbluth et al., 2011; Frischknecht et al., 2014). This proportion has been rising from 1996 to 2011 (Frischknecht et al., 2014), and can be explained to a large extent by the fact that Switzerland is a growing economy with a high share of services, but one relying on other parts of the world for production of the goods consumed internally.

This is true for most developed countries. The EU also largely relies on the rest of the world for its consumption as shown by its carbon, water and land footprints. Other countries such as Brazil or China are, on the contrary, providing their resources to other countries (Tukker et al., 2014).

In this paper, we present the first consistent methodology to guide national governments in their reflection about the potential of environmental indicators based on the PB framework. The resulting indicators offer an indication of the environmental sustainability of the socio-economic activities induced by the consumption of the inhabitants of a country in a long-term global perspective.

Our present research was developed with the aim that the downscaling of Planetary Boundaries and the quantification of the impacts of consumption can be replicated for any country or territory. It builds up on a preceding partial assessment for Sweden (Nykvist et al., 2013), which was the pioneer study applying the PB framework at the national level. They applied this framework to Sweden to address four policy questions, and thus were applied to four PBs using both territorial and consumption analysis. Fang et al. (2015) proposed another assessment, covering 28 countries, but they identified as a limitation of their study a lack of consistency in the choice of the system perspective, concluding that in future assessments both numerator (current footprints) and denominator (limit value) should be either production-based (territorial) or consumption-based.

Two other studies used the PB framework and its extension of social well-being, known as "the Safe and Just Operating Space" (Raworth, 2012). One at the national level for South Africa (Cole et al., 2014) is based on national data sets and experts' judgements, while Dearing et al. (2014) produced an analysis for two low-income rural communities in China. These studies consider regional rather than global sustainability. The environmental processes and the limits considered are loosely connected from the original Planetary Boundaries. A study in Europe (Hoff et al., 2014) applied a straightforward equal per capita allocation of the Planetary Boundaries and a consumption based quantification of the European environmental impacts, but did not address the historical responsibility of the footprints.

By consistent methodology, we imply: a) the proposition of several types of indicators considering yearly limits and limits over time; b) the consideration of people and countries' needs; c) the conversion of biophysical indicators into indicators that can be related to socio-economic activities enabling the computation of limits and of footprints; and d) the computation of performance indicators relying on quantitative results and long-term trends.

This new methodology can be used for computing limits at the national level as well as for estimating the current status of the impacts induced by each country, not only on their territory, but also through the consumption of its inhabitants (footprints). As this research began in 2014, it uses the references and terminology from the initial PB framework as developed by (Rockström et al., 2009). The subsequent PB framework from (Steffen et al., 2015b) provides several improvements and updates, but was published at a stage where the current research was already too advanced. Also, for adapting the PB concept to national entities, the indicators needed to be adapted by moving up in the causal chain, e.g. if we use the DPSIR framework from *States* (Green House Gases (GHG) concentration and radiative forcing) to *Pressure* (emissions of GHG).

2. Limits of the planet: review from concepts to integration into policy

2.1. Evolution of the international awareness

International awareness of the limits of our planet has been increasing since the 1950s and warnings have been expressed about the dead ends of continuous growth on a finite planet (Boulding, 1966).

In the early 1970s, the report from the Club of Rome "The Limits to Growth" (Meadows et al., 1972), using dynamic models, and Georgescu Roegen, who applied the laws of thermodynamics to the economy (Georgescu-Roegen, 1979, 1971), both denounced the impossibility of continuous economic growth based on natural resources. During this same time, international recognition of the importance of the environment took off. For example, the Ramsar Convention on Wetlands was signed in 1971, and the United Nations Conference on the Human Environment was held in 1972 in Stockholm, leading to the creation of the United Nations Environment Programme (UNEP) the same year. During these years, the concept of "carrying capacity" was applied to estimate how large a population could be supported by a given area in the long term. Then, to go beyond this neo-Malthusian model of demographic limits and fixed resources, the IPAT equation (Ehrlich and Holdren, 1971) has been proposed. The impacts on the environment (I) are not only a function of population size (P), but also of affluence (A), i.e. consumption per capita, and technology (T).

In the mid-1980s, the Chernobyl nuclear accident (1986) and the discovery of the ozone hole (and the subsequent signing of the Montreal Protocol in 1987) demonstrated that environmental impacts do not stop at national borders. The research on global environmental change revealed that a cluster of other concerns, e.g. deforestation, pollution and decline of biodiversity, are global and can threaten the ecosystems that sustain human well-being (Turner II et al., 1990). The sustainable development concept gained broad recognition with the Brundtland Report (United Nations, 1987). Since then, development has no longer been only about economic growth, but includes social and environmental dimensions.

The 1990s brought the recognition of global environmental issues. The first report from the Inter-Governmental Panel on Climate Change (IPCC, 1990) and the United Nations Conference on Environment and Development (UNCED, Rio 1992) led to the three main global conventions related to biological diversity (CBD), climate change (UNFCCC) and desertification (UNCCD). During this period, the ecological footprint concept was developed by (Rees, 1992; Wackernagel, 1994). It integrates the multiple impacts of human consumption in a normalised unit of "global hectares" that would be needed to regenerate the natural capital consumed (energy, biomass, materials, water, etc.). This ecological footprint is then compared to the biocapacity of the Earth to provide a synthetic perspective of the number of Earths needed to sustain current lifestyle and consumption patterns.

Since 2000, the Millennium Development Goals (MDGs) were introduced by the United Nations, with Goal 7 "to ensure environmental sustainability" setting concrete targets and indicators for the period 2000-2015. The post-2015 agenda was adopted in September 2015, including 17 Sustainable Development Goals (SDG) with 169 targets; SDG 12 is dedicated to sustainable consumption and production. The year 2015 also saw the greatest progress on climate change policy with the adoption of the Paris Agreement at the COP-21, aiming at keeping global temperature rise between 1.5 and 2°C as compared with pre-industrial temperatures.

2.2. Multiple concepts to address the limits of the Planet

Several concepts have thus been developed to address the limited capacities of the Planet to cope with global environmental impacts, among which are:

a) Limits (limit to growth, carrying capacity).
b) Policy targets (MDGs, SDGs, internationally agreed environmental goals drawn from existing international treaties and non-legally binding instruments (http://geg.informea.org/about)).

c) Footprints based on a Life Cycle Perspective (carbon footprint, water footprint, biodiversity footprint, land use footprint, et al.).

The concept of PBs, first published in 2009 (Rockström et al., 2009) and later updated in 2015 (Steffen et al., 2015b) is in the first category, i.e. a limit. It is important to stress that limits such as PBs are not targets (category 2): the objective is not to reach them; instead, they act as an upper bound which should not be transgressed. For the PBs that have already being surpassed, returning to the limit may be set as a target. More generally speaking, a limit value is a science-based threshold that could be used by political and business decision makers; but setting targets informed by such limit values depends on political will, perceptions of equity, efficiency and feasibility, amongst others.

While there have been proposals to link the PBs to development goals (Hoff and Lobos Alva, 2017; Raworth, 2017, 2012) and while a growing number of international actors are showing interest in this concept (Häyhä et al., 2016; Hoff, 2017), it is currently not yet formally linked to any policy or reporting framework. Some countries including Switzerland are however moving towards such integration.

2.3. Integration of footprints and the Planetary Boundaries within the Swiss policy framework

The Swiss government adopted a Green Economy Action Plan in 2010 and renewed it in 2013 and 2016. This action plan embedded the PB concept. It entails 23 measures focusing on: (1) the sustainability of consumption; (2) moving towards a circular economy; and (3) overarching instruments including measuring progress in a new way, as well a dialogue on targets.

The Swiss Sustainable Development Strategy 2016-2019, adopted in 2015 by the Swiss government, reflects the 2030 United Nations Agenda for Sustainable Development. Both the PBs and the vision of trying to reduce environmental impacts along the value chain (i.e. a footprint perspective) are mentioned (see e.g. Action area 1 – Consumption and production).

In September 2016, a constitutional amendment (proposed by a popular initiative validated by 112’098 signatures), aiming to set in the Constitution a target of an “Ecological Footprint” of one

Earth for Switzerland (when extrapolated to world population) by 2050 (against the current Switzerland's Ecological Footprint of ~3 Earths), was rejected in a public vote (63.6% against). The vote stimulated a public debate on the question as to whether current patterns of consumption are sustainable in the future and confirmed the interest of the Swiss Federal Office for the Environment to assess how to apply the PBs for Switzerland.

3. Data and Methods

A three-stage approach is applied in order to: a) better characterise the PBs and understand which limits can effectively be currently quantified; b) compute values for limits and footprints as well as global and national performances; and c) suggest priorities for action.

3.1. Identification of the Planetary Boundaries and selection of indicators

The selection of the Planetary Boundaries is based on an in-depth review and consultation of experts. Five PBs have been selected for this study: Climate Change, Ocean Acidification, Land Cover Anthropisation, Biodiversity Loss, Nitrogen and Phosphorus Losses (two different computations, but considered by Rockström et al. (2009) as one PB). The original names of some PBs (Rockström et al., 2009; Steffen et al., 2015b) have been modified in order to be closer to the selected socio-economic related indicators. For example, the indicator provided by Rockström et al., 2009) for climate change (CO_2 concentration in the atmosphere: 350 ppm and radiative forcing: 1 W m^{-2}) is a "state" indicator (see DPSIR classification in Kristensen, 2004). To assess the contribution (or the share) of a specific country, one needs to look at what led to this "state" which is the result of GHG emissions. GHG emissions is a "pressure" indicator and can be attributed to specific countries.

A summary of our rationales for the selection is provided in the remainder of this chapter.

While Rockström et al. (2009), claim that all PBs are global, numerous discussions can be found in the literature concerning the global versus local nature of some included phenomena (see discussion on spatial scale in (Nykvist et al., 2013). We base our selection applying Turner II et al. 1990 who differentiate two types of global environmental changes: systemic and cumulative.

Hence, within the PB framework, three cases emerge: global systemic, global cumulative or regional issues:

1. The global systemic changes include local sources of changes leading to (a) global effect(s) and with a global limit. This is the case for Climate Change, Ocean Acidification and Stratospheric Ozone Depletion.

2. The global cumulative changes include multiple transformations having local impacts, but which can nevertheless be considered global because they are occurring on a worldwide scale and can have global consequences. This is the case for Nitrogen and Phosphorus Losses, Land Cover Anthropisation and Biodiversity Loss.

3. The third PB category includes issues that, according to current knowledge and data, are at regional scale only: a global limit cannot be identified at the time being. This is the case for Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution. The term 'regional' does not preclude that regional pollutants can travel or be transported (due to trade) over long distances and can be transboundary, i.e. become a global issue. Rockström et al. (2009) did not characterise Atmospheric Aerosol Loading and Chemical Pollution but Steffen et al. (2015b) proposed indicators. For Freshwater Use, the overuse and/or pollution of freshwater can have significant impacts locally (or regionally, i.e. downstream watersheds), but without compromising other regions outside the watersheds, except maybe for oceans, e.g. the case of plastic/marine litter, which is not (yet) a PB and beyond the scope of this study.

We thus selected the PBs from the first two types, for which a global limit can be identified (even if the existence of a global limit in the second case is a matter of discussion, see Nykvist et al. (2013) as well as the refinement of the freshwater and biodiversity boundaries in Steffen et al. (2015b)). While classified “global systemic”, the PB on Stratospheric Ozone has however not been included. This PB is well addressed via the Montreal Protocol, with 98% of Ozone Depleting Substances (ODS) have being phased out globally, compared to 1990 levels (UNEP, 2017) although recent findings shows that monitoring is still required (Montzka et al., 2018).

For each of the PBs, the selection of an indicator is then based on three main criteria listed below. Selecting a different indicator than the one proposed by Rockström et al. (2009) and Steffen et al.

(2015b) is required in order to enable linking a PB described in biophysical terms to the socio-economic activities inducing it, i.e. to compute a footprint. While Rockström et al. (2009) and Steffen et al. (2015b) assessed which boundaries are crossed at the current point in time, the indicators selected in this study consider whether current yearly footprints are respecting these boundaries. The criteria are:

a. The representativeness of the indicator with respect to the PB definition. The indicator should be recognised scientifically as being linked with the boundaries; however, it can be of different types such as state (average biodiversity damage), pressure (CO_2 emissions per year), or driving forces (use of fertilizer with phosphorus per year). For explanations regarding these different levels in the causal chain, we can use the Driving Forces-Pressure-State-Impacts-Response (DPSIR) framework (EEA, 2005; Kristensen, 2004).
b. Data quality and availability for computing the global and national limits.
c. Data quality and availability to compute global and national footprints.

Table 1 gives a summary of the indicators selected. A detailed description of indicators is provided in the supplementary material.

Planetary Boundary	Description of the indicators	Units	Type
Climate Change	Remaining cumulative GHG emissions (including land cover changes) for a 50% chance to stay below a 2°C increase by 2100 compared with pre-industrial level.	$GtCO_2eq$/year	Pressure
Ocean Acidification	Remaining cumulative emissions of carbon dioxide (CO2) from human activities to maintain an acceptable calcium carbonate saturation state Ω.	$GtCO_2$/year	Pressure
Nitrogen (N) and Phosphorus (P) Losses	N: Loss of reactive N into the environment. Considering losses into soil, water (NO3-) and air (partially, i.e. NH_3 but not NOx).. P: Use of fertilizers with Phosphorus.	N: Tg N/year P: Tg P/year	N: Pressure P: Driving-force
Land Cover Anthropisation	Surface of anthropised land, i.e. agricultural and urbanised (sealed) land, as percentage of ice-free land (water bodies excluded).	km^2	State
Biodiversity Loss	Potential damages to biodiversity per land cover types accounting for the level of biodiversity per biome	unitless	State

Table 1 Selection of indicators

3.2. *Computing the limits*

3.2.1. Global limits

The PBs are limits at a global scale. They can be understood as the maximum quantities of various resources that could be used on Earth. Resources are usually allocated through economic or political mechanisms (negotiated, voluntary). However, there exists no recognised quantitative mechanism for the allocation of global resources, what- or whomever the beneficiaries (countries, public or private organisations, people) concerned.

Limits refer to threshold values (e.g. the concentration GHG in the atmosphere) beyond which unacceptable impacts are much more likely to occur. The limits were determined by science, based on general consensus within the scientific community. Due to the different levels of scientific understanding on the issues covered by the PBs, several types of sources have been used to identify the global limits. A thorough literature review was performed to establish these limits, which were then proposed to a group of experts who provided further advice. The limits were sometimes different from those selected in the initial PB framework (Rockström et al., 2009; Steffen et al., 2015b), since it was necessary to move further up in the causal chain to assess the responsibility of a specific country in a PB. For example, on climate, Rockström et al. (2009) use 350 ppm of CO_2 and 1 W m^{-2}, which are state indicators and cannot be linked to a specific country. By moving to GHG emissions (a pressure indicator), it becomes possible to identify the role of countries. Further details on this are provided in the supplementary material.

3.2.2. Distributional principles for defining a country's share

Once global limits are computed, setting limits per country requires thus defining a mechanism of allocation that will attribute part of the global limit to each country. A country limit can thus be understood as the exclusive share of the planet's resources as allocated to a given country. An exclusive share means that the total of all country shares sum up to the global limit.

An initial straightforward approach to compute shares can be a so-called "equal share per capita", as applied for Sweden in the first conversion of the PBs to the national level by Nykvist et al. (2013). We used the same approach by allocating each individual the same amount of resources. It is computed by dividing the global limit by the global population to obtain a global share per capita. A country share is obtained by multiplying the global per capita share by the total population of the country. This approach is easy to understand and to compute, but also has certain drawbacks:

1) The different needs of the inhabitants of Earth and the different amount of resources needed to satisfy these needs are not always considered. For example, living in Northern European countries requires heating houses for a longer period than in Southern Europe. In addition, the perception of what is required varies in each culture, a factor not easy to take into account.

2) Past emissions and use of resources are not considered, while they differ to a great extent between countries/regions of the world.

3) The role of countries, being the current main way of allocating resources between people, is not considered.

However, any broadly accepted way of going beyond the "equal share per capita" approach is currently lacking. So-called “ethical approaches” have been applied to climate change in the literature on burden sharing (Shue, 1999; Höhne et al., 2014). For instance, the Greenhouse Development Rights (GDR) Framework (Baer et al., 2008) defines sharing efforts in climate change mitigation, based on justice principles. Starting from the postulate of a right to development, GDR proposes a quantification of responsibilities and capacities to be equally shared between people, once a certain development threshold is attained. The Contraction and Convergence (C&C) model (Meyer and Bruges, 2000) is a framework for defining and negotiating differentiated paths of greenhouse gases reduction (contraction), until per capita emissions reach a level that is equal for all countries (convergence). The Science-Based Targets initiative (http://sciencebasedtargets.org/) allocates carbon budgets to companies based on so-called “proportional approaches”, considering economy-wide emissions based on IPCC scenarios or so-called “technological approaches” estimating the remediation capabilities of technologies based on long-term International Energy Agency (IEA) scenarios.

A pragmatic approach was thus adopted, since justification for the allocation can be based on various grounds (e.g. ethical, political, economic or legal), and data are often lacking for the computations. Firstly, the allocation can be computed with existing public data, and secondly, the allocations are based on the principles of Sustainable Development (UN document “Our Common Future, From One Earth to One World”, chapter 3. Sustainable Development), assuming that past, current and future populations of Earth have, by definition, similar rights to resources. Our approach thus adds a temporal dimension to the "equal share per capita" approach, taking into account historical and future resource use where feasible and relevant. A second factor taken into consideration with this pragmatic approach is that people are ultimately the final beneficiaries of the allocation of resources, but only indirectly through the intermediary allocation of resources by countries.

Starting from the previously computed global limits, the PBs are first allocated to people based on the global population at the reference year based on population data from the United Nations (UNPD, 2013): an equal share per capita is thus computed first. Then a country limit is computed for the reference year as its population share with respect to the global population.

Two different approaches are applied depending on whether the PBs are considered as yearly budgets (Land Cover Anthropisation, Biodiversity Loss, Nitrogen and Phosphorus Losses) or budgets over time (Climate Change, Ocean Acidification).

3.2.3. PBs with yearly budgets

For yearly budgets, this country limit remains fixed for all subsequent years. This means that the per capita limit will fluctuate over time according to population changes in a given country (e.g. decrease of per capita limit in the case of a population increase). The national yearly limits per capita thus evolve differently in subsequent years for each country, depending on national demographics.

For budgets over time, the country limit for a given year is computed as the product of the projected country population for that year and the limit per capita.

For the annual budget, a country limit is computed as follows (Equation 1):

Equation 1. Yearly budget

$$Lc = \frac{Pc_y}{Pw_y} \cdot Lw_y$$

Where:

Lc = Country limit

Lw_y = World limit at reference year

Pw_y = World population at reference year

Pc_y = Country population at reference year

3.2.4. PBs with budget over time

Budgets over time are estimated for a period of several years (the period might be different for each PB): a finite amount of a resource is shared among past, current and future beneficiaries. The global budget over time (e.g. the remaining cumulative GHG emissions 1990-2100) is divided by the cumulative sum of the yearly population in the period considered: the global yearly limit per capita is identical each year. Conversely, the global yearly limit varies each year according to the global population.

For budgets over time, a country limit is computed as follows, using the example of Climate Change for 2010 (Equation 2):

Equation 2. Budget over time

$$Lc_{2010\_2100} = \frac{Pc_{1990}}{Pw_{1990}} \cdot Lw_{1990\_2100} - Uc_{1990\_2010}$$

Where:

Lc_{2010_2100} = Country budget remaining for 2015-2100

Pc_{1990} = Country population 1990

Pw_{1990} = World population 1990

Lw_{1990_2100} = World limit 1990-2100, total budget over the period

Uc_{1990_2100} = Country resource use 1990 to 2014

For the Climate Change limit in 2010, the starting date of the period date was fixed at 1990. Rationales for selecting 1990 are: a) knowledge since the first IPCC report was released in 1990, shedding scientific light on this issue; b) 1990 is the reference date used in international negotiations; and c) accessible data of good quality are available from 1990. The end of the period is 2100, in order to match IPCC scenarios. The global yearly per capita limit is identical each year: the global budget over time (remaining cumulative GHG emissions 1990-2100) is divided by the cumulative sum of the yearly population in the period considered (UNPD, 2013). Conversely, the global yearly limit varies each year according to the global population.

In the case of Switzerland, the Swiss share of the global limit over time (Equation 2) is defined relative to the Swiss share of the global population at the reference year (1990), i.e. 0.125%. The Swiss share is fixed over the period 1990-2100. The country limit for a given year is calculated by subtracting from the 1990-2100 budget the resources used since the beginning of the period. The per capita limit is fixed over the remaining period (i.e. 2015-2100). It is obtained by dividing the country budget by the sum of the country population each year over the remaining period, based on UNPD demographic projections (UNPD, 2013). The country budget for a given year varies according to the country's population in that year.

Planetary Boundaries	**Global Limit**	**Swiss limit**
Climate Change	12.3 GtCO2eq	4.8 MtCO2eq
Ocean Acidification	7.6 GtCO2	5.7 MtCO2
Biodiversity Loss	0.16 (unitless)	0.16 (unitless)
Nitrogen Losses	47.6 Tg	53.8 t
Phosphorus Losses	31 Tg	43.6 Kt
Landcover Anthropisation	1'936'200 km2	21'900 Km2

Table 2 Limits used at Global and Swiss levels

3.3. Computing country footprints

The footprints are the current use of resources (or the cumulative use of resources, if the PB is of a budget type). To stay within planetary boundaries, the footprints should be smaller than the PBs. Footprint indicators are tools for measuring actual environmental impacts in a synthetic manner (Hoekstra and Wiedmann, 2014) going beyond the classical territorial perspective. Footprints quantify environmental impacts occurring in- and outside a country due to domestic consumption. Footprints are based on scientifically validated rationales and apply an approach called Life Cycle Thinking.

Ideally, the country footprint should be computed with the same set of data as the global footprint to ensure a coherent overview and compatibility between the assessments of countries. In our case study on Switzerland, however, a proprietary environmental database was used from the Swiss Federal Office for the Environment, developed for existing assessments of the Swiss footprint (Frischknecht et al., 2014, 2013). This database combines official Swiss territorial data and modelled environmental data for imports and exports, using the ecoinvent 2.0 database. Life

Cycle Impact Assessment approaches were then used to convert this inventory into values compatible with the computed limits when required.

3.4. Performance and priority assessment

Since uncertainties are large in this type of assessment, the performance and priority assessment combine quantitative results with a qualitative evaluation on data quality and long-term global trends. For each PB, global and national, quantitative scores are first computed as the ratio of the yearly footprint over the yearly limit (scores between 1 and 2 are clasified as "small to medium", above 2 as large). Then, taking into account a judgement (based on own knowledge and views from consulted experts) on the uncertainty and the trend (rapidity of the degradation) of the global footprint, scores are classified into one of the four following categories: Clearly safe, Safe, Unsafe, Clearly unsafe. The four categories of performance are shown in Table 3.

Performance	***Score***	***Confidence in Score***	***Trend***
Clearly unsafe	Large overshoot	High	Rapidly deteriorating
	Small to medium overshoot	Medium to low	Rapidly deteriorating
Unsafe	Small to medium overshoot	Medium to low	Slow evolution
	No overshoot	Medium to low	Rapidly deteriorating
Safe	No overshoot	Medium to low	Slow evolution
Clearly safe	No overshoot	High	Slow evolution

Table 3 A performance defined with four categories

3.4.1. Principles for setting priorities

The proposed analysis identifies potential issues at two different scales (global and country scale). Two types of situations can be identified based on the combination of the performances at these two scales:

PBs to be considered as a priority: PBs with a Clearly Unsafe or Unsafe performance at global scale are clearly a first priority, since current global socio-economic activities are putting the current global Safe Operating Space in jeopardy. International discussions and scientific developments in regard to these issues should be promoted. Every country is concerned, whatever size their footprint is. Countries overshooting these PBs should, in addition, take national action to reduce their footprint.

PBs that are not a priority: PBs with a Safe or Clearly Safe performance at global scale are not a priority. While some countries are overshooting these PBs, the PB framework cannot be used as a justification to take national action in order to reduce these footprints (some other frameworks or local considerations could however offer valid arguments).

4. Results

4.1. Limits, current footprints and performances

As shown on Figure 2, from a global perspective, three of the six computed performances show a Clearly Unsafe situation, either because of a large overshoot of current global yearly footprints over yearly global limits (Climate Change and Ocean Acidification), or because of an overshoot combined with a rapidly deteriorating trend (Biodiversity Loss). One performance is qualified as Unsafe because there is an overshoot combined with a slowly evolving situation (Nitrogen Losses), and two performances are considered as Safe (Land Cover Anthropisation and Phosphorus Losses).

The performance was not computed for four PBs (Stratospheric Ozone Depletion, Atmospheric Aerosol Loading, Global Freshwater Use and Chemical Pollution). While further research is needed to assess their performance, there is no evidence in the literature that the limits of these PBs are currently exceeded and in the case of ozone depletion, thanks to the actions following the Montreal Protocol, one observes an ongoing recovery of the stratospheric ozone layer.

As a result, one concludes that the global yearly limits are crossed for four out of nine PBs (considering N and P as one PB as in Rockström et al. (2009)), with a Clearly Unsafe situation for three of them (Climate Change, Ocean Acidification and Biodiversity Loss). These results in terms of the level of current socio-economic practices are thus in line with results based on the crossing of the biophysical global limits (Steffen et al., 2015b) for Biodiversity Loss and Land Cover Anthropisation. The current results show, however, greater urgency for Climate Change and much greater urgency for Ocean Acidification, while showing a lower urgency for Nitrogen and Phosphorus Losses. The difference for Phosphorus with Steffen et al. (2015) results from three aspects. First, as mentioned in the supplementary materials, the estimates of global P releases differ among global models. Due to the fact that a global anoxic event has not happened yet, we estimate that the current limit is not overshoot by definition and selected the model with the lower bound accordingly. Second, Steffen et al. (2015) propose a limit for the global P release going from 11 to 100 Tg P per year. Even assuming that the models with the higher P releases are correct (i.e. 22 Tg P per year) as in Steffen et al. (2015), a possible overshoot would only happen in the lower part of the range of the limit. Thirdly, Bouwman et al. (2013) project that releases will be up to 23 P per year in 2050, which is still in the lower part of the limit range.

As shown in Figure 2, the situation for Switzerland is very similar to the global situation for three PBs, while two are worse and one is unknown: the situation is worse for Nitrogen Losses (large overshoot); i.e., a Clearly Unsafe situation, as well as for Land Cover Anthropisation; i.e., Unsafe, due to a rapidly evolving footprint.

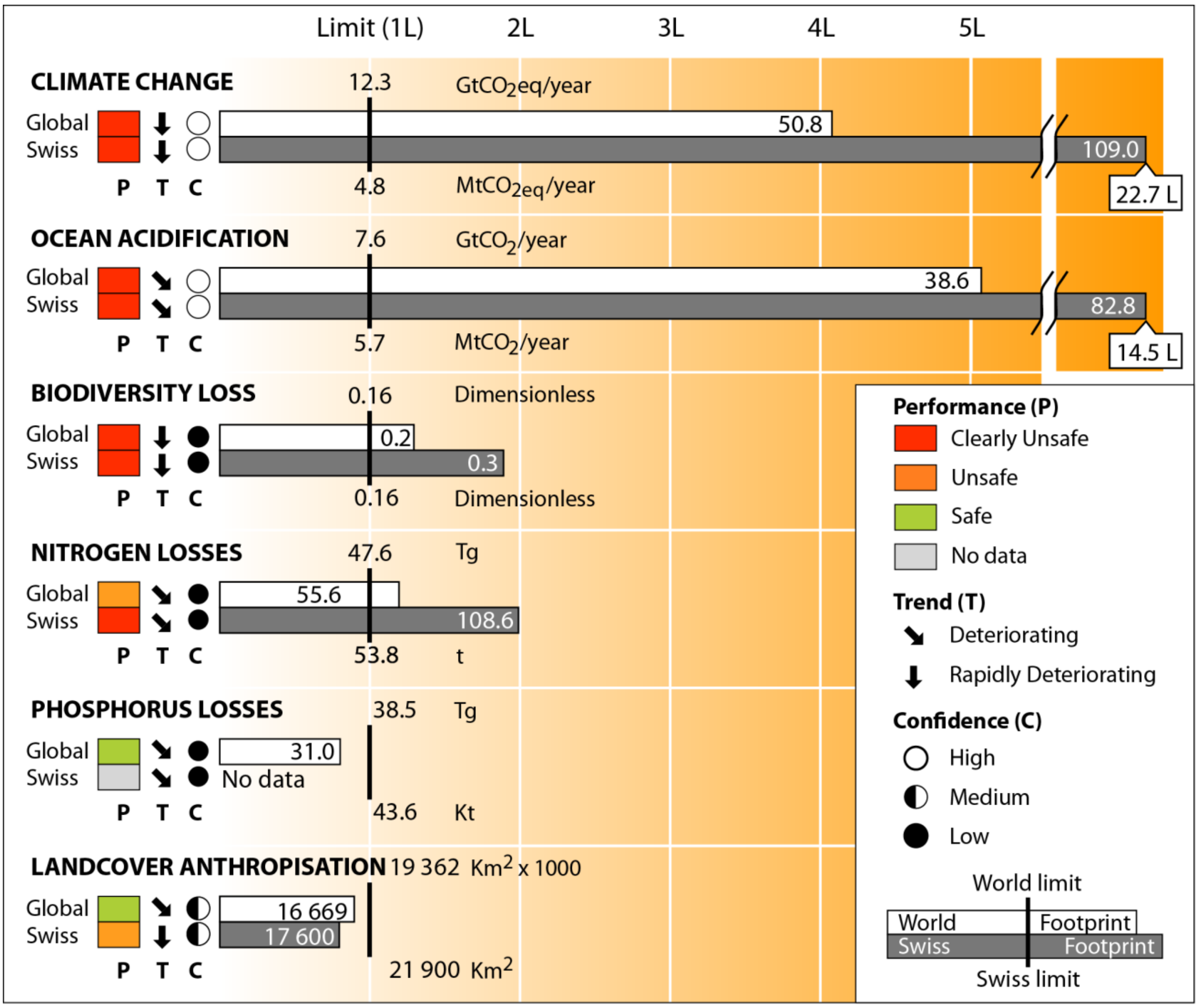


Figure 2. Summary of the results

Results for climate change are based on a target of +2°C and a likelihood of the outcome of 50%. While values would be different if selecting a global temperature change of +1.5° (i.e. resulting in a smaller budget overtime) and/or a 33% or 66% confidence level (the higher the confidence, the smaller the budget), the message would be the same: even under a conservative approach as selected here, the current footprints strongly exceed the limits, by a factor 4.1 for the World and 22.7 for Switzerland.

4.2. Thinking ahead with Business As Usual scenarios

Simple projections can be made with respect to the projected evolution of the population. The global and Swiss populations will evolve similarly. Thus, for indicators considered as yearly budgets, the limits per capita will be reduced by around 10% in 2020, 18% in 2030 and 29% in 2050. Maintaining the same global and Swiss performances in the future thus requires reducing the yearly per capita footprints by the same amount. Due to population growth, and assuming a constant footprint per capita, the limit will be attained for all PBs assessed with a yearly budget before 20 years.

For PBs with indicators considered as budgets over time, the evolution of the future population is already considered in the computations. Assuming a constant footprint per capita, the budget over time for Climate Change will be reduced to 0 in 2020 (Switzerland) and 2041 (globally). For Ocean Acidification, the biophysical limit will be attained in 2021 (Switzerland) and 2035 (globally).

4.3. Priority assessment

From the above assessment, it can be recommended that Climate Change, Ocean Acidification, Biodiversity Loss due to land use and Nitrogen Losses are considered as priorities: these PBs with a "Clearly Unsafe" or "Unsafe" performance at global scale should be managed. Global current footprints are above an ecologically sustainable level, and thus international discussions and scientific developments on these issues should be promoted. This is also the case for Switzerland, which should take action to reduce its footprints.

Land Cover Anthropisation and Phosphorus Losses have not yet reached the limit, and are therefore not at the same level of priority, despite the fact that their trends are declining.

5. Discussion

The generated values are based on modelling which by definition implies making simplifications and assumptions to answer a specific set of questions. The validity of the indicators is thus limited to the scope of these questions.

The generated indicators and values are adequate to identify large overshoots, orders of magnitude and analyse long-term trends, i.e. relative differences over five to10 year periods of aggregated values. They are not adequate to monitor precise values nor for identifying small overshoots, and monitor small variations (e.g. 10%) over short periods (e.g. yearly variations). The indicators are thus not appropriate to set operational target values linked to the importation of a specific product, e.g. palm oil. More disaggregated data or models, a narrower focus on specific products and a focus on Driving Forces should be used for these purposes.

5.1. Allocation

The choice of the allocation mechanism can potentially largely influence the results per country. While science can provide information to compare the mechanisms, the selection of the allocation mechanism is ultimately a policy decision.

5.2. Historical contributions

Considering past resource uses and pollutions is a well-known subject of debate in the context of environmental negotiations. Taking into account historical environmental impacts is, however, not a straightforward task. Setting a starting date for past contributions may depend on various criteria such as the availability of data, awareness of the problems, date of political decisions or access to means for reducing impacts potentially leading to different results. In the present study, historical contributions were included for PBs considered as budgets over time (Climate Change and Ocean Acidification). The chosen starting date of 1990 responds to several of the above criteria, but would certainly be relevant to test other starting dates further in the past, which would require some estimations of country data. In terms of Climate Change, considering past emissions thus reduces the current limit per capita to 0.6 t CO2-eq per capita in 2011, instead of 1.7 t CO2-eq per capita without considering them.

5.3. Limits for climate change: political values.

In this study, the computation for climate change has been carried out for 2°C (50% confidence). However, the 2°C limit and the 1.5 °C limit since the COP-21 (Paris Agreement) are political limits resulting from negotiations, not biophysical limits. In the original article by Rockström et al. (2009), the limit was set to 350 ppm CO_2 and 1 W/m^2. A pathway to return to a 350 ppm level by 2100 has been evaluated by Hansen et al., 2013. .This pathway would necessitate restricting emissions from fossil fuel emissions to 129 GtC by 2050 and to 14 GtC by 2100, while at the same time trapping 100 GtC in forest and soils through reforestation and agricultural practices. Such an approach would result in a budget over time of 43 GtC compared to the computed 305 GtC, i.e. more than seven times lower.

5.4. Linkages between PBs

Rockström et al. (2009) explain that the limits are valid while they are respected for all the PBs. In addition, PBs are computed independently from each other while they are, in reality, not independent and influence each other. For example, deforestation (land cover change) has direct impact on climate change (CO_2 emissions, change in albedo), on biodiversity (through habitat losses) and also affects precipitation hence freshwater. Given their interconnectivity, the level of pressure on one PB is likely to be more severe if pressures on other related PBs are considered, as compared with any given PB being evaluated separately.

Fortunately, this works both ways: if policies are set to reduce the pressures on one PB, they can also reduce the pressure on other linked PBs. For example, reforestation will help to absorb more CO2, restore precipitation regimes and support biodiversity (if the appropriate species are planted). Thus, this is likely to reduce pressures on the Climate, Biodiversity and Freshwater PBs.

6. Conclusions

6.1. Added-value of the approach

This research confirms the already well-known importance of acting to manage Climate Change and Biodiversity Loss. It adds Ocean Acidification and Nitrogen Losses to the list of the key topics, Thanks to its focus on the consumption-based quantification of the environmental impacts resulting from current socio-economic practices.

Combining PBs and footprinting provides a complementary perspective to existing analyses at national scale. It uses a multi-criteria assessment and identifies other global priorities than Climate Change, allowing actions to be taken on these at national or more local scales. If applied to all countries, it could help to better understand the role of specific countries vis-a-vis these global priorities. Such a quantitative approach allows to compare the footprint against the absolute limits to compute a given country's performance. This can be then used as a benchmark to identify progress. It offers a more detailed alternative to the Ecological Footprint. Specific assessments could be performed on environmental domains, economic sectors or even for a single company.

It should also be emphasized that this paper focuses only on globally significant environmental processes. Some regional environmental issues may require actions at a global policy level, but these were outside the scope of the current study and hence were not included.

Some of these regional environmental issues are thus subject to international protocols such as the Convention on Long-Range Transboundary Air Pollution (13 November 1979). In addition, issues not mentioned as first priority in this specific analysis may be of high priority for other reasons, such as being a key input for the agro-industrial system, e.g. phosphorus, or for local health, e.g. mercury (Minamata Convention).

6.2. Lesson learned: a new way of thinking

PBs are not straightforward to grasp because they require thinking differently: in terms of spatial scope first (the global Earth system versus the national territory), and then because their focus may differ from national preoccupations for the same environmental issues: e.g. the PB Land Cover Anthropisation is primarily about global carbon sequestration and albedo, not about land-planning or the quality of landscapes.

The study opens the path to establishing a new mindset based on the recognition of global environmental limits, the possibility to quantify these limits as well as the footprints of nations. It has the potential to change the way we practice environmental assessments and environmental policies, both at the global and national levels.

6.3. Recommendations for further research

This exploratory work shows the interest - as well as the limits - of the current understanding of the PB concept and outlines the need for further developments. Firstly, indicators and limits are still to be identified for three PBs (Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution).

Secondly, a large number of approximations are performed in studies in the literature, as in this work, to compute the global limits and footprints. Better indicators, better defined models and more data would enable reducing them for all PBs.

Thirdly, the distributional aspects for the downscaling of global limits to countries' limits are limited to simple aspects computable with the available data. Further developments are needed to explore in more detail the quantitative differences induced by the existing distributional concepts.

Fourth, the application of the methodology to other countries faces the challenge of finding appropriate data for footprints. Several multi-regional/national databases exist and can already be used, even if the current methodology has to be slightly adapted.

Five, further developments should attempt to make footprint indicators more spatially explicit where relevant (e.g. for biodiversity and freshwater scarcity; see Chaudhary et al., 2016 and Frischknecht et al., 2016), and also aim at highlighting which economic sectors contribute most to the status of each PB. This can be useful to prioritise operational measures for reducing national footprints.

Finally, questions of technical and economic feasibility of future reductions of the Global and country footprints should be addressed. The potential to reduce Carbon, Biodiversity and Nitrogen footprints should be evaluated within different domains of consumption and production.

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National environmental limits and footprints based on the Planetary Boundaries framework: the case of Switzerland.

Supplementary material

Table of Content

Acronyms

BDP	Biodiversity Damage Potential
C&C	Contraction & Convergence model
CBD	Convention on Biological Diversity
DPSIR	Driving forces, pressures, states, impacts, responses (model)
ENA	European Nitrogen Assessment
FOEN	Swiss Federal Office for the Environment

FSO	Swiss Federal Statistical Office
GDP	Gross domestic product
GDR	Greenhouse Development Rights framework
GEG	Global Environmental Goals
GHG	Greenhouse gas
GRID	Global Resource Information Database
IPCC	Inter-Governmental Panel on Climate Change
LCA	Life Cycle Assessment
LPI	Living Planet Index
MDG	Millennium Development Goals
MRIO	Multi-regional Environmentally Extended Input-Output Model
SDG	Sustainable Development Goals
UNEP	United Nations Environment Programme

A1. Definitions of concepts

1.1. Limits

Limits refer to threshold values (e.g. the concentration of CO_2 in the atmosphere) beyond which unacceptable impacts are much more likely to occur. The threshold values should be determined by science, based on a large agreement from the scientific community, even if the uncertainty range is large. The impacts must be specifically defined: e.g. effects on the ecosystem stability (e.g. global warming), on the provision of resources and services (e.g. food production), or on human health (e.g. disaster risk).

At local scale and in specific domains, these limits are sometimes expressed as “critical levels” (e.g. concentration of atmospheric pollutants) and/or “critical loads” (e.g. deposition of atmospheric pollutants on ecosystems).

In the field of global change the term “tipping point” is often used for a value at which a system changes from one stable (steady) state to another.

1.2. Targets

A target can be defined as “a value that the indicator should reach, accompanied or not by a deadline to achieve this value (target year)” (Eurostat, 2014). Targets are set through policy processes with short-term and achievable objectives in mind. They may be based on scientific evidences, but not only. Targets are most often the results of negotiations, which relate other dimensions such as power relations, economic considerations, public pressure, social values and perceptions.

The link between limits and targets is not straightforward. Even if a scientific limit is identified, it does not directly translate into an identical policy target, either, for instance, because the limit is seen as too difficult to attain (e.g. too expensive in economic terms), or because the limit is a value to be avoided rather than to be reached.

1.3. Footprints

Footprint indicators are tools for measuring actual environmental impacts in a synthetic manner (Hoekstra and Wiedmann, 2014) going beyond the classical territorial perspective. Footprints quantify environmental impacts occurring in- and outside a country due to domestic consumption. Footprints are based on scientifically validated rationales and they apply an approach called Life Cycle Thinking.

Footprints have started to be more known to the general public in the 2000's (e.g. carbon footprint, water footprint). Due to the large development of the last 15 years, footprints can now be computed for thousands of different releases to the environment and resource uses mainly using top-down (Environmentally Extended Input-Output Analysis) (Sue, 2009) or bottom-up approaches (mainly process Life Cycle Assessment, see e.g European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010)[1]. The interest in footprint indicators for the quantification of environmental objectives is recognised (BIO Intelligence Service and Institute for Social Ecology and Sustainable Europe Research Institute, 2013, 2012). Data is however still scarce outside Europe and the aggregation of data into meaningful figures requires generally large amount of work.

[1] For an evaluation on recent footprint indicators see also (Frischknecht et al., 2013).

61 # A2. The nine Planetary Boundaries (2009)

Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary boundary (zone of uncertainty)	State of knowledge*
Climate change	Atmospheric CO_2 concentration, ppm; Energy imbalance at Earth's surface, W m^{-2}.	Loss of polar ice sheets. Regional climate disruptions. Loss of glacial freshwater supplies. Weakening of carbon sinks.	Atmospheric CO_2 concentration: 350 ppm (350-550 ppm) Energy imbalance:+1 W m^{-2} (+1.0 – +1.5 W m^{-2}).	1. Ample scientific evidence. 2. Multiple sub-system thresholds. 3. Debate on position of boundary.
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag}).	Conversion of coral reefs to algaldominated systems. Regional elimination of some aragonite- and high-magnesium calcite-forming marine biota Slow variable affecting marine carbon sink.	Sustain ≥ 80 % of the preindustrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80 % - ≥70 %).	1. Geophysical processes well-known. 2. Threshold likely. 3. Boundary position uncertain due to unclear ecosystem response.
Stratospheric ozone depletion	Stratospheric O_3 concentration, DU.	Severe and irreversible UV-B radiation effects on human health and ecosystems.	<5% reduction from preindustrial level of 290 DU (5 - 10 %).	1. Ample scientific evidence. 2. T hreshold well established. 3. Boundary position implicitly agreed and respected.
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis.	Disruption of monsoon systems. Human health effects. Interacts with climate change and freshwater boundaries.	To be determined	1. Ample scientific evidence. 2. Global threshold behaviour unknown. 3. Unable to suggest boundary yet.
Nitrogen and phosphorus inputs to the biosphere and oceans	P: inflow of phosphorus to ocean, increase compared to natural background weathering N: amount of N_2 removed from atmosphere for human use, Mt N yr^{-1}	P: avoid a major oceanic anoxic event (including regional), with impacts on marine ecosystems. N: slow variable affecting overall resilience of ecosystems via acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems.	P: < 10× (10× - 100×) N: Limit industrial and agricultural fixation of N_2 to 35 Mt N yr^{-1}, which is ~ 25% of the total amount of N_2 fixed per annum naturally by terrestrial ecosystems (25- 35%)	P: (1) Limited knowledge on ecosystem responses; (2) High probability of threshold but timing is very uncertain; (3) Boundary position highly uncertain. N: (1) Some ecosystem responses known; (2) Acts as a slow variable, existence of global thresholds unknown; (3) Boundary position highly uncertain.
Global freshwater use	Consumptive blue water use, km^3 yr^{-1}.	Could affect regional climate patterns (e.g., monsoon behaviour). Primarily slow variable affecting moisture feedback, biomass production, carbon uptake by terrestrial systems and reducing biodiversity	< 4,000 km^3 yr^{-1} (4,000 - 6,000 km^3 yr^{-1})	1. Scientific evidence of ecosystem response but incomplete and fragmented. 2. Slow variable, regional or subsystem thresholds exist. 3.. Proposed boundary value is a global aggregate, spatial distribution determines regional thresholds.
Land system change	Percentage of global land cover converted to cropland.	Trigger of irreversible & widespread conversion of biomes to undesired states. Primarily acts as a slow variable affecting carbon storage and resilience via changes in biodiversity and landscape heterogeneity.	≤ 15% of global ice-free land surface converted to cropland (15 – 20%).	1. Ample scientific evidence of impacts of land cover change on ecosystems, largely local and regional. 2. Slow variable, global threshold unlikely but regional thresholds likely. 3. Boundary is a

Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary boundary (zone of uncertainty)	State of knowledge*
				global aggregate with high uncertainty, regional distribution of land system change is critical.
Biodiversity loss	Extinction rate , extinctions per million species per year (E/MSY).	Slow variable affecting ecosystem functioning at continental and ocean basin scales. Impact on many other boundaries – C storage, freshwater, N and P cycles, land systems. Massive loss of biodiversity unacceptable for ethical reasons.	< 10 E/MSY (10 – 100 E/MSY)	1. Incomplete knowledge on the role of biodiversity for ecosystem functioning across scales. 2. Thresholds likely at local and regional scales 3. Boundary position highly uncertain.
Chemical pollution	For example, emissions, concentrations, or effects on ecosystem and Earth system functioning of persistent organic pollutants (POPs), plastics, endocrine disruptors, heavy metals, and nuclear wastet.	Thresholds leading to unacceptable impacts on human health and ecosystem functioning possible but largely unknown. May act as a slow variable undermining resilience and increase risk of crossing other threshold.	To be determined	1. Ample scientific evidence on individual chemicals but lacks an aggregate, global-level analysis. 2. Slow variable, large-scale thresholds unknown. 3. Unable to suggest boundary yet.

* State of knowledge regarding three factors: 1. Basic understanding of Earth system process. 2. Existence of threshold behaviour. 3. Position of the boundary

Source : Stockholm Resilience Centre http://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/quantitative-evolution-of-boundaries.html

An update of the Planetary Boundaries has been published in 2015 (Steffen et al., 2015), While their number remain unchanged, some names (and descriptions) have evolved: Climate Change, Ocean acidification, Stratospheric ozone depletion, Atmospheric aerosol loading, Nitrogen and phosphorus flows to the biosphere and oceans, Freshwater consumption and the global hydrological cycle, Land system change, Loss of biosphere integrity (biodiversity loss and extinctions), Chemical pollution and the release of novel entities.

A3. Limits, footprints & performances for Switzerland and the World

3.1. Climate Change

Our climate is changing due to anthropogenic emissions of greenhouse gases (GHG) as well as changes in land cover (IPCC, 2013). Due to the long term residence of GHG emissions in the atmosphere (multi-century to millennial time scale), elevated temperatures will remain for many centuries after a complete cessation of net anthropogenic GHG emissions (IPCC, 2013). This climate change will induce significant social, economic and environmental long-term impacts, and a wide range of sectors will be affected (IPCC, 2014).

3.1.1. Description

This Planetary Boundary is set to avoid regional modifications at global scale including, among others: climate disruptions; reduction of land glaciers mass and related threat to water supply; complete loss of arctic sea ice, and weakening of carbon sinks; increase impacts from extreme events; changes in temperatures and precipitation patterns; shift in biodiversity and agriculture, as well as sea level rise and related coastal erosion.

Climate Change is a global issue since GHG emissions are accumulating in the atmosphere whatever their location of origin. The global limit for Climate Change is set with an indicator expressed in terms of *the remaining cumulative GHG emissions (including land cover changes) for a 50% chance to stay below a 2°C increase by 2100 compared with pre-industrial level*.

3.1.2. Methodology

Selection of the indicator

Several references and limits have been suggested in the literature: CO_2 concentration in the atmosphere, with a limit of 350 ppm; a Radiative Force (RF) of 1 W/m^2 (Hansen et al., 2013; Johan Rockström et al., 2009) or a global temperature increase of 1.5 or 2°C.

According to Hansen et al. (2013), a limit of 350 ppm, compatible with a target of 1°C temperature increase, corresponds to a “Safe Operating Space”. No new evidences were found which contradict this limit, and therefore this value is kept as the theoretical reference. This theoretical reference of 350 ppm has already been exceeded, the current value (April 2014) being 401.3 ppm (NOAA, 2014). Keeping the global temperature increase under 1°C is thus extremely unlikely, i.e. 0-5% chances. This is however still possible following IPCC RCP2.6 scenario (IPCC, 2013).

The target of a 2°C temperature increase as compared with pre-industrial time is the main target currently discussed (Stocker et al., 2013). IPCC (2013) warns however that "there are already clear indications of undesirable impacts at the current level of warming and that 2°C warming would have major deleterious consequences". These impacts are well described in IPCC AR5, WG2 report (IPCC, 2014). Here are some examples of these consequences:

- Negative impacts to agriculture (although individual locations may benefits).
- Global mean sea level rise for 2081–2100 relative to 1986–2005 will likely be in the range of 0.44 m (0.26 to 0.55).
- A reduction of 70% of Northern Hemisphere September sea ice extent as compared with 2005.
- Biodiversity losses, with many species and systems with limited adaptive capacity subject to very high risks, particularly in polar, mountainous and coral-reef systems.

Despite the fact that the 2°C target does not correspond to a truly "Safe Operating Space", the objective to keep the global temperature below a 2°C increase over pre-industrial level by 2100 is selected as the reference since selecting a more stringent objective (e.g. the 2°C at 66% probability mentioned at the COP21) would not add much due to the severity of the current situation and the already very large changes required to reduce GHG emissions in order to respect the limit of this Planetary Boundary. Keeping the global temperature increase below the 2°C limit will already be very difficult to achieve.

To assess this Planetary Boundary, an indicator of yearly GHG emissions is selected. Climate Change being a largely studied issue, the link between the increase in global temperature, the increase in atmospheric carbon concentration, the GHG emissions and other land cover changes are now well known. "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC, 2013).[2] A limit computed with an indicator at the Pressure level in the DPSIR framework (EEA, 2005) can thus be based on strong scientific evidence. In addition, good data on GHG emissions from human activities are available enabling the computation of national footprints.

Setting limits

The global limit is computed first and then downscaled to compute the Swiss limit. The global limit per capita represents an equal share perspective. The global limit accounts for future emissions while the Swiss limit accounts for future emissions and for part of the historical emissions. Limits are expressed in terms of average yearly values corresponding to a theoretically acceptable rate of exhaustion of the budget of the remaining GHG emissions. The exhaustion of emissions is set in 2100.

Global limit

According to IPCC (2013), limiting temperature increase can be achieved by limiting the cumulative GHG emissions from human activities and land cover changes, with the addition of GHG mitigating action. Due to the complexity of the climate systems and uncertainties, the amount of greenhouse gases (GHG) emissions for staying below 2°C warming is a question of level of confidence.

Knowing that 515 GtC have already been emitted between the industrial revolution and 2011 (IPCC, 2013), the remaining emissions estimated for the different levels of confidence are shown in Table 1. These values represent cumulative emissions of CO_2 equivalent and can be considered as a budget over time.

Level of confidence	Max. emissions accounting for non-CO_2 forcing	Stock of remaining emissions	
> 33%	900	385	in GtC
> 50%	820	305	in GtC
> 66%	790	275	in GtC

[PP1]

[2] Extremely likely expresses a level of likelihood comprised between 95% and 100% probability.

Source: IPCC, 2013

Table 1. Level of emissions (in GtC) according to the different levels of confidence.

For the selected indicator, *the remaining cumulative emissions (including land cover changes) for a 50% chance*[3] *to stay below a 2°C increase by 2100 compared with pre-industrial level*, remaining emissions are 305 GtC, corresponding[4] to 1473 $GtCO_2eq$ in 2010. The current global budget for 2015 is equal to 1315.6 $GtCO_2eq$, computed by subtracting global emissions from 2011 to 2014 (extrapolated from 2010 values).

On average, this results in 15.5 $GtCO_2eq$ GHG yearly emissions until the exhaustion of the budget in 2100, i.e. in 85 years.

Computing an *equal share per capita* value requires considering current and future populations of the Earth. Dividing the budget by the sum of all yearly inhabitants until 2100[5] results in a global per capita yearly limit of 1.7 tCO_2eq. The global per capita value is fixed over time but the yearly global limit varies according to the yearly global population. The resulting limit for the world is 12.3 $GtCO_2eq$ for 2015. This is smaller than the average yearly value since the world population will be larger in the future.

Comparison with earlier studies

In the original Planetary Boundaries by Rockström et al. (2009), the limit was set to 350 ppm CO_2 and 1 W/m^2. A pathway and return to 350 ppm level by 2100 is described by Hansen et al. (2013). This pathway would require to restrict emissions from fossil fuel emissions to 129 GtC by 2050 and to 14 GtC by 2100, while, at the same time, trapping 100 GtC in forest and soils through reforestation and agricultural practices. Such approach results in a budget of 43 GtC compared to

[3] The 50% chance is selected for its compatibility with Swiss climate policies.

[4] The GHG total, expressed in $MtCO_2$ equivalent is calculated using the GWP100 metric of UNFCCC (IPCC, 1996). The GHG are composed of CO_2 totals excluding short-cycle biomass burning (such as agricultural waste burning and savannah burning) but including other biomass burning (such as forest fires, post-burn decay, peat fires and decay of drained peatlands), all anthropogenic CH_4 sources, N_2O sources and F-gases (HFCs, PFCs and SF6).

[5] The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2013) estimation of the world population until 2050, then assuming a stable population until 2100. The computation is 7.32 billion in 2015 + 7.40 in 2016 +… + 9.55 in 2050 + … 9.55 in 2100 = 784.8 billion people-year.

the here computed 305 GtC. The computed limit is thus around 7 times larger than the implementation of the proposal from Rockström et al. (2009).

In the first computation of national limits, Nykvist et al. (2013) have selected the yearly emissions of CO_2 based on a budget over time. The methodology presented here extends this application in three ways by considering:

- GHG emissions as well as land cover changes rather than CO_2 only
- Past emissions

Limit for Switzerland

Switzerland, like all developed economies, has already emitted a large amount of GHG emissions. To account for part of the historical contributions, the limit for Switzerland is set by downscaling the global limit with the hybrid-allocation approach described in chapter 4: the Swiss share of the global GHG emissions over time is defined relatively to the Swiss share of the global population at a past reference date. The Swiss share is fixed over time. For Climate Change, this reference date is 1990. Rationales for selecting 1990 are (a) knowledge since the first IPCC report was released in 1990, shedding the scientific light on this issue, (b) 1990 is the reference date used in international negotiations, and (c) accessible data of quality is available from 1990.

As shown in Equation 1, the budget over time (maximum future emissions) of Switzerland is computed by:

- Computing the global GHG budget over time in 1990 by adding global past emissions to the budget over time computed for 2010.
- Getting the Swiss share of this budget using the share of the Swiss population as compared to the world population in 1990 (0.125%).
- Deducting the past Swiss emissions from a footprint perspective to get the current Swiss budget over time.

$$FE_{CH} = CHP_{1990} / WP_{1990} \, (FE_W + PE_W) - PE_{CH} \qquad \text{Equation 1}$$

Where,

FE_{CH} Maximum future emissions for Switzerland (from 2015 onward)

CHP_{1990} Swiss population in 1990

WP_{1990} World population in 1990

FE_{W} Maximum future emissions for the World (from 2015 onward)

PE_{W} World past emissions (1990 to 2014)

PE_{CH} Past emissions induced by the Swiss consumption (1990 to 2014)

The computed budget over time of GHG emissions for Switzerland in 1990 is 3.03 $GtCO_2eq$. Subtracting historical footprint emissions for 1990-2014, the budget over time for Switzerland is 0.52 $GtCO_2eq$**.** Values for 1990 to 1995 have been taken from (Jungbluth et al., 2011) and values for 1996-2011 from (Frischknecht et al., 2013). On average, this results in yearly emissions equivalent to 6.1 $MtCO_2eq$ GHG until the exhaustion of the budget in 2100, i.e. in 85 years. This means that Switzerland becomes carbon neutral after this date.

The Swiss per capita limit is computed by considering the current and future population of Switzerland. The Swiss budget is divided by the sum of all the yearly inhabitants of Switzerland until 2100[6] resulting in a Swiss per capita yearly limit of 0.6 tCO_2eq. The Swiss per capita value is fixed over time but the yearly Swiss limit varies according to the yearly Swiss population. The resulting limit for Switzerland is 4.8 $MtCO_2eq$ for 2015. The value is smaller than the yearly average since the Swiss population will be larger in the future.

Data sources & evaluation of the indicator

The data sources for the limits and the global footprint are presented in Table 2.

[6] The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2013) estimation of the Swiss population until 2050, then assuming a stable population until 2100. The sum equals 896 million people-year.

Data	Data sources	Units
Limit of future emissions (global)	Hansen et al 2013, Stocker et al. 2013	C
National (territorial and footprint) emissions from 1990 to current	For 1990-1995: Jungbluth et al. 2011, for 1996-2011: Frischknecht et al. 2013	CO_2
World emissions of all GHG from 1990 to current	EDGAR 2011	CO_2
National population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants
World population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants

Table 2. Climate Change: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 3. Climate Change being a largely studied issue, the overall quality of the assessment can be considered as high.

Quality assessment		
PB relevance	++	
Focus on the overall picture	++	
Reliability (data, models)	+	
Transparency	++	
Communication	+ / -	The limit is different from the one defined by (Rockstöm et al 2009).
Coherence / comparability	+	
Availability of information	++	
Timely	++	

Legend : ++ : High **+** : Acceptable **+ / -** : Potentially problematic **-** : Problematic

Table 3. Climate Change: quality assessment.

Computing current footprints

The general description of the computation of the footprints is presented in the main part of the article. The specificities for Climate Change are presented in this supplementary document.

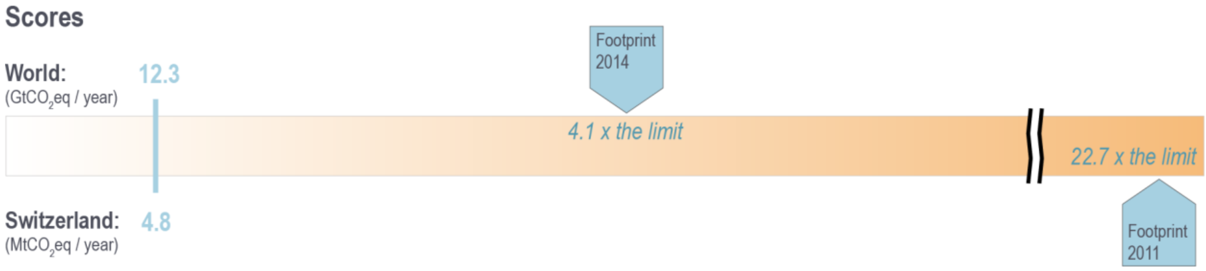
The global emissions (equivalent to the global footprint) are based on the EDGAR database (2011). Data is extrapolated for 2011 based on the average growth rate for 2006-2010.

The Swiss footprint is based on the FOEN proprietary database. Footprints are computed for the years 1996-2011. The inventory of GHG emissions contains all anthropogenic CO_2, CH_4 sources, N_2O sources and F-gases (HFCs, PFCs and SF_6). The inventory is converted to CO_2eq with the conversion factors provided for GWP100 by Forster et. (2007).

3.1.3. Current performance

The Planetary Boundary Climate Change is largely overshot globally and from a Swiss perspective and the evolution is very rapid. Confidence in the results is high. The global and Swiss performances are thus qualified as Clearly Unsafe.

Results[7] are presented for 2015 limits and for current footprints (global: 2014, Switzerland: 2011) in Figure 1. The global yearly limits consider current and future populations, i.e. they represent the equal share perspective. The limits for Switzerland consider, in addition, past Swiss emissions.



	World	Switzerland
Confidence in score	High	High
Trend	Rapidly deteriorating	Rapidly deteriorating
Performance	Clearly Unsafe	Clearly Unsafe

Figure 1. Climate Change: global and Swiss performances.

At global scale, the global limit is at 12.3 $GtCO_2eq$ for 2015 due to a per capita limit set at 1.7 tCO_2eq. With a current global footprint estimated to be 50.8 $GtCO_2eq$ for 2014, and a per capita footprint at 7.3 tCO_2eq, the limit for Climate Change is globally exceeded by a factor 4 for 2014. The situation is clearly an overshoot. This is also the case when comparing the footprint with the average yearly limit value (15.5 $GtCO_2eq$) until 2100.

For Switzerland, the pattern is similar and the Swiss footprint is largely over its long-term acceptable average. The Swiss limit is at 4.8 $MtCO_2eq$ for 2105 due to a per capita limit set at 0.6

[7] The values consider all greenhouse gases while the results for Ocean Acidification consider CO_2 only.

tCO_2eq. With current footprint emissions estimated to be 109 $MtCO_2eq$ for 2011 for Switzerland, and a current per capita footprint at 13.7 tCO_2eq (Frischknecht et al., 2014) this limit is exceeded for Switzerland by a factor 23 for 2011. If the past would not be considered, i.e. in an equal share perspective, the limit would still be exceeded by a factor 8 for 2011.

Setting a shorter term duration for the use of the budget, for example with an exhaustion in 2050, the situation would appear, at first, less dramatic. The underlying assumption is however drastic since this duration implies that there won't be any emissions of GHG starting in 2050. In such a context, the 2015-2050 average yearly limit for Switzerland would be 14.9 $MtCO_2$, i.e. an overshoot by a factor 3.

Since the limits are based on a 2015-2100 budget, several options are possible to spend this budget. The Swiss budget of GHG emissions corresponds to:

- *4.8 years of emissions* (until mid-2019) at the current Swiss yearly emissions rate.
- *Less than 7 years* with an ongoing yearly reduction of 10%. This would result in cumulative long-term emissions at 980 rather than 500 $MtCO_2eq$.
- *Less than 11 years* with an ongoing yearly reduction of 15%. This would result in cumulative long-term emissions at 618 rather than 500 $MtCO_2eq$.
- *Sustainable* with an ongoing yearly reduction of 17.5%, resulting in cumulative long-term emissions at 513 $MtCO_2eq$.

3.1.4. Discussion: Climate Change

The theoretically correct limit set by Hansen et al. (2013) and Rockström et al. (2009b) to stay in a "Safe Operating Space" being extremely unlikely (Stocker et al., 2013), another limit based on the remaining budget of GHG emissions has been set. This limit is based on a potentially (50% chance) achievable objective, a 2°C target. Respecting this limit will require tremendous efforts since the Swiss footprint is currently drastically larger than the average yearly limit. This is notwithstanding the fact that such results are computed with a 50% chance only, representing thus a significant risk with respect to the issues at stake.

Considering the global budget as a whole and a yearly rate of global emissions similar to the current rate, the global budget would be exhausted in 26 years, by 2041, i.e. 20 years after the exhaustion of the Swiss share of the budget.

Looking at the historical situation over 1996-2011 shows a cumulative increase of the Swiss footprint of 7% (+ 0.5% yearly). Domestic efforts to reduce carbon emissions are visible (- 16.9% for the part of the Swiss production consumed in Switzerland) but are more than counteracted by the GHG emissions due to imports (+ 56%). Figure 2 shows the GHG emissions induced by the Swiss consumption, i.e. the domestic emissions from the Swiss production minus domestic emissions for exports plus the foreign emissions for imports.

To respect the yearly limit, the reduction in Switzerland should thus increase in pace (a yearly decrease equivalent to the total decrease over the period 1996-2011 would be adequate) and the tendency for the emissions due to imports be inversed. Such inversion can be performed in two ways: by reducing the quantity of imports and by reducing their carbon intensity.

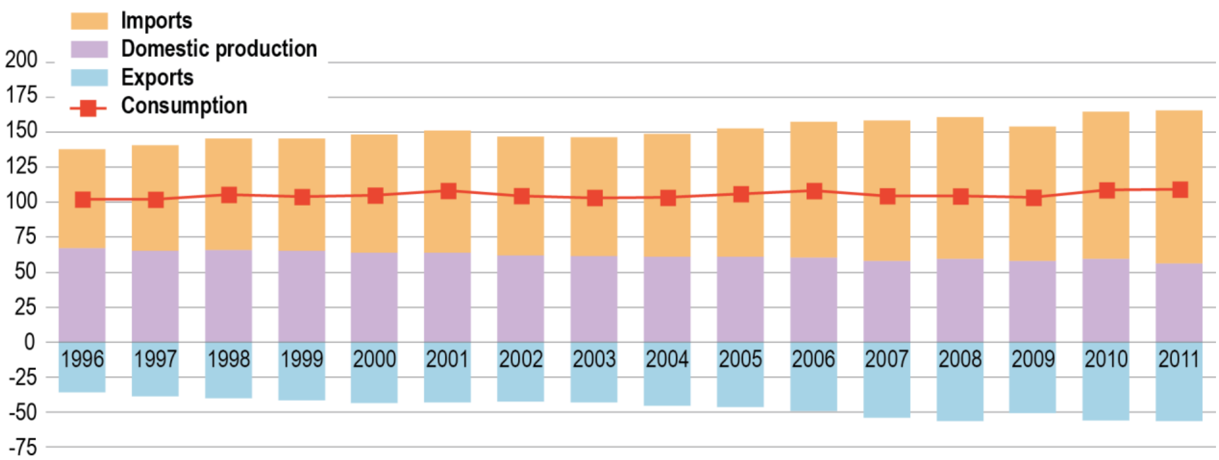


Figure 2. GHG emissions (in $MtCO_2eq.$) induced by the Swiss consumption.

Comparing the Swiss GHG footprint to Swiss territorial emissions for 2011 show that both values are almost equal, but that over time the difference is increasing (4% of difference in 2011). Assuming a territorial perspective, as it is usually the case in the international climate negotiations, rather than a footprint perspective as in this study, would thus result in the same the conclusion.

With respect to potential solutions, any additional emissions over the limit can be considered in two ways in the present international environmental regime: through local reduction or through offsetting by either negative emissions (e.g. reforestation and improved agricultural practices) or by supporting other countries in limiting an equivalent amount of GHG emissions.

Current offsetting practices are however not sufficient: current forest policies aim at using wood in a sustainable way, not at storing carbon over the long term. "Afforestation and reforestation remove CO_2 from the atmosphere, and result in a net accumulation of carbon in living biomass. However, if the forest is subsequently destroyed the carbon will be released, so this option depends on addressing issues of long term forest management." (Meadowcroft, 2013). For this reason, many scenarios for remaining below the 2°C target assume negative emissions (i.e. carbon storage) in the second half of the century (Guivarch and Hallegatte, 2013; Peters et al., 2011). Deforestation has led to a production of 100 GtC and reforestation as well as improved agricultural practices could be used to store part of the CO_2 back in forest and soils (Hansen et al., 2013).

3.2. Ocean Acidification

Ocean acidification is sometimes referred to as "the other CO_2 problem" (Doney et al., 2009). Ocean acidification is not caused by climate change, however, both issues share the same origin, i.e. the amount of anthropogenic CO_2 emitted into the atmosphere. The two issues need however to be treated separately since their limits and underlying causes differ: ocean acidification is nearly entirely caused by CO_2 emissions, whereas climate change is induced by all greenhouse gases as well as by changes in land cover.

From all the CO_2 emitted, 43% (± 2%) remains in the atmosphere and contributes to climate change. Another 29% is stored in forests and soils. The remaining 28% (± 5%) enters oceans (Stocker et al., 2013) and interacts with water to generate carbonic acid (H_2CO_3). It dissociates into H^+ ions and bicarbonate HCO_3^- (see Equation 2) and leads to ocean acidification (Doney et al., 2009; Feely et al., 2009; Steinacher et al., 2009).

$$CO_2 + H_2O \Longrightarrow H_2CO_3 \Longrightarrow HCO_3^- + H^+ \qquad \text{Equation 2}$$

More CO_2 may be beneficial to some species capable of photosynthesis, e.g. algae. The issue is for organisms using aragonite, i.e. calcium carbonate ($CaCO_3$) to form their shells, e.g. molluscs, or their calcareous exoskeleton, e.g. corals. With more CO_2, the chemical equilibrium described in Equation 3 is shifted to the left, resulting in a lesser concentration of ions CO_3^{--}. Below a critical concentration of carbonate ions, aragonite shells or exoskeleton produced by marine organisms dissolve spontaneously (Bopp et al., 2013; Feely et al., 2009).

$$2HCO_3^{-} \Longleftrightarrow CO_3^{--} + CO_2 + H_2O \qquad \text{Equation 3}$$

This Planetary Boundary has a strong connection with climate, but also with marine biodiversity. The main impacts from ocean acidification being on marine fauna and flora, affecting carbon sinks as well as on industries linked with marine resources, e.g. fisheries and tourism.

3.2.1.Description

This Planetary Boundary is set to avoid the conversion of coral reefs to algal-dominated systems, the regional elimination of some aragonite - and high-magnesium calcite - forming marine biota.

Ocean Acidification is a global issue since CO_2 emissions are accumulating in the oceans whatever their location of origin. It is global, albeit with regional variations: the solubility of aragonite, governed by the concentration of CO_2 in the ocean, varies with contextual parameters. The solubility of aragonite increases at lower water temperature, with higher depth (pressure) and higher salinity. Because of this, the impacts from the increase concentration of CO_2 into the atmosphere will differ from one location to another. E.g., cold water (polar) will be more rapidly affected given its higher capacity to dissolve CO_2 (Steinacher et al., 2009). In certain regions, the isocline (depth at aragonite saturation) could reach surface water.

The global limit for Ocean Acidification is set with an indicator expressed in terms of *the remaining cumulative emissions of carbon dioxide (CO_2) from human activities to maintain an acceptable calcium carbonate saturation state* Ω*.*

3.2.2.Methodology

Selection of the indicator

Several ways were explored to assess ocean acidification. First, by looking at pH. Since 1750, the ocean pH has decreased from 8.2 to 8.1.[8] Depending on scenarios, the pH is expected to be reduced[9] by 0.2 to 0.4 by the end of 21st century.

Second, by looking specifically at one of the main consequences of ocean acidification. Rockström et al. (2009) use the concentration of aragonite as an indicator. Based on the calcium carbonate saturation state Ω, they fixed the limit at 2.75 Ω_{arag}. The current value of Ω is 2.90, meaning that the limit has not yet been exceeded (a higher Ω is better).

This limit with respect to the concentration of aragonite (2.75 Ω_{arag}) in oceans can be related to the increase in atmospheric CO_2 concentration. The tipping point has been identified[10] at 450 ppm (McNeil and Matear, 2008). This choice is compatible with (IPCC, 2013): "surface waters may become seasonally corrosive to aragonite in parts of the Arctic and in some coastal upwelling systems within a decade, and in parts of the Southern Ocean within 1 to 3 decades in most scenarios. Aragonite undersaturation becomes widespread in these regions at atmospheric CO_2 levels of 500 to 600 ppm".

To assess this Planetary Boundary, an indicator of yearly CO_2 emissions has been selected since the link between CO_2 emissions and the atmospheric CO_2 concentration is based on strong scientific evidence. This indicator is thus a Pressure within the DPSIR framework (EEA, 2005). Good data on CO_2 emissions from human activities are available enabling the computation of national footprints.

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[8] The term acidification doesn't mean that the ocean will become acidic (pH < 7), but that the pH trend is toward lower pH values.

[9] The pH is a logarithmic scale: 1 unit corresponds to a tenfold change in hydrogen ion concentration.

[10] Literature review and personal contact with an expert in ocean acidification (Doney, 2014).

Setting limits

The global limit is computed first and then downscaled to compute the Swiss limit. The global limit per capita represents an equal share perspective. The global limit account for future emissions while the Swiss limit accounts for future emissions and for part of the historical emissions. Limits are expressed in terms of average yearly values corresponding to a theoretically acceptable rate of exhaustion of the budget of the remaining CO_2 emissions. Exhaustion is assumed in 2100.

Global limit

CO_2 emissions accumulate within the atmosphere, having a long-term residence. Since the reference with respect to the concentration of aragonite (2.75 Ω_{arag}) in oceans can be related to the equivalent atmospheric concentration of CO_2 (450 CO_2 ppm), the limit is based on the cumulative CO_2 emissions until the maximum concentration corresponding to a “Safe Operating Space” is achieved. A concentration just below the 450 ppm, at 445 CO_2 ppm has been selected.

The remaining emissions can be considered as a budget over time. The computed budget, expressed in $GtCO_2$, includes CO_2 emissions from fossil fuel, cement production and land cover changes (forest fires, peat fires and decay of drained peatlands).

Between 1990 (353.6 ppm) and 2010 (388.4 ppm), the concentration of CO_2 increased by 34.8 ppm (Stocker et al., 2013, p. 1401-1402). During the same period an amount of 644.1 $GtCO_2$ (EDGAR, 2011) was emitted. Hence, on average 18.5 $GtCO_2$ (5 GtC) emitted leads to one additional atmospheric CO_2 ppm.[11] Using the 18.5 $GtCO_2$ factor, the budget corresponding to the maximum possible emissions to reach the reference of 445 CO_2 ppm is computed as in Equation 4.

$$E_1 = (ppm_l - ppm_c) \cdot C \qquad \text{Equation 4}$$ [PP2]

Where,

[11] The theoretical conversions of 1 ppm atmospheric CO_2 is 2.12 GtC atmospheric (Hansen et al., 2013) or 2.13 GtC (CDIAC, 2012). Knowing that 43% (± 2%) of CO_2 remains in the atmosphere, these theoretical values confirm this figure (2.13/0.43 = 4.95 GtC emissions per ppm).

E_l = Maximum emissions of CO_2 to reach the limit

ppm_l = Selected limit of atmospheric CO_2 (here 445 ppm)

ppm_c = Current CO_2 atmospheric concentration (401 ppm)

C = Quantity of CO_2 emissions leading to an additional CO_2 ppm

The current concentration is 401 ppm (NOAA, 2014), this is 44 ppm below the reference of 445 ppm. For the selected indicator, *the remaining cumulative emissions of carbon dioxide (CO_2) from human activities to maintain an acceptable calcium carbonate saturation state* Ω*,* the world remaining emissions are 814 $GtCO_2$ in 2014. On average, this results in 9.6 $GtCO_2$ global yearly emissions until the exhaustion of the budget in 2100, i.e. in 85 years.

Computing an *equal share per capita* requires considering current and future populations of Earth. Dividing the budget over time by the sum of all yearly inhabitants until 2100[12] results in a global yearly limit per capita[13] of 1 tCO_2. The global per capita value is fixed over time but the yearly global limit varies according to the yearly global population. The resulting limit for the world is 7.6 $GtCO_2$ for 2015. This is smaller than the average yearly value since the world population will be larger in the future.

Comparison with earlier studies

In the first application to compute national limits, Nykvist et al. (2013) do not consider Ocean Acidification as a specific Planetary Boundary.

Limit for Switzerland

Switzerland, like all developed economies, has already emitted a large amount of CO_2 emissions. To account for part of the historical contributions, the limit for Switzerland is set by downscaling the global limit with the hybrid-allocation approach described in the main part of the article: the Swiss share of the global CO_2 emissions over time is defined relatively to the Swiss share of the global

[12] The sum of inhabitants over the years is computed using United Nations Population Division (UNPD, 2013) estimation of the world population until 2050, then assuming a stable population until 2100. The computation is 7.32 billion in 2015 + 7.40 in 2016 +… + 9.55 in 2050 + … 9.55 in 2100 = 784.8 billion people-year.

[13] Reminder: Unlike the limit on Climate Change, this limit is set on CO_2 only (other greenhouse gases are not relevant).

population at a past reference date. The Swiss share is fixed over time. For Ocean Acidification, this reference date is 2005 since it is the turning point in term of awareness.[14]

As shown in Equation 5, the budget over time (maximum future emissions) of Switzerland is computed by:

- Computing the global CO_2 budget over time in 2005 by adding global past emissions to the budget over time computed for 2014.
- Getting the Swiss share of this budget using the share of the Swiss population as compared to the world population in 2005.
- Deducting the past Swiss emissions from a footprint perspective to get the current Swiss budget over time.

$$FE_{CH} = CHP_{2005} / WP_{2005} (FE_W + PE_W) - PE_{CH} \qquad \text{Equation 5}$$

Where,

FE_{CH}	Maximum future emissions for Switzerland (from 2015 onward)
CHP_{2005}	Swiss population in 2005
WP_{2005}	World population in 2005
FE_W	Maximum future emissions for the World (from 2015 onward)
PE_W	World past emissions (2005 to 2014)
PE_{CH}	Past emissions from Swiss consumption (2005 to 2014)

The computed budget of GHG emissions for Switzerland in 2005 is 1.45 $GtCO_2$. Having already emitted 0.96 $GtCO_2$ from 2006 to 2014, as extrapolated from Jungbluth et al. (2011) (for period 1990-1995) and Frischknecht et al. (2013), equivalent to 66% of its budget, the remaining budget in 2014 is 489 MtCO2. On average, this results in 5.7 $MtCO_2$ yearly emissions until the exhaustion of the budget in 2100, i.e. in 85 years. This means that Switzerland becomes carbon neutral after this date.

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

The Swiss per capita limit is computed by considering the current and future population of Switzerland. The Swiss budget is divided by the sum of all the yearly inhabitants of Switzerland until 2100[15] resulting in a Swiss per capita yearly limit of 0.5 tCO_2. The Swiss per capita value is fixed over time but the yearly Swiss limit varies according to the yearly Swiss population. The resulting limit for Switzerland is 4.5 $MtCO_2$ for 2015. The value is smaller than the average since the Swiss population will be larger in the future.

3.2.3. Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are presented in Table 4. Other sources of data on CO_2 emissions could have been taken for an increased precision. The choice was to take EDGAR world emissions for all greenhouse gases (EDGAR, 2011) and using a correcting factor of 76% – as used in Nykvist et al. (2013) – in order to take into account all the CO_2 emissions and to be comparable with the computation for the Climate Change Planetary Boundary.

Data	Data sources	Units
CO_2 ppm concentration to aragonite saturation	CDIAC 2012, McNeil and Matear 2008	CO_2 ppm
Limit of future emissions (global)	IPCC ARS 2013, Hansen et al. 2013	C
National (territorial and footprint) emissions from 1990 to current	For 1990-1995: Jungbluth et al. 2011, for 1996-2011: Frischknecht et al. 2013	CO_2
World emissions of all GHG from 1990 to current	EDGAR 2011	CO_2
National population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants
World population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants

Table 4. Ocean Acidification: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 5. The overall quality of the assessment can be considered as high.

[15] The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2013) estimation of the Swiss population until 2050, then assuming a stable population until 2100. The sum = 896 million people-year.

Quality assessment		
PB relevance	++	
Focus on the overall picture	++	
Reliability (data, models)	+	
Transparency	++	
Communication	+ / -	The limit is different from the one defined by (Rockstöm et al 2009).
Coherence / comparability	+	
Availability of information	++	
Timely	++	

Legend **++** : High **+** : Acceptable **+/-** : Potentially problematic **-** : Problematic

Table 5. Ocean Acidification: quality assessment.

1.1.1.1. Computing footprints

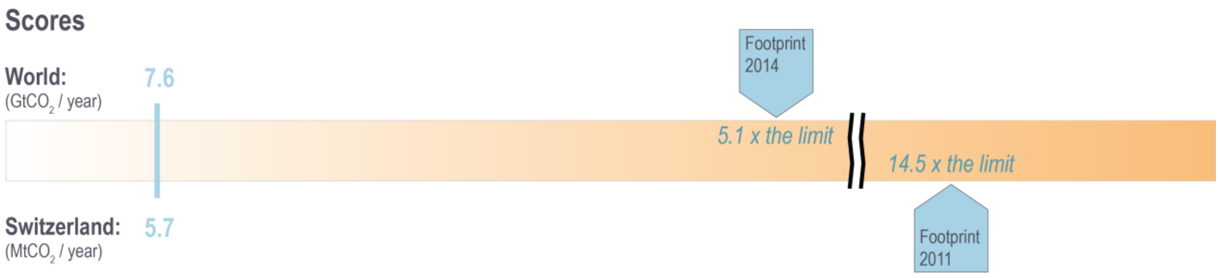
The general description of the computation of the footprints is presented in the main part of the article. The specificities for Ocean Acidification are presented here.

The global footprint is based on the EDGAR database (2011). Data is extrapolated for 2011 based on the average growth rate for 2006-2010. The Swiss footprint is based on the FOEN proprietary database. Footprints are computed for the years 1996-2011.

1.1.2. Current performance

The Planetary Boundary Ocean Acidification is largely overshoot globally and from a Swiss perspective and the evolution is rapid. Confidence in the results is high. The global and Swiss performances are thus qualified as Clearly Unsafe.

Results are presented for 2015 limits and for 2011 footprints in Figure 3. The global yearly limits represent the equal share perspective. They consider current and future populations. The limits for Switzerland consider, in addition, past Swiss emissions.



	World	Switzerland
Confidence in score	High	High
Trend	Rapidly deteriorating	Rapidly deteriorating
Performance	Clearly Unsafe	Clearly Unsafe

Figure 3. Ocean Acidification: global and Swiss performances.

At global scale, the global limit is at 7.6 GtCO_2 for 2015 due to a per capita limit set at 1 tCO_2. With a current global footprint estimated to be 38.6 GtCO_2 for 2011, and a per capita footprint at 5.5 tCO_2, the limit is <u>globally exceeded by a factor 5.5 for 2011</u>. The situation is clearly an overshoot. This is also the case when comparing the footprint with the average yearly limit value (9.6 GtCO_2) until 2100.

For Switzerland, the pattern is similar and the Swiss footprint is largely over its long-term acceptable average. The Swiss limit is at 5.7 MtCO_2 for 2015 due to a per capita limit set at 0.5 tCO_2. With current footprint emissions estimated to be 82.8 MtCO_2 for 2011 for Switzerland, and a per capita footprint at 10.1 tCO_2 (Frischknecht et al. 2014), this limit is <u>exceeded for Switzerland by a factor 14.5 for 2011</u>. If the past would not be considered, i.e. in an equal share perspective, the limit would still be exceeded by a factor 10 for 2011.

Since the limits are based on a 2015-2100 budget, several options are possible to spend this budget. The Swiss budget of CO_2 emissions corresponds to:

- *6 years of emissions* (until end 2020) at the current Swiss yearly emissions rate.
- *More than 8 years* with an ongoing yearly reduction of 10%. This would result in cumulative long-term emissions at 745 rather than 489 MtCO_2.

- *Sustainable* with an ongoing yearly reduction of 15%. This would result in cumulative long-term emissions at 470 rather than 489 $MtCO_2$.

1.1.3. Discussion: Ocean Acidification

Based on scientific evidence, it was possible to relate the reference value for Ocean Acidification (445 ppm) with CO_2 emissions, enabling the link with the global and Swiss footprints. Using a budget over time approach, yearly limits have been computed for the remaining emissions. These yearly limits are very largely overshoot at global and at Swiss level showing the far from acceptable yearly rate of use of the budget.

Considering the global budget and a yearly rate of global emissions similar to the current rate, the global budget corresponding to the 445 ppm would be exhausted in 20 years, by 2035, i.e. 15 years after the exhaustion of the Swiss share of the budget. Being a landlocked country, Switzerland will not be affected directly by ocean acidification. However, indirectly there will be economic impacts on industries related to fisheries and tourism.

The reference date happens to be critical to compute the country limit. If the reference date had been set in 1990, the Swiss budget 2015-2100 would have been almost divided by two (162 instead of 489 $MtCO_2$), as would have been the Swiss yearly limits. The overshoot would thus be doubled. The choice of the reference date does not however modify the conclusions due to the very large Swiss overshoot.

The situation is thus very comparable to Climate Change, however this is because the 2° target was selected for Climate Change rather than the initial 350 ppm limit as defined by (Johan Rockström et al., 2009).

Respecting the limit to stay in a Safe Operating Space will thus require tremendous effort. Since CO_2 emissions are the main gas of greenhouse gases emissions in CO_2eq (around 76%). The reader can refer to the discussion on Climate Change for further information on historical values.

3.3. Nitrogen and Phosphorus Losses

Nitrogen and phosphorus are two essential nutrients for plants and all other living organisms. Their bioavailability in the environment has largely increased in the past century: the bioavailability of nitrogen (N) has doubled and the bioavailability of phosphorus (P) has tripled (Howarth and Ramakrishna 2005). Agriculture, wastewater and sewage as well as fossil fuel combustion are the most common anthropogenic source of P and N delivery to freshwater systems (Liu et al 2011). As a result, eutrophication has become a serious threat to freshwater quality. The same can be said for water quality in coastal areas (Selman et al. 2008).

Nitrogen

Over the past century the conversion, i.e. the fixation, of atmospheric biologically unavailable nitrogen (N_2) into reactive compounds[16] (Nr) by humans has caused unprecedented changes to the global nitrogen cycle. Reactive forms of nitrogen are those capable of cascading through the environment and causing an impact through global warming, the formation of tropospheric ozone as well as eutrophication and acidification of ecosystems leading to biodiversity loss. The total yearly fixation of N has more than doubled globally and more than tripled in Europe during this period. N is a key input for the agriculture and N fertilisers are one of the key aspects for global food security, allowing nourishing around half of the world population. They are also a key component of self-sufficiency in cereals in the EU (Sutton 2011). Fertilisers represented 75% of the EU industrial production of N in 2008. Fertilisers represent 63% of the N_2 global conversion (natural or industrial) in 2005. The second important source of N fixation is the current industrial and transport system (13% of worldwide N fixation in 2005) that releases large quantities of NO_x emissions due to the combustion of fuels (Sutton 2011).[17]

The situation is however unevenly distributed around the globe. Europe can be considered as an area with excess nitrogen. Some parts of the USA, China, India and Latin America are in a similar situation while some developing regions like Africa are clearly lacking nitrogen for food production (Sutton 2011). The consequences of nitrogen losses to the environment are thus more visible in Europe and are, on average, larger in this region than in the rest of the world. While the annual nitrogen inputs have been decreasing in Europe since a peak in 1980, nitrogen loss is still

[16] Reactive nitrogen compounds include nitrous oxide (N_2O), nitric oxides (NO_x), nitrate (NO_3^-), ammonia (NH_3), and ammonium (NH_4^+).

[17] The remaining 24% are natural biological fixation.

considered a threat to European water, air and soil quality as well as a threat to the EU greenhouse gas balance, terrestrial ecosystems and biodiversity (Sutton 2011).

Phosphorus

Phosphorus (P) is an essential element for all life, and also one of the key limiting factors for agricultural production. Its inorganic form as rock phosphate, which is the ingredient for all chemical P-based fertilisers, is a non-renewable resource. The finite supply of P is a key concern because there are no substitutes (Cordell et al., 2009). The overuse of P resources is thus both a threat to food security and to downstream ecosystems: excessive P losses to aquatic ecosystems through runoff and erosion have caused the eutrophication of many lakes and coastal systems. Sources of P losses in the environment come from fertilisers, detergents additives, animal feed supplements and other industrial uses. P in rivers and lakes stems almost entirely from P fertiliser, manure and untreated sewage (Bouwman et al., 2013; Carpenter and Bennett, 2011; Cordell et al., 2009; Seitzinger et al., 2010). The situation varies according to regions (Potter et al., 2010).

1.1.4. Description

The Nitrogen and Phosphorus Losses Planetary Boundaries are discussed jointly. A specific indicator is proposed for each of them but N and P nutrients are considered jointly for setting the global limits, hence for the assessment of the global performance.

The objective of the Nitrogen Losses Planetary Boundary is to reduce the impacts of reactive nitrogen losses to the environment leading to eutrophication and acidification of terrestrial and coastal ecosystems causing loss of biodiversity, climate change and formation of high ozone concentrations in the lower atmosphere. The Phosphorus Losses Planetary Boundary is defined more narrowly by Rockström et al. (2009). The objective is to avoid a major oceanic anoxic event (including regional), with impacts on marine ecosystems. Phosphorus (P) inflow to the oceans has been suggested as the key driver behind global-scale ocean anoxic events, potentially explaining past mass extinctions of marine life (Handoh and Lenton 2003). “It is uncertain what qualitative changes and regional state changes such a sustained inflow would trigger, however, current evidence suggests that it would induce major state changes at local and regional levels, including widespread anoxia in some coastal and shelf seas.” (Rockström et al. 2009).

Nitrogen and phosphorus are usually considered regional rather than global issues since effects occur at a local or regional scale. A global perspective could however be adopted if nitrogen and phosphorus losses to the environment affect the earth system. Due to the spatial variability of the impacts, the existence of a global threshold is however difficult to prove with certainty (Rockström et al. 2009). Nordhaus (2012) and Lewis (2012), cited in de Vries (2013), criticise the notion of a global limit for nitrogen.

The Nitrogen Losses Planetary Boundary is thus conceptually conceived as an aggregation of regional thresholds. The global limit for Nitrogen is set with an indicator expressed in terms of *agricultural N losses from N-fertilisers and manure*. The same type of reasoning is applied to the Phosphorus Losses Planetary Boundary: the limit is conceived as a sum of aggregated regional thresholds. The global limit for Phosphorus Losses is set with an indicator expressed in terms of *the consumption of P-fertilisers.*

1.1.5. Methodology

Selection of the indicators

Nitrogen

In the European Nitrogen Assessment (ENA), Sutton et al. (2011) develop the first integrated nitrogen budget for Europe. The situation is described for Switzerland in (Heldstab et al., 2010; Heldstab, J. et al., 2013). This budget provides a synthetic perspective of how nitrogen diffuses into environmental media in a cascading-like effect, leading to several recognised environmental impacts. The lack of recognition of this nitrogen cascade in current environmental policies, established in a fragmented way (air, water, soil compartments), is a key reason of their inability to achieve objectives yet (Sutton et al., 2011). Due to the cascade, a comprehensive assessment at the level of the State, e.g. concentrations, as defined in the DPSIR framework (EEA, 2005) is also very difficult to implement, while such an indicator would be the preferred level of measurement for a Planetary Boundary. An indirect indicator has thus to be defined, at the level of Driving-Forces or Pressures.

The original definition by Rockström et al. (2009) focuses on the N fixation by human activities (industry and agriculture). Nykvist et al. (2013) propose an indicator that depicts a Driving Force (N fertilisers use). This indicator is the simplest to compute since data is available but the impacts of reactive nitrogen are not linearly related to N_2 fixation or to the use of N. This indicator is thus a poor proxy for damages. The level of Pressure, i.e. the N losses to the environment, is an intermediary position between damages and N_2 fixation or N use. This is the preferred level of assessment in this study.

An aggregated value for N losses should ideally be computed with a bottom-up approach to consider the spatial variations in the quantity of applied active nitrogen, in the vulnerability of receptors, and the cascading effect. This means having knowledge on regional conditions for the whole globe or, in the context of this study, on all regions involved in the production of goods imported in Switzerland.

Knowing that data on imports for computing footprints is only available on a country basis[18], a detailed regional knowledge on losses is however not directly exploitable to generate a detailed country footprint. More aggregated values, e.g. the current global average or averages for large areas or countries, can be used as proxy as it is usual in Life Cycle Assessment.

Phosphorus

The fate of phosphorus into the environment also extends into multiple environmental compartments. The fate of P in the environment differs from the fate of N because part of the P surplus in soils accumulates in soil, where it can be used by crops years later or result in later environmental loss through runoff. According to Bouwman et al. (2013), the global N surplus in soils almost doubled between 1900 and 1950. During this period, the global P surplus increased

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[18] This situation will perpetuate for figures at meso and macro levels since modeling global supply chains at a detailed regional level is barely feasible since (a) it requires an enormous amount of work, (b) it should be updated very regularly to reflect constantly evolving supply chains. The situation is different for specific products that can be modeled with details.

eight times. Aggregated values should thus, similarly as in the N case, ideally be computed with knowledge on regional conditions for the whole globe.

Since the limitations for import data (availability at country level only) to compute the P footprint of countries also applies similarly to N, a detailed country footprint would be however difficult to compute and some proxy has to be identified.

Selected indicators

For the Nitrogen Losses Planetary Boundary, the preference[19] has been given to an indicator in terms of agricultural N losses into the environment considering losses into soil, water (NO_3^-) and air (partially, i.e. NH_3 but not NO_x). This indicator covers *agricultural N losses from N-fertilisers and manure* but does not include further losses resulting from crop residues. Neither industrial emissions nor emissions from combustion are considered.

The selected indicator for the Phosphorus Losses Planetary Boundary is the *use of P-fertilisers*. This indicator is computed back from the ratio of P-fertilisers to P entering into the oceans based on the global values from the NEWS model (Seitzinger et al., 2010). The provided values are a rough approximation but they allow computing the data with existing sources, e.g. FAO fertiliser use.

Setting the global limit for nitrogen

The global limits are computed first and then downscaled to compute the Swiss limits. Global and Swiss limits are expressed in terms of yearly budget corresponding to (a) theoretically acceptable nitrogen losses, and (b) theoretically acceptable uses of P-fertiliser. The global and Swiss limits are constant over time and the per capita values evolve according to the global/Swiss population size. The global limit per capita represents an equal share perspective.

Global limit for nitrogen: the rationales

Rockström et al. (2009) stipulate that the limit expressed in terms of N fixation was already exceeded, setting the limit at 25% of its current value, i.e. at 35 Tg N yr^{-1}. This limit is clearly

[19] This choice is mainly based on data availability but is supported by conclusion 5 on page 44.

declared a "first guess" and that "given the implications of trying to reach this target, much more research and synthesis of information is required to determine a more informed boundary."

De Vries et al. (2013) suggest a way to go beyond this first guess while being clear that this is only a first trial that should be refined. They focus on the exceedance of local limits (in terms of concentration) for two reactive N compounds: ammonia (NH_3) and N runoff to surface water, considering the whole globe based on a spatially explicit model (IMAGE) used by IPCC for 2000. Averaging the local exceedances, they generate global average ratios of N losses to limit for NH_3 and for N runoff. Then, using these ratios and the N flows, as well as the related "intended[20] N-fixation", for 2000, they backcompute the global limits in terms of N losses and in terms of apparent intended N fixation. They also compute a global limit for nitrous oxide (N_2O) with another approach based on Radiative Forcing.

The local limits identified by de Vries et al. (2013) are:[21]

- Atmospheric NH_3 concentrations in view of adverse biodiversity effects[22] (1-3 mg per m^3).
- Dissolved inorganic N concentrations (1-2.5 mg per liter) related to eutrophication or acidification.
- Radiative Forcing[23] (1-2.6 W per m^2).

The related computed losses and N fixations are presented in Table 6.

	Losses (in Tg N y^{-1})	**N fixation (in Tg N y^{-1})**
NH_3	24.9 - 32.1	89 - 115
N runoff to surface water	0.8 - 5.3	62 - 82
N_2O	5.4 - 7.2	20 - 133

Table 6. Limit values (in Tg N y^{-1}) in terms of N losses and N-fixation computed by de Vries et al. (2013).

[20] The "intended N-fixation" considered includes fertiliser use and N fixation by crops. It left out unintended fixation by combustion processes: NO_x emissions from fossil fuels in the industry and for transportation.

[21] Two values are proposed per limit : a lower and an upper-bound.

[22] De Vries is omitting the critical loads for N deposition which lead to more stringent targets than NH3 concentration limit values in Switzerland (Heldstab, J. et al., 2013).

[23] With respect to the contribution of N to global warming, for Europe there is an estimated overall cooling effect (Sutton et al., 2011).

Referring to Dentener et al. (Dentener et al., 2006), they assess that for the year 2000, the losses for NH_3 (34 Tg N y^{-1}) and N to surface water (10.7 Tg N y^{-1}) are globally exceeding the limits. By comparing the limits with values from Bouwman et al. (2013) for N fixation (121.5 Tg) in 2000, they arrive at the same conclusion. By comparing these values with the level of N fixation needed in view of food security based on current N use efficiencies (80 Tg N y^{-1}), they conclude that the limit set by Rockström et al. (2009) at 35 Tg N y^{-1} is below the quantity needed to feed the global population.[24]

Based on their results, they conclude that a limit in the 60 - 100 Tg N y^{-1} seems appropriate for N-fixation (with the exception of the lower-bound for N_2O).

The global N budget

Looking at the global N budget allows getting a better understanding of the limits proposed by Rockström et al. (2009) and de Vries et al. (2011).

Bouwman et al. (2013) propose a global agricultural N budget from 1900 to 2050 with future scenarios based on IAASTD[25] projections. NH_3 volatilisation is estimated at 24 Tg N y^{-1} in 2000, close to the lower-bound for N losses for NH_3. N_2O emissions are estimated at 7 Tg N y^{-1} for the same year, close to the proposed upper-bound for N losses. N leaching and runoff is estimated at 57 Tg N y^{-1}, much larger than the boundary for NO_3. Liu et al. (2011) confirm the situation for N in water flows. They compute the water pollution level for past and future trends of N and P inputs into major rivers around the world. Using the global NEWS model (Seitzinger et al., 2010) to compute grey water footprints (Hoekstra et al. 2011), they show that:

- In 2000, the pollution assimilation capacity of two thirds of the basins has been exceeded.
- This situation is quite stable since 1970 (global increase of 0.5%) but with regional differences. Scenarios for 2050 based on (Alcamo et al. 2006) show a limited potential increase of excess between 5 and 9%.

[24] With a possible 25% improvement in N use efficiency, this quantity would reduce to 50 Tg N y^{-1}.

[25] The International Assessment of Agricultural Knowledge, Science and Technology for Development was an intergovernmental process running from 2005 to 2007 under the co-sponsorship of the FAO, GEF, UNDP, UNEP, UNESCO, the World Bank and WHO.

The global projections from Bouwman et al. (2013) show that the global N situation from agriculture will evolve in a much closer range over the next 50 years than between 1950 and 2000 (the increase was 380%): N fertiliser inputs will increase by around 31%, the total N inputs will increase by around 40%, and the total N budget will increase by around 23% (meaning that total N withdrawal will increase faster than additional N inputs). These projections contrast with past global N creation computed by Galloway et al. (2008), showing a continuous acceleration in the period going from 1995 to 2005 from 156 Tg to 187 Tg (among which a production with the Haber-Bosch process going from 100 to 121 Tg). Over this period NO_x emissions were however already stable at around 25 Tg per year. These projections also contrast with the fast increase in N fertiliser use shown by FAO data, going from 89 Tg in 2002 to 122 Tg in 2012.

Based on Bouwman et al. (2013) and Liu et al. (2011), we can conclude that:

1. For losses, the limit proposed by de Vries et al. (2011) is almost reached or exceeded for NH_3 and N_2O and exceeded for N in water flows.
2. The future N budget for agriculture and losses to the environment will evolve in a much closer range (20-40%) during the coming 50 years than during the same period in the past. This range is very probably within the range of uncertainty of the proposed limit values by de Vries et al. (2011).

Taking a larger perspective, Fowler et al. (2013) show that half (210 Tg N) of the yearly global N contribution (413 Tg) to terrestrial and marine ecosystems is from anthropogenic origin.[26] The fixation of nitrogen through Haber-Bosch amounts to 120 Tg in 2010, among which 80% is used as fertilisers and 20% is used in the chemical industry. Fixation by crops amounts to around 60 Tg while 40 Tg are emitted by the industry as NO_x. Emissions to the air amount to 100 Tg, with 40 Tg in the form of NO_x and 60 Tg in the form of NH_3. Run-off and leaching ending into coastal areas and the open ocean are in the 40-70 Tg range (NO_3^-), and an additional 30 Tg is entering the oceans through atmospheric deposition.

According to IPCC scenarios discussed in Fowler et al. (2013), global NO_x emissions are projected to stay constant at 40 Tg until 2040 and then reduce to 30 Tg. Reduced nitrogen (NH_3) emissions

[26] The detailed numbers sum to to 120 Tg (and not to 110 Tg) similarly to the publication by Fowler et al. (2013).

will increase from 60 to 70-80 Tg by 2100, i.e. a 15 to 30% increase. Due to temperature increase, such values could however be close to 130 NH_3 Tg (Sutton et al., 2011).

Based on Fowler at al. (2013), we can conclude that:

3. The current global situation is (a) a doubling of the global cycling of nitrogen, (b) a doubling of the marine biological fixation (140 Tg), (c) an industrial fixation which is the double of the natural terrestrial sources of N (63 Tg).
4. The global footprint comparable with the proposal of the global limit proposed by de Vries et al. (2011) is equal to 154 Tg (use of fertilisers, i.e. 80% of the N_2 fixed with the Haber-Bosch process (96 Tg) and the N fixation by crops[27] (60 Tg)). Similarly than for the data from Bouwman et al (2013), this amount is larger than the upper-bound of the 60-100 Tg proposal.
5. The unintended N_2 anthropogenic fixation not considered by de Vries et al. (2011) amounts to 29 % of anthropogenic fixation. This value is considered almost constant over time in the literature:
   - N fixation in the chemical industry: 24 Tg.
   - NO_x emissions: 40 Tg, expected to stay constant until 2040 and then reduced by 25%.

Global processing of N by the Earth system

Looking at the global processing of N by the earth system is a second way to get a better understanding of the limits proposed by Rockström et al. (2009) and de Vries et al. (2011).

According to Fowler et al. (2013), knowledge about processing of N by the earth system is much lower than for the N budget and many uncertainties remain. They provide however some estimates with respect to the terrestrial processing of N (240 Tg), the processing by oceans (230 Tg) and the atmospheric processing (100 Tg). We sum this processing capacity to 570 Tg with an uncertainty of 25%, i.e. a range going from 428 to 712 Tg. [28]

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[27] Fixation by crops is a value with high uncertainty (Bouwman et al., 2013).

[28] In their article, Fowler et al. (2013) do not sum these capacities and do not make any comparison with the values they propose for the yearly global N contribution from anthropogenic origin to terrestrial and marine ecosystems.

Based on Fowler at al. (2013), we can conclude that:

6. Based on a very rough estimate of the processing capacity of the earth system, the current yearly global N contribution from anthropogenic origin (413 Tg) to terrestrial and marine ecosystems is close to the lower bound of the computed processing capacity.

Computing the global limit for nitrogen

In the light of the preceding six conclusions, and since there is no evidence that a global limit exist for N and that it has been reached, we propose a new value for the global limit.

This proposal is based on (a) the rationales for the computation of N losses proposed by de Vries et al. (2013), and (b) the fact that the upper-bound of their proposal in terms of N fixation seems the most representative of the current global situation. The proposed limit is thus based on a bottom-up approach and is compatible with the fact that important regional issues due to N losses are occurring all over the world, with regional limits overshoots in many places.

De Vries et al. (2013) apply the global average computed from regional data to set the relationship between N losses and N fixation. It is thus an apparent relationship. We keep this approach because it avoids computing N fixation from N losses for each region. Since there is no linear relationship between N losses and N fixation (N losses depend on nitrogen use efficiency and application of best available techniques for emission reduction), this is a clear advantage. Their focus on agriculture is also of interest because it reduces the amount of data needed and seems acceptable: the unintended N_2 anthropogenic fixation (i.e. industrial N fixation and combustion processes) amounts to 29% of anthropogenic fixation and is considered almost constant over time. The N from wastewater is also absent from this approach. It is estimated by Drecht et al. (2009) to be around 6.4 Tg.

In this study, a preference is given to computing a limit in terms of N losses rather than focusing on intended fixation (N fertilisers and N fixation by crops) as in de Vries et al. (2013). The relationship between inputs and losses is shown in Equations 1 to 3 for a simplified soil budget similar to Bouwman et al. (2013). The model is a simplified one that does not consider, for example, N from crop residues (which amount for 33% of N fixation by crops at EU scale (Sutton et al., 2011).

A simplified N budget for soils:

$$N_{inputs} = N_{fertilisers} + N_{manure} + N_{fixation\ by\ crops} + N_{deposition} \quad \text{Equation 6}$$

$$N_{losses} = NH_{3\ volatilisation} + NO_2 + NO + N_{leaching\ and\ run\text{-}off} \quad \text{Equation 7}$$

$$N_{budget} = N_{inputs} - N_{withdrawal} = N_{losses} + N_{denitrification} \quad \text{Equation 8}$$

Where,

$NH_{3\ volatilisation}$	Volatilisation of NH_3 from fertilisers and manure applications
$N_{withdrawal}$	Withdrawal through harvest of crops

We also differ from de Vries et al. (2013) in the type of N losses considered. To consider the importance of manure, not considered explicitly[29] by de Vries et al. (2013), but nevertheless a key[30] input of N for the agriculture, we compute N use in terms of application, i.e. N-fertilisers and N-manure, rather than in terms of N fixation, i.e. N-fertilisers and N fixation by crops. This approach enables also increasing the compatibility with LCA databases and global data from FAO.

We compute the value for the N application[31] using the same dataset as by Vries et al. (2013) to compute N fixation. According to Bouwman et al. (2013) 175 Tg[32] of N-fertilisers and N-manure have been applied in 2000. To compute N losses from the global application, volatilisation to NH_3 and N losses to soil have to be considered separately for N-fertilisers and N-manure. The applications values, conversion factors and resulting losses in 2000 (56.6 Tg) are presented in Table 7. The conversion factors to NH_3 are from Bouwman et al. (2002), used in Bouwman et al. (2013) as well as in the official European recommendation (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) for computing N

[29] Manure is not considered since it is not a source of N fixation. N contained in manure comes from animal feeds and is thus implicitly considered in fixation by crop (as are N losses from crop wastes).

[30] Around 20% larger than N-fertiliser in 2000 according to Bouwman et al. (2013).

[31] To compute the global limit for other years than 2000, there is a need to compute first a value in terms of N use and then to compute the resulting losses.

[32] Tg stands for Teragram, i.e. 10^{12} grams. It is equivalent to 1 Megaton.

eutrophication in Life Cycle Impact Assessment using the RECIPE methodology (Goedkoop et al., 2009). The conversion from inputs to leaching is based on a value selected between the value computed from Bouwman et al. (2013) (25%) and the net/gross conversion values for Europe as proposed in RECIPE (11.7% for N-fertilisers and 7% for manure). This value corresponds to leaching from loam in arable and natural land proposed by RECIPE for the rest of the world based on values from (Potting and Hauschild, 2005).

	Application	Conversion factors to NH_3 losses	Conversion factors to run-off
N-fertilisers	83 Tg	7% = 5.8 Tg	18% = 14.9 Tg
N-manure	92 Tg	21% = 19.3 Tg	18% = 16.6 Tg

Table 7. Global applications of N-fertilisers and N-manure (Bouwman et al. 2013), conversion factors to inputs and losses for the year 2000.

Knowing the global N losses from agriculture for 2000 from the preceding computation, we can compute the global limit, in terms of agricultural N losses, by multiplying the losses with a modified global average ratio[33] of losses to limits computed by de Vries et al. (2013). The global limit for agricultural N losses equal to 47.6 Tg.

Setting the global limit for Phosphorus [PP3]

Global limit for phosphorus: ocean anoxic conditions

Rockström et al. (2009) suggest a boundary based on oceanic conditions. They propose the limit to be ten times the pre-industrial flows to the oceans, i.e. 11 Tg P y^{-1}.

The evaluation of the P flows in the literature, all based on models, vary by a factor of three. Bouwman et al. (2013) propose a P budget for agriculture for the period 1900 to 2050. Future

[33] de Vries et al. (2013) propose two values (up and lower bound) to compute the local limits: the modified ratio applied in this study (0.84) is the mid value between the ratio for the lower (0.73) and upper-bound (0.95) for NH_3. This is compatible with the conclusion on page 45 that the upper-bound leads to a value which is too high compared to the apparently appropriate limit for N fixation (60 - 100 Tg N y^{-1}).

scenarios are based on IAASTD[34] projections. They compute that 3 Tg of P fertilisers were used globally in 1950, increasing to 14 Tg in 2000. Projections show an additional increase up to 18-24 Tg for 2050, i.e. a 29-71% increase. The main increase in inputs is coming from manure, going from 17 Tg in 2000 to a range between 25 Tg and 29 Tg in 2050. Considering withdrawals, the projected global increase of the P budget is around 50% over the same period of time. The resulting P runoff is also projected to grow by 50% from 2000 to 2050. This runoff increase contrasts strongly with the increase during the 1950-2000 period, an estimated four times growth (4 Tg in 2000).

Adding urban wastewater to consider P in detergents allows for building a more complete picture. 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 P run-off from agriculture are thus 10 times larger than P from urban wastewater.

Seitzinger et al. (2010) compute a value of 7.6 Tg of P transported by rivers to the ocean for 2000. This is much lower than earlier estimates close to 20 Tg of P. Carpenter and Bennett (2011) estimate that current (around year 2000) flows to the oceans are three times pre-industrial flows (22 Tg vs 8 Tg P y^{-1}) to which a sedimentation of around 20% should be retired to get the value entering the oceans. Current flows are higher because the P stored in soils subject to leaching and runoff has increased due to the inputs of P from mining (18.5 Tg P) and a natural weathering of rocks (10 to 15 Tg) now complemented by human induced weathering (resulting in around 15-20 Tg per year).

The lesson we can get from these values is that the current flows are either larger than the limit proposed by Rockström et al. (2009) by a factor of two or close to the limit. Due to the fact that regional anoxic events are regularly observed but that this is not the case for an anoxic event at global scale, we can conclude that the current real global flows are below the real global limit.

[34] The International Assessment of Agricultural Knowledge, Science and Technology for Development was an intergovernmental process running from 2005 to 2007 under the co-sponsorship of the FAO, GEF, UNDP, UNEP, UNESCO, the World Bank and WHO.

Since the limit proposed by Rockström et al. (2009) is the only limit identified in the literature and since the newest studies tend to propose values for global flows lower than this limit, keeping the limit proposed by Rockström et al. (2009) is compatible with what is observed. The limit proposed by Rockström et al. (2009) is thus taken as a reference in this study.

The linkage between P fertiliser use and P entering the ocean is largely dependent on regional conditions (land cover, type of soils and water flows). Computing a global ratio of P fertiliser use to P runoff is thus a very rough approximation. It is however representative for the average conditions on earth and can be taken as the best approximation with the information available to date.

Using the global values from Bouwman et al. (2011), we compute the apparent[35] ratio of global P fertiliser to global P runoff for 2000 and 2050 for the different scenarios. Computed values are in the 3.5-3.83 range. Taking the lower bound, we set a limit in terms of fertiliser use by multiplying the limit proposed by Rockström et al. (2009) by 3.5. The global yearly limit value for fertiliser consumption applied in this study is thus 38.5 Tg P per year.

Limit for Switzerland (N and P)

The limit for Switzerland is set by downscaling the global limit with the hybrid-allocation approach described in chapter 5 in order to consider the past: the Swiss shares of the yearly global N losses and of the yearly global P fertiliser use are defined relatively to the Swiss share of the global population at a past reference date. For Nitrogen and Phosphorus Losses, this reference date is 2011, resulting in a Swiss share of 0.113%. The year 2011 has been selected because it is the latest year with available data for Switzerland and there is no evidence that knowledge of the issue was important in the past. The Swiss limits are fixed over time and the per capita limits evolve according to the yearly Swiss population.

For agricultural N losses, the resulting yearly limit for Switzerland is 53.8 kilotons of N losses. The Swiss per capita limit is 6.8 kg of N losses in 2011.

[35] The so-called "apparent ratio" is so called because it is the ratio of one input of the model (P-fertilisers) over one output of the model (P runoff) but the output is also influenced by the other P inputs like manure.

For P fertilisers use, the resulting yearly limit for Switzerland is 43.6 kilotons of P. The Swiss per capita limit is 5.5 kg of P in 2011.

Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are and (Bouwman et al., 2009, 2013) for N and (Bouwman et al., 2009, 2013) as well as (J. Rockström et al., 2009) for P.

The evaluation of the indicators with respect to eight criteria is presented in Table 10 Nitrogen and Phosphorus Losses being assessed with a basic approach based on a reduced set of data from the literature, the overall quality of the assessment can be considered as low.

Quality assessment

PB relevance	+ / -	Not State level
Focus on the overall picture	++	
Reliability (data, models)	+ / -	
Transparency	++	
Communication	+ / -	Two indicators combined in one PB
Coherence / comparability	++	
Availability of information	+ / -	
Timely	+ / -	

Legend : ++ : High **+** : Acceptable **+ / -** : Potentially problematic **-** : Problematic

Table 8. Nitrogen and Phosphorus Losses: quality assessment.

Computing footprints

The general description of the computation of the footprints is presented in chapter 5. The specificities for Nitrogen and Phosphorus Losses are presented here.

The global footprints are based on the same source than for computing the global limits. The Swiss footprint for agricultural N losses is based on the FOEN proprietary database. The conversion factors from Recipe (Goedkoop et al., 2009) are applied[36] to compute values in term of N. Footprints are computed for the years 1996-2011.

[36] The releases (according to the ecoinvent terminology) considered are (a) to air: ammonium, ammonia, nitrate, nitrogen dioxide, nitric oxides, (b) to soil: manure applied and fertiliser applied, and (c) to water: ammonia, nitrogen, ammonium, nitrate, nitrite, nitrogen organic bound and cyanide.

We were unable to compute the Swiss footprint for P based on the FOEN proprietary database at hand. This should however be possible with a more complete version of the database.

3.3.1. Current performance

The global footprint for the Nitrogen Losses Planetary Boundary is above the global limit while the global footprint for the Phosphorus Losses Planetary Boundary is below the global limit. The Swiss footprint for N is largely above the Swiss limit while the situation is unknown for P. Confidence in the results is low for the global and Swiss values. The global and Swiss footprints are evolving slower than in the past. The global performance for N (Unsafe) and P (Safe) combined is qualified as Unsafe while the combined Swiss performance is qualified as Clearly Unsafe.

Results are presented for yearly limits and yearly footprints computed for 2000 (global) and 2011 (Switzerland) in Figure 4. The yearly global limit per capita represents the equal share perspective.

Confidence in score	Low	Low
Trend	Slow evolution	Slow evolution
Performance	**Unsafe**	**Clearly Unsafe**
	World	Switzerland

Figure 4. Nitrogen Losses: global and Swiss performances.

At global scale, the global limit computed in terms of N losses is 47.6 Tg (computed for 2000), corresponding to a limit in term of application of fertilizers and manure equivalent to 147 Tg of N. This limit considers NH_3 losses as well as run-off and leaching from N-fertilisers and N-manure application. The resulting limit per capita, equivalent to the equal share perspective is 7.8 kg in

2000 and 6.9 kg in 2011. With a global footprint estimated to be 55.6 Tg for 2000 and a per capita footprint at 9 kg, the global footprint is 17% above the limit in 2000.

For N losses, the Swiss footprint is largely over its long-term acceptable average. The Swiss limit is at 53.8 kilotons (computed for 2011) and the resulting per capita limit is set at 6.9 kg for 2011. With a current (2011) footprint estimated to be 108.6 kilotons in 2011 for Switzerland, and a per capita footprint at 13.7 kg, the Swiss footprint is about two times above the limit for Switzerland.

At global scale, the global limit computed in terms of P use is 38.5 Tg for 2000. The resulting global limit per capita, equivalent to the equal share perspective is 6.3 kilos in 2000. With a global footprint estimated to be 31 Tg for 2000 and a per capita footprint at 5, the footprint is around 25% below the limit in 2000.

3.3.2. Discussion: Nitrogen and Phosphorus Losses

Setting the global limits for Nitrogen and Phosphorus Losses has been a challenge. However, while results should be improved in future assessments, the proposed results are in line with the existing assessments in the literature.

Figure 5 show the Nitrogen Losses induced by the Swiss consumption, i.e. the domestic inputs from the Swiss production minus the domestic inputs for exports plus the foreign inputs for imports. The computed Swiss footprint for Nitrogen Losses has been growing over the last six years after almost ten years of stability. Its cumulative growth is 10% between 2005 and 2011. On the long run the overall situation is considered as slowly deteriorating. While the domestic part of the footprint has been decreasing (-5.6%) over the last fifteen years, imports (57%) have been growing more rapidly than exports (46%). The largest share of the footprint for Nitrogen is thus occurring outside of Switzerland.

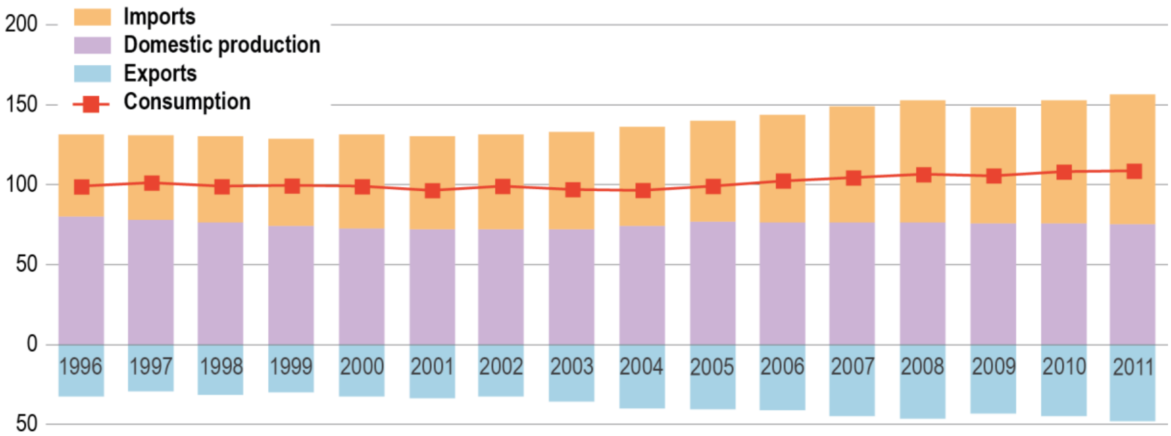

Figure 5. Nitrogen Losses (in kilotons) induced by the Swiss consumption.

The limit for the Phosphorus Losses is much less drastic (by a factor three) than the first guess of Rockström et al. (2009). This is coherent with the fact that our analysis did not allow to confirm a global overshoot of the magnitude (four times the limit as a first guess) proposed by Rockström et al. (2009). Since our proposal is based on limit adapted from de Vries et al. (2013), qualified by the authors as 'a first trial', the same qualification applies to the limit computed here, i.e. it is subject to change.

3.4. Land Cover Anthropisation

Land use and land cover changes started in pre-history as direct and indirect consequences of human actions to secure essential resources. Initiated with land burning to enhance the availability of food, land cover changes accelerated with the birth of agriculture. In 1750, an estimated 6 to 7% of the global land surface was under cultivation or pasture mainly in Europe, India and China (IPCC, 2007). During industrialisation, agriculture intensified and human populations concentrated within growing urban and sealed areas. Croplands and pasture expanded until 1950. Since then, an opposite trend can be observed in Europe and China, where cropland areas have been stabilising or decreasing. Reforestation has also been observed in Western Europe and North America. Tropical areas are nevertheless still facing rapid deforestation.

Land cover changes result in today’s widespread anthropised landscape and cleared land. Croplands and pasture represent 37% of the original land cover while forests extend over 31% of the global land area (40 mio km^2) (FAO, 2010) in comparison with an estimated pre-industrial state of 41-42% (53-54 mio km^2) (IPCC, 2007).

3.4.1. Description

The objective of the Planetary Boundary Land Cover Anthropisation is to avoid irreversible and widespread conversion of biomes to undesired states by limiting the expansion of anthropised areas. Anthropisation of land (through deforestation, cultivation and soil sealing) acts as a slow variable affecting several environmental aspects such as climate, soil, landscape, water, biodiversity.

Land cover is usually considered a regional issue rather than a global issue since changes occur at a local or regional scale. A global perspective can however be adopted when considering how land cover changes affect the global Earth system, in particular through their impacts on climate change (UNEP, 2012) as well as on global biodiversity. Since 1959, land accounts for around 28% of the carbon sequestration by global carbon sinks (45% is stored in the atmosphere and 27% in the oceans) (Le Quéré et al., 2014). Over the period 2000-2009, land cover changes contributed to an estimated 12.5% of the total carbon emissions (Friedlingstein et al., 2010). Land cover is currently considered as a net carbon sink despite emissions due to land cover changes (Houghton et al., 2012). Another impact of land cover change, in particular deforestation, is on global temperature that will in the future “depend largely on the relative importance of increased surface albedo in winter and spring (exerting a cooling) and reduced evaporation in summer and in the tropics (exerting a warming)” (IPCC, 2007). The modification of land cover towards less natural states (in particular through deforestation, soil sealing, monocultures) also affects negatively biodiversity but this aspect is treated in a specific Planetary Boundary (Biodiversity Loss).

The global limit for Land Cover Anthropisation is set with an indicator expressed in terms of *the surface of anthropised land, i.e. agricultural and urbanised (sealed) land, as percentage of ice-free land (water bodies excluded)*.

3.4.2. Methodology

Selection of the indicator

Two types of indicators have been explored. First, an indicator related to the type of land cover, e.g. the percentage of anthropised surface or the percentage of forest (with possibly rates of change as well as a distinction between forest types) has been explored. Such an approach provides a basic synthetic view without making any quantitative assumptions about the relationship between land cover types and the potentially affected environmental dimensions.[37]

A second type of indicator, focusing on the functions of land cover, has been explored. The objective was to test the construction of a composite indicator measuring the different influences of land cover on climate: the two aspects mentioned by Rockström et al. (2009), i.e. carbon sequestration and albedo, have been considered.[38]

The second type of indicator could be interesting for further developments but we were unable to generate an indicator of enough quality. Albedo taken from Teggi et al. (2008) showed very similar values per type of land cover which would not allow for sufficient differentiation between the different types of land cover required in this study. The same issue happened for carbon sequestration. The available global data did not provide enough relevant discrimination of the land cover types considered and the carbon sequestration by soils is missing. In addition, the precise modelling of effects of land cover related processes (forest fires, peat fires and decay of drained peatlands) was beyond the scope of this study.

Selected indicator

The selected indicator focuses on the anthropised surface. This indicator has been preferred to forested areas, because better data is available and the anthropised surface can be linked to human activities, enabling thus the computation of footprints.

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[37] This means that no weighting is applied between the different types of land cover. Taking into account ecosystem services would be one of the possible approach to set weights. Many issues should however be solved to enable such approach, e.g. many ecosystem services are not global and some of them are indirectly captured in the dedicated Planetary Boundary Biodiversity Loss.

[38] Biodiversity, the third aspect mentioned by Rockström (2009), has been left out because it is the subject of a dedicated Planetary Boundary (number 8).

Similarly to Rockström et al. (2009), the selected indicator can thus be understood as a rough proxy for albedo and for carbon storage through the measure of the share of the land cover types having a low carbon sequestration potential and high albedo, i.e. agricultural land and urban land. The effect of land cover change on biodiversity is not considered here since it is approached with a similar methodology in the dedicated 8th Planetary Boundary.

From a conceptual point of view, this indicator measures a State of the Planetary Boundary, which is the preferred level of measurement in this study. From an empirical point of view, global data are available, among which time series on agricultural land per country from FAO and data to compute the footprints.

Setting limits

The global limit is computed first and then downscaled to compute the Swiss limit. Global and Swiss limits are expressed in terms of yearly values corresponding to a theoretically acceptable share of anthropised land cover. The global and Swiss limits are constant over the years but the per capita values evolve according to population size. The global limit per capita represents an equal share perspective.

Global limit

The surface of anthropised land considered in this study covers agricultural land (arable land and permanent crops, e.g. grapes) and urbanised land (considered as sealed land). A third type of anthropised agricultural land, pastures and meadows, has not been considered since the distinction between natural and anthropised meadows is not clear enough, leading to inconsistencies across the datasets at hand. The surface is computed as a percentage of ice-free global land, excluding water bodies. Since the indicator is a proxy, the exact relationship between the types of land cover and albedo/carbon storage is not quantified.

A logic similar to Rockström et al. (2009) is applied to compute a new limit accounting for the types of land considered in this study: 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.

The current anthropised land is computed as 16'669'000 km^2 for 2010, equivalent to 12.9% of the global land cover (own calculation based on data from FAOSTAT and Schneider et al. (2009). For the selected indicator, *the surface of anthropised land, i.e. agricultural and urbanised (sealed) land, as percentage of ice-free land (water bodies excluded),* the global limit is set[39] at 15% of the global land cover[PP4], which happens to be a value similar to Rockström proposal (based on changes in the albedo effect). The global limit is equivalent to 19'362'000 km^2. For 2010, the global limit per capita is 2'800 m^2.

Comparison with earlier studies

The original Planetary Boundary by Rockström et al. (2009) is named ”Land system change”. The name has been modified to be closer to the selected indicator. The influence on biodiversity, mentioned (and dealt with implicitly) by Rockström is not considered in this indicator since it is the focus of a specific Planetary Boundary on its own.

The first application by Nykvist et al. (2013) considered cropland only. The methodology presented here is an extension of this approach including an additional type of land cover type (urbanised land) with a strong impact on albedo and carbon storage. The proposed limit has the same limitations, i.e. it is a proxy only and does not consider the different uses of the land, among others.

Limit for Switzerland

The limit for Switzerland is set by downscaling the global limit with the hybrid-allocation approach described in chapter 5 in order to consider the past: the Swiss share of the global anthropised land cover is defined relatively to the Swiss share of the global population at a past reference date. For Land Cover, this reference date is 2010, resulting in a Swiss share of 0.113%. The year 2010 has

[39] 13% + 0.8% + 1% = 14.8% Note: this equation assumes that urban expansion occurs exclusively on non forest lands. In many places urbanisation takes place at the expense of agricultural land. In Switzerland this is the case due to a strictly enforced legislation on forests. But the assumption should certainly be nuanced country by country.

been selected because it is the year of the Global Forest Resource Assessment by FAO (FAO, 2010), serving as reference for the computation of the UNEP objective for the reduction of the deforestation (Trumper et al., 2009).

The Swiss limit is fixed and the per capita limit evolves according to the yearly Swiss population. The resulting yearly limit for Switzerland is 21'900 km^2. The Swiss per capita limit is 2'770 m^2 in 2011, which is very close to the global limit of 2'800 m^2 per capita.

Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are presented in Table 9. Data for urban areas have been adapted from the map of urban extent by Schneider et al. (2009). Due to the resolution of the map (500m), only large continuous areas are represented, e.g. roads are missing, and values are known to underestimate the real urban areas. After a comparison with the Swiss national data, values have been doubled to take into account the other types of sealed areas.

Data	Data sources	Units
Cropland area	FAOSTAT http://faostat.fao.org	ha x 1 000
Ice and permanent snow	GlobCover (300m spatial resolution) http://due. esrin.esa.int/globcover	23 land cover classes
Urbanized land	Global 500m MODIS map of urban extent (Schneider et al. 2003)	Binary values
National (territorial and footprint) land use	Frischknecht et al. 2013	m^2 x year
National population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants
World population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants

Table 9. Land Cover Anthropisation: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 10. Land Cover Anthropisation being assessed with a basic approach based on well-known datasets, the overall quality of the assessment can be considered as medium. For the sake of comparison, the indicator computed with our approach for the Swiss territory is equal to 6'900 km^2, i.e. 8.8% less than the 7’600 km^2 computed with the FOEN database (based on FSO land cover figures).[40]

[40] For the Swiss domestic part, the estimated footprint will thus be closer to the limit that if it would have been computed with global data. However, such information cannot be used to infer the overall quality of the assessment since the

Quality assessment

PB relevance	+ / -	Basic approach. A composite indicator of more focused aspects could be better.
Focus on the overall picture	++	
Reliability (data, models)	+	FAO: at national level and few categories only. Limited spatial resolution (500m) for urban areas
Transparency	++	FAO classification and methods are published, same for the global map of urban extent
Communication	+ / -	Risk of confusion with current national land use indicators
Coherence / comparability	++	
Availability of information	++	
Timely	+ / -	Urban extent: 2009 only; irregular updates of GlobCover with poor comparability

Legend **++** : High **+** : Acceptable **+/-** : Potentially problematic **-** : Problematic

Table 10. Land Cover Anthrophisation: quality assessment.

Computing footprints

The general description of the computation of the footprints is presented in chapter 5. The specificities for Land Cover Anthropisation are presented here.

The global footprint is based on the same dataset than for computing the global limit. Data is extrapolated for urban areas for 2011 based on projections of urban population (UNPD, 2013) assuming a constant urban area per capita. The Swiss footprint is based on the FOEN proprietary database. Footprints are computed for the years 1996-2011.

3.4.3. Current performance

The global footprint for the Planetary Boundary Land Cover Anthropisation is below the global limit. This is the logical outcome of the way the limit has been set, i.e. as a relative increase from the current situation based on global policy objectives. The situation is similar for Switzerland. Confidence in the results is medium for the global and Swiss values. The evolution is however different: the evolution of the global footprint is slow but the evolution of the Swiss footprint is rapid. The global performance is thus qualified as Safe while the Swiss performance is qualified as Unsafe.

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major part of the Swiss footprint is occurring outside Switzerland (imports) and is based on modelling, not on Swiss data.

Results are presented for yearly limits and yearly footprints computed for 2010 (global) and 2011 (Switzerland) in Figure 6. The yearly global limit per capita represents the equal share perspective.

	World	Switzerland
Confidence in score	Medium	Medium
Trend	Slow evolution	Rapidly deteriorating
Performance	Safe	Unsafe

Figure 6. Land Cover Anthropisation: global and Swiss performances.

At global scale, the global limit is 19'362'000 km^2 (computed for 2010) and the resulting per capita limit is set at 2'800 m^2. With a current global footprint estimated to be 19'669'000 km^2 for 2010 and a per capita footprint at 2'712 m^2, <u>the global footprint is 14% below the limit</u>.

For Switzerland, the pattern is similar and the Swiss footprint is below its long-term acceptable average. The Swiss limit is at 21'900 km^2 (computed for 2010) and the resulting per capita limit is set at 2'770 m^2 for 2011. With a current (2011) footprint estimated to be 17'600 km^2 in 2011 for Switzerland, and a per capita footprint at 2'224 m^2, <u>the Swiss footprint is 20% below the limit</u> for Switzerland. The footprint figures presented in Figure 6 for Switzerland and for the world are not based on the same dataset and are thus difficult to compare. Both performances can be considered similar.

3.4.4. Discussion: Land Cover Anthropisation

The Planetary Boundary Land Cover Anthropisation is assessed with a rough proxy for albedo and carbon sequestration. The limit is, by definition, currently neither crossed globally nor for Switzerland. It could, however, be discussed whether the limit for Land Cover Anthropisation is strict enough, given its relevance for the Boundaries of Climate Change and Ocean Acidification that are largely overshot.

The evolution of the global footprint over the period 1961-2011 is shown in Figure 7.[41] The cumulative growth over this period is 21%. This is equivalent to an average growth rate of 0.42%. Assuming a future global growth rate equivalent to the average growth rate of the last 15 years (0.3%), the global limit will be reached in 45 years.

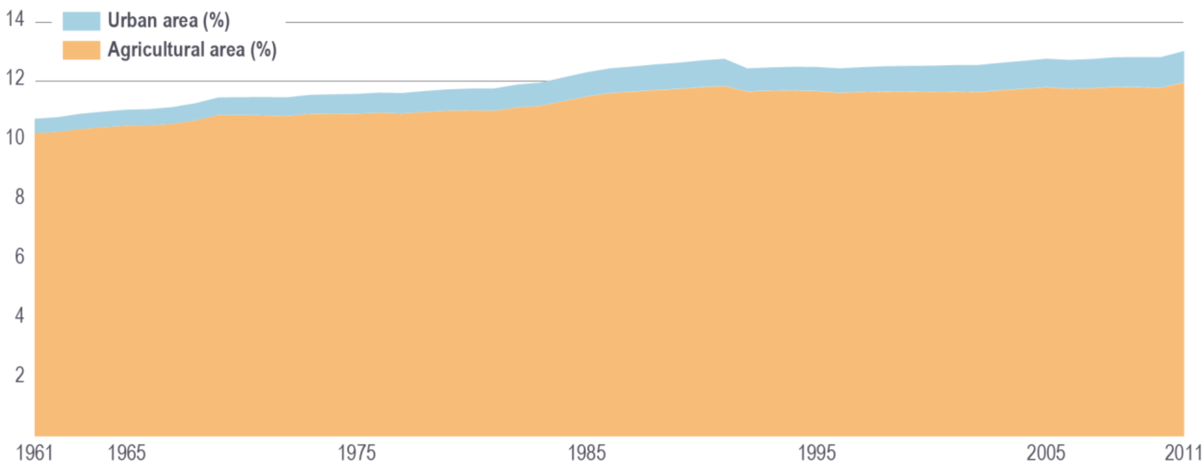

Figure 7. Anthropised Land Cover (in % of of global area w/o ice and snow) - global footprint.

The Swiss footprint for Land Cover Anthropisation has been rapidly growing over the last 15 years. Its cumulative growth is 26 % over 1996 to 2011, i.e. a yearly average growth rate of 1.7%. The Swiss footprint is thus growing much more rapidly than the global footprint. At the average growth of rate over this period, the Swiss limit will be attained in less than 10 years.

In 2011, the largest share of the Swiss footprint was occurring outside of Switzerland (see Figure 8). The size of the footprint due to import is more than twice as large as the part of the footprint[42] for the production consumed domestically. The anthropised land cover of the production part for domestic consumption has been stable between 1996 and 2011 and the footprint increase is due to the larger increase of imports over exports. Imports have been growing slightly more rapidly than exports (with a cumulative growth of 56% vs. 51% respectively) and have a larger basis.

[41] Values for urban areas have been computed with a 2009 basis and extrapolated based on the evolution of the urban population with a constant urban area per capita.

[42] The Swiss footprint is equivalent to production (domestic + imports) plus imports minus exports.

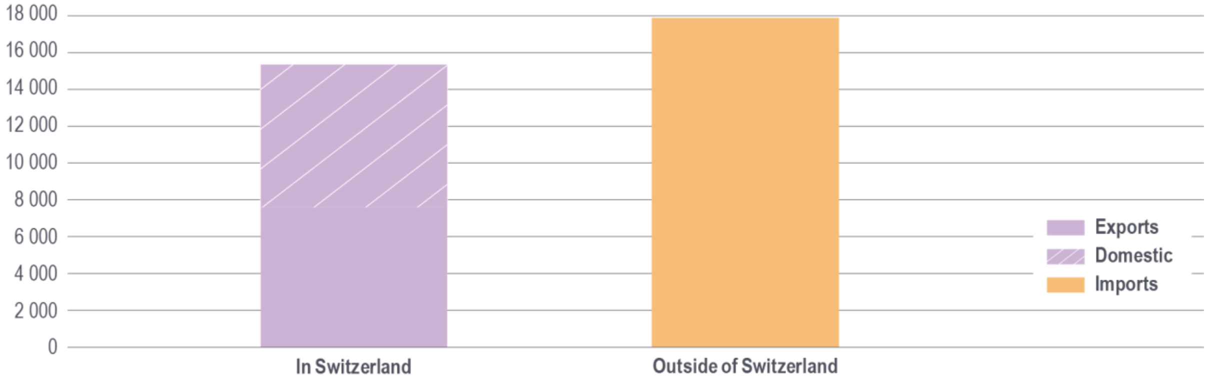

Figure 8. Anthropised Land Cover (in km²) - Swiss footprint.

In Figure 9, the evolution of the shares per land cover type is shown for the Swiss footprint from 1996 to 2011. Shares are rather stable with a dominance of arable land (60%), an increasing share of permanent land (+ 4%) and a slightly reduced share of urban land (- 2%). The stability of urban land is probably due to the underlying dataset since it does not account for the increase in sealing over the years.

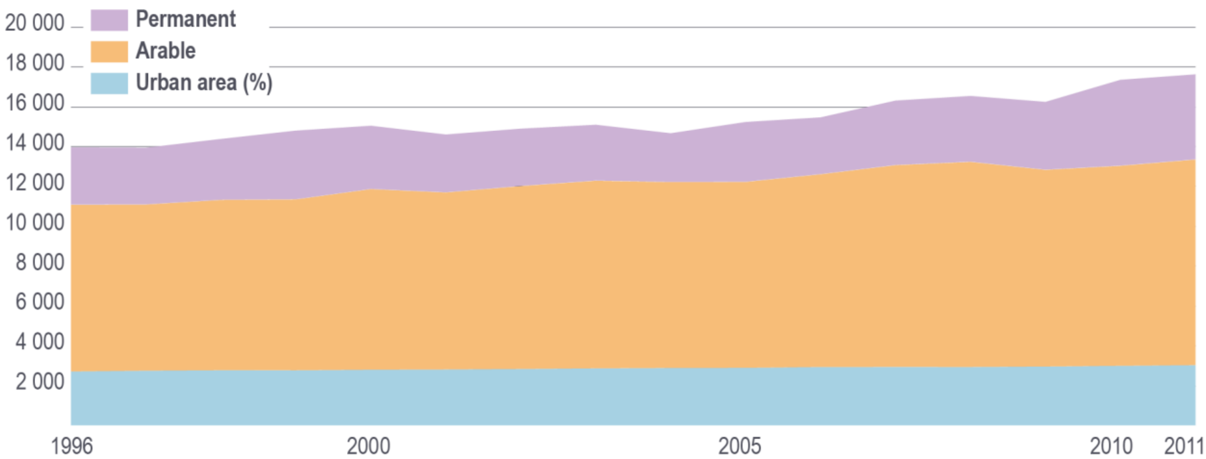

Figure 9. Anthropised Land Cover (in km²) - Swiss footprint: share per type of area.

3.5. Biodiversity Loss

Cardinale et al. (2012) summarise the current knowledge about how loss of biological diversity will alter the functioning of ecosystems and the resulting impacts on their provision of goods and services to society. They define biodiversity as "the variety of life, including variation among genes, species and functional traits", ecosystem functions as "ecological processes that control the fluxes of energy, nutrients and organic matter through an environment" and ecosystem services as "the suite of benefits that ecosystems provide to humanity. (…) Provisioning services involve the production of renewable resources (for example food, wood, fresh water). Regulating services are those that lessen environmental change (for example climate regulation, pest/disease control)."

The loss of biodiversity in the current era is enormous (Millennium Ecosystem Assessment, 2005) and seems to have comparable impacts as other global drivers of change, such as warming, ozone and acidification (Hooper et al., 2012). The global Living Planet Index (LPI) shows that the population of wild vertebrate species felt by an average of nearly one-third globally between 1970 and 2006. The decline has been particularly severe in the tropics (around 60%) while a recovery (around 15%) can be seen in the temperate zone (Secretariat of the Convention on Biological Diversity, 2010).

3.5.1.Description

The objective of the Planetary Boundary Biodiversity Loss is to avoid a level of biodiversity loss that would lead to irreversible and widespread undesired states of ecosystems. Biodiversity acts as a slow variable affecting the resilience of ecosystems, hence the services they provide, e.g. carbon storage or freshwater. Habitat loss and degradation are two of the main causes of biodiversity loss (Brook et al., 2008). However, there are other important biodiversity pressures (climate change, invasive species, nutrient inputs, etc.).

Biodiversity is usually considered a regional issue rather than a global issue since changes occur at a local or regional scale. A global perspective can however be adopted since evidence for the important role of biodiversity for ecosystem functioning and human well-being is considerable (Cardinale et al., 2012; Estes et al., 2011; Hooper et al., 2005).

The global limit for Biodiversity Loss is set with an indicator expressed in terms of *the potential damages to biodiversity per land cover types accounting for the level of biodiversity per biome*.

3.5.2.Methodology

Selection of the indicator

(Barnosky et al., 2012) assume that a planetary-scale tipping point of the biosphere is plausible and (Rockström, 2009) suppose in the concept of Planetary Boundaries that biodiversity loss has already passed the critical boundary. It is however still a matter of intense research to which degree a global boundary (critical range) can really be delimited for biodiversity loss (and probably for the other dimensions as well), or whether functions will gradually decrease with increasing loss of biodiversity (or change of other dimensions) (Mace et al., 2014). Huitric et al. (2010) also acknowledged the difficult endeavour to find suitable indicators and to set limits for biodiversity from a functional perspective. (Huitric et al., 2010)

Similarly to other Planetary Boundaries, an indicator that is as direct as possible, i.e. a State would be the best option. Possibilities would be an indicator based on the Red Lists of species, the rate of extinction as in the publication by (Rockström, 2009) or - in the future - an indicator based on Red Lists of habitat types that Rodriguez et al. (2011) have begun to develop.[43] However, for a footprint-based indicator, it should be possible to relate it to consumption, as it is the case for a Pressure indicator like land use. Land cover types can be understood as a rough proxy for biodiversity loss since "habitat change and land use are among the main drivers of current and projected future biodiversity loss" (Baan et al., 2013; Rodríguez et al., 2011).

Selected indicator

Following the approach from Frischknecht et al. (2013), we used a modified version of the average Biodiversity Damage Potential (BDP) from de Baan et al. (2013). The indicator is an estimation of the species richness relative to a (semi-)natural reference situation. The approach to calculate BDP applies weights, representing estimates of the potential negative impact of land cover types on the relative richness of species, to the different land cover types in different biomes. Both natural and anthropised types of terrestrial land are considered. Aquatic (freshwater and marine)

[43] None of these potential indicators consider the intrinsic value of biodiversity. If intrinsic value is weighed very high, every loss of species or other biodiversity components is inacceptable.

biodiversity is however not considered while it accounts for large parts of life on earth and is endangered by many factors, e.g. ocean acidification or overfishing. The global and Swiss limits and footprints are computed as the average values of BDP per land cover type weighted by areas.

The advantage of this approach is to exploit further land use information to get an indicator at the State level (potential biodiversity loss) within the DPSIR framework (EEA, 2005), computable at the global scale and allowing a comparison of countries' performances due to the use of global datasets. This indicator also allows the computation of national footprints.

The constructed indicator is clearly a rough approximation of biodiversity since the number of land cover types is limited and the relationship with biodiversity damages is modelled with limited data (see the section on the evaluation of the indicator for more information) and high uncertainties.

This approach is however clearly in line with current practices in Life Cycle Assessment (the main approach for footprinting) and is applied in the Ecological Scarcity Method 2013 published by the Swiss Federal Office for the Environment (Frischknecht et al., 2013).

Setting limits

The global limit is an index (a relative value of species richness as compared to a (semi-)natural reference situation). In this case, given the nature of the indicator chosen, the allocation mechanism based on population was not applied: the same relative value is used for the global, the Swiss and the per capita limits. In further studies, computation of absolute quantities based on BPD values (Frischknecht and Büsser Knöpfel, 2013) could be explored.

Global & Swiss limits

Considering the difficulty to set a limit for biodiversity based on well-accepted scientific evidence, an approach based on policy targets has been adopted, using the Aichi Biodiversity Targets of the Convention on Biological Diversity (CBD). Three targets related to land cover (under Strategic Goal B and C)[44] were selected:

[44] http://www.cbd.int/sp/targets/#GoalB

- "Target 5: By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced".
- "Target 7: By 2020 areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity".
- "Target 15: By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification."

Based on these objectives, the limit is simulated by modifying the global dataset representing the current situation, i.e. the current global footprint, generated with the most recent global land-cover map (Globcover 2009) and BDP factors from Frischknecht and Büsser (2013).

Frischknecht and Büsser (2013) use the values for the global mean of the various types of land use (e.g. forest – broad-leafed, arable land, permanent crops, etc.) according to de Baan et al. (2012) for the BDPs of the biome 5 (temperate coniferous forests), updating the BDP for forests to account for managed forests based on the Swiss situation. They compute the BDPs factors for the other biomes with single multiplying factors per biome representing the ratio of species densities from Kier et al. (2005). BDPs are thus available for the 14 Biomes defined by Olson et al. (2001).

BDP factors were applied to each pixel of the Globcover raster dataset, according to the land cover type and the biome it belongs to get the potential damages to biodiversity of each area.

To account for organic agricultural areas, not modelled in the Globcover dataset, the share of organic areas can be computed from FAO data. Due to the low global share of organic agricultural areas (around 2% of permanent and arable crops) the correction has however not been applied because results at global scale would have been modified only marginally. Urban (sealed) areas are known to be underestimated in Globcover. They represent around 1% of global land use: using more precise data would thus not lead to significant changes in the results at global scale and better data has thus not been integrated. It should however be better integrated in future studies. Managed forests have not been considered either. While not yet fully harmonised at global scale, some data is available from the FAO and should be considered in future updates of the study.

The global BDP index was then computed as the global area weighted by the average of BDP values. A schematic description of the process is shown in Figure 10.[45]

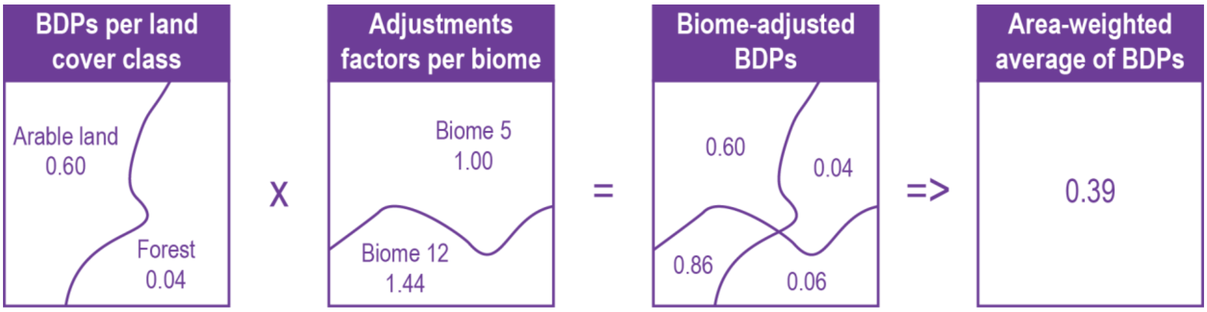

Figure 10. Biodiversity Damage Potential: schematic description.

The computed current (2009) global average Biodiversity Damage Potential is 0.2. This BDP is, by definition, also equivalent to the current global footprint.

Starting from the situation of 2009 (date of the existing dataset), and with the dataset at hand, the limit is computed by applying the following changes:

- The zero-loss objective (Target 5) is modelled by keeping stable the situation of 2009.
- The sustainable management (Target 7) and improved ecosystem resilience (Target 15) are approximated with a full conversion of conventional agricultural land to organic land.

As shown in Table 11, the applied changes are a reduction of the BDP (for biome 5: temperate coniferous forests) of agricultural land by 65% in accordance with the ratio between the BDP conventional land use and organic use.

	Conventional	Organic	Ratio
Arable land	0.60	0.21	0.35
Permanent crops	0.42	0.15	0.36
Pastures and meadows	0.33	0.12	0.36

[45] The calculations reproduce only partly the approach by Frischknecht and Büsser (2013). BDP values are not converted in equivalent built-up area, nor in eco-factors. The two latter do not provide additional information in our case (they are linearly linked to BDP). Above all, this is to avoid irrelevant comparisons with the results of the two mentioned studies that used more detailed land cover data, and also to avoid confusion with the land areas displayed in the 7th Planetary Boundary Land Cover Anthropisation.

Table 11. Comparison of the BDP for conventional and organic agricultural areas in biome 5 (temperate coniferous forests).

Simulating the objectives of Aichi with this approach we get a global BDP value of 0.16 which is taken as the global limit. The global limit is thus 20% below the current global BDP, i.e. 20% below the current global footprint. The same limit is applied to Switzerland since it is an index.

Comparison with earlier studies

The original Planetary Boundaries by Rockström et al. (2009) is named "Rate of biodiversity loss". The suggested indicator is the "extinctions per million species-years (E/MSY)", with a limit set at 10 E/MSY.

The selected indicator has been preferred to the following three possible indicators suggested by Nykvist et al. (2013):

- The number of species threatened within the national territory per million capita, using data from Lenzen et al. (2012).(Lenzen et al., 2012)
- The number of species threatened globally through consumption including international trade, using data from Lenzen et al. (2012).
- The percentage of marine and terrestrial areas protected, using data from IUCN and UNEP/WCMC.

The first two were not considered because the way the Red List species are modelled[46] in Lenzen et al. (2012) provides, to our perspective and in the current version of the model, a false sense of precision while causality is rather weak. The protected areas are interesting because they correspond to an important Aichi Biodiversity Target. They do not reflect however the actual biodiversity level as they are a Response (in the DPSIR framework). Moreover, biodiversity exists outside of protected areas as well. In addition, they are spatially restricted and cannot be linked to human activities for computing footprints.

[46] Red List species are linked to industries in a binary way: they are affected or not by an industry. A normalisation is then performed based on production values. As a result, the number of species affected is directly proportional to the values of imported goods.

Mace et al. (2014) propose other alternatives but data is not available yet. Recent updated estimations of biodiversity impacts from habitat changes should be explored in future studies (e.g. Chaudhary et al., 2015).

Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are presented in Table 12.

Data	Data sources	Units
National land use from 1996 to current	Frischknecht et al. 2013 (1996-2011)	ha x 1 000
Land-cover classes	GlobCover (300m spatial resolution) http://due. esrin.esa.int/globcover	23 land cover classes
BDP values, per land-cover type and per biome	Frischknecht et al. 2013, Frischknecht et al. 2014	%
National population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants
World population (1990 - 2050) - UN medium	UN Dep. of Econ. and Social Affairs	Inhabitants

Table 12. Biodiversity Loss: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 13. Biodiversity Loss is assessed with an approach relying on a simple model and can only be taken as a rough approximation. The overall quality of the assessment is thus low.

The main critical points regarding the BDP approach (Baan et al., 2013) are:

- The uncertainty on the density factors used in the BDP method can be very high, especially in areas under conversion (deforestation, regeneration).
- Only impacts from occupation are considered and not impacts from transformation.
- The temporal dynamics of ecosystems are not considered.
- A default equal weight is given to all species.
- There is no or very little biodiversity data for five out of the fourteen biomes.

In addition, the dataset for land cover is coarse (300 meters spatial resolution and accuracy limitations (Bontemps et al., 2011)), and the average values of BDP per land cover category are only rough estimates.

In terms of communication, BDP is less straightforward and known than biodiversity for the general public, but it still remains understandable.

Quality assessment		
PB relevance	++	
Focus on the overall picture	+ / -	Biodiversity in aquatic ecosystems and beta-biodiversity are not considered
Reliability (data, models)	-	Very basic approach of biodiversity with coarse datasets
Transparency	++	
Communication	+ / -	The concept of BDP is not easy to understand outside of the LCA community
Coherence / comparability	++	
Availability of information	++	
Timely	-	Irregular updates of the GlobCover with poor comparability

Legend **++** : High **+** : Acceptable **+/-** : Potentially problematic **-** : Problematic

Table 13. Biodiversity Loss: quality assessment.

Computing footprints

The general description of the computation of the footprints is presented in chapter 5, whereas the specificities for the Planetary Boundary Biodiversity Loss are presented here.

The global footprint is based on the same dataset as the global limit. The Swiss footprint is based on a modified version of the FOEN database resulting from Frischknecht et al. (2014) since the location of land use induced by imports cannot be identified from the database. These locations have been inferred from the results of the CREEA project for Europe (Tukker et al., 2014). An average BDP has also been computed for each of the regions of origin to enable the computation of a weighted BDP for imports. The conclusion based on these assumptions is considered robust for imports based on the results of a sensitivity analysis.[47]

The computed global BDP does not account for organic agriculture (2% of global areas) nor for managed forests (which have a BDP of 0.04 compared to 0 for non-managed forests). Another sensitivity analysis has been performed on organic areas and managed forest for the exports and results can be considered as robust.[48]

[47] The computed BDP for imports varies in a range of 0.24 to 0.27.

[48] The average BDP varies by only 1% when considering them or not.

3.5.3. Current performance

The footprint for the Planetary Boundary Biodiversity Loss is overshooting the limit. The confidence in results is low. The evolution is very rapid. The global and Swiss performances are thus qualified as Clearly Unsafe.

Results are presented for yearly limits and yearly footprints computed for 2009 (global values) and 2011 (Swiss values) in Figure 11.

	World	Switzerland
Confidence in score	Low	Low
Trend	Rapidly deteriorating	Rapidly deteriorating
Performance	Clearly Unsafe	Clearly Unsafe

Figure 11. Biodiversity Loss: global and Swiss performances.

At global scale, the global limit is at 0.16 (computed for 2009) and the resulting per capita limit is similar, by definition. With a current global footprint estimated to be at 0.2 for 2009, the footprint was 25% above the limit.

For Switzerland, the pattern is similar and the Swiss footprint is above its long-term acceptable average. The Swiss limit is also at 0.16, by definition, as is the resulting per capita limit. With a current (2011) footprint estimated to be at 0.3 in 2011 for Switzerland the Swiss footprint was 87% above the limit for Switzerland.

3.5.4. Discussion: Biodiversity Loss

Facing the impossible task of setting a scientifically validated limit for biodiversity loss, well-accepted global policy targets at the international level have been selected to model a limit with the available datasets.

The computed global footprint is larger than the global limit. However, comparing this result to Rockström et al. (2009), estimating a global extinction rate, the computed overshoot is much smaller (10 times). The capability of representing adequately biodiversity loss with the presented indicator is thus subject to discussion and should be taken with caution (as it is the case for the current other proposals for computing footprints).

While Switzerland's footprint is also much larger than its limit, the analysis of the relative performance of Switzerland compared to the world is not straightforward due to the difference in the datasets. However, the conclusions are considered robust based on sensitivity analyses.

Firstly, we performed a sensitivity analysis with alternative datasets in order to get an idea of the accuracy of the used global spatial dataset. The Swiss territorial BDP computed with our approach is 0.24. Using the database resulting from Frischknecht et al. (2014), we get a value of 0.25, whereas using official[49] Swiss land cover data a value of 0.22. The average BDP for the domestic part of the Swiss footprint can thus be considered larger than the world average when domestic organic agricultural areas are not considered. Considering organic agricultural areas (7.5% of Swiss agricultural areas in 2011 according to FAO (11% according to Swiss national data) does not change the conclusion since the Swiss territorial BDP is reduced by only 1%. The global average BDP would neither be modified significantly by considering the 1-2% global organic areas: the territorial Swiss average BDP is thus probably very close (slightly higher) to the global BDP when considering organic areas.

Secondly, for the two other components of the Swiss footprint, i.e. exports and imports, computed with the database resulting from Frischknecht et al. (2014) with imports modified, the average BDPs are 0.20 and 0.27 respectively. Because the Swiss footprint is computed as a domestic part

[49] http://www.bfs.admin.ch/bfs/portal/fr/index/themen/02/03/blank/data/01.html

plus imports minus exports and since the area for imports is larger than the area for export, the Swiss footprint has a higher BDP than the Swiss territorial BDP.

The larger BDP of the Swiss footprint compared to the global footprint cannot be validated with certainty due to the different databases but seems a plausible explication due to the structure of Swiss imports (industrial and agricultural goods) and their origin (biomes with higher multipliers than the biome in which Switzerland is located (temperate coniferous forests)).

Due to the overshoot of the global and Swiss limits, actions are needed in Switzerland itself as well as abroad. Respectively the most important actions would be:

- To stop or at least greatly slow down the conversion of natural habitats.
- To switch to much more sustainable land use practices respectively to reduce the negative impacts of the current practices.
- To restore ecosystems (on a large scale), especially the ones playing the most important roles for global processes

Furthermore it has to be considered that the concept of the Planetary Boundaries addresses only aspects of biodiversity that are relevant for global processes. Intrinsic values, local biodiversity values and effects on local ecosystem services that can be directly experienced by local people are not addressed here.

A4. Experts consulted

Members of the Advisory group convened by FOEN

Andreas Hauser (lead), Adrian Aeschlimann, Andreas Bachmann, Loa Buchli, Paul Filliger, Peter Gerber, Hans Gujer, Klaus Kammer, Anik Kohli, Nicolas Merky, Silvia Rauch, Ruedi Stähli, Gaston Theis, Markus Wüest (all Federal Office for the Environment FOEN), Anne-Marie Mayerat (Federal Statistical Office FSO).

Other experts consulted

Markus Fischer and Jodok Guntern (Swiss Biodiversity Forum), Josef Tremp and Martin Pfaundler (Federal Office for the Environment FOEN), Rolf Frischknecht (Treeze)

Participants of the workshop held in Bern (17 March 2014)

A workshop was organised and held in Bern on 17 March 2014. Its overall objective was to validate reference values, downscaling options and take stock of recommendations on resource sharing. More than forty experts participated. Four sessions were organized (climate change, land system changes, nitrogen and freshwater use) allowing to canvass expert’s opinions on strategies to be taken for computing the Swiss limits and on how to take into consideration the historical contribution of Switzerland.

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