Environmental Limits and Swiss Footprints Based on Planetary Boundaries

A study commissioned by the Swiss Federal Office for the Environment (FOEN)

Final Report

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Abstract

The goal of this study is to develop recommendations for a set of footprint limits for a Green Economy, by translating the environmental limits of our planet ("Planetary Boundaries") to the context of Swiss demand (i.e. consumption). The proposed limit values serve as a rough orientation on a sustainable level of resource consumption from a scientific point of view; they are not meant as directly applicable political targets.

We conclude that Switzerland should, as a priority, act on its footprints related to Climate Change, Ocean Acidification, Biodiversity Loss and Nitrogen Losses. This suggestion is based on the importance of these environmental processes for the good functioning of the global Earth system, the current global pressure on them as well as on the Swiss contribution to these pressures.

About this document

This report was commissioned in November 2013 by the Swiss Federal Office for the Environment to the Global Resource Information Database (UNEP/GRID-Geneva) and the Institute of Environmental Sciences (University of Geneva). It has been written in collaboration with the NGO Shaping Environmental Action.

The document is structured in eight parts:

1. An introduction to the idea of a complementary perspective to consider global environmental issues, based on footprinting
2. A presentation of the objectives of the project
3. An introduction to the concept of Planetary Boundaries
4. A presentation of the distributional principles to define a country share of the Planetary Boundaries
5. A description of the approach applied in this report
6. Limits, footprints & performances for Switzerland and the World for each Planetary Boundary studied
7. Synthetic results for Switzerland and the world
8. Conclusion and perspectives

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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

1. Introduction

1.1. New approaches for global environmental issues: planetary tipping points and footprinting

1.1.1. The classical perspective is territorial

The international environmental regime is highly dynamic. More than 500 multilateral agreements exist and the number of parties is constantly growing (UNEP, 2012a). Main clusters concern atmosphere, biodiversity, chemicals and waste, desertification as well as water. This regime sets the basis for multilateral environmental co-operation through the sharing of common objectives, actions and potentially targets.

While the number of measures taken by countries in co-operation is increasing, the focus of action has been and is still the national territory. Most of the existing national indicators concerning international issues are thus looking exclusively at the situation from a territorial perspective, e.g. reporting on domestic greenhouse gases emissions under the Kyoto Protocol.

1.1.2. Footprints provide a complementary perspective

Environmental footprint indicators provide a complementary perspective to the territorial indicators. This footprint perspective is also known as life cycle perspective or consumption perspective. Footprints aggregate environmental impacts and/or resource uses along global production-consumption chains (EPA, 2006). By adopting a functional focus rather than a geographical focus, they allow to quantify the environmental impacts induced by the consumption of the inhabitants of a country wherever these impacts occur on Earth.

A footprint perspective is particularly relevant for economies relying on external countries for a large part of the production of the consumed goods, i.e. for small, open or service-oriented economies. This perspective is increasingly relevant in our interlinked global economy (Friot, 2009) since a rising part of the impacts on a territory are generated to satisfy consumers in other countries. As shown in Figure 1, some of the environmental impacts occurring in Switzerland are generated for the consumption of the inhabitants of other countries (exports) while some of the impacts generated for the consumed goods and services are occurring outside of Switzerland (imports).[1]

Footprint indicators show thus the magnitude and location of the environmental impacts induced by a population as well as the reliance on foreign environmental resources. Furthermore they can also be used to quantify the environmental consequences of production and consumption choices in terms of burden shifting among countries. As a result, the consumption-based indicators provide a needed complementary perspective to existing territorial-based indicators. They will however not replace them: both are needed.

[1] The figure is a simplification: (a) going from the territorial to the footprint perspective requires passing through a production perspective, (b) consumption is equivalent to final demand, i.e. it includes the final consumption of inhabitants the final consumption by government, and by non-profit organisations serving households as well as gross fixed capital formation. See http://www.eea.europa.eu/publications/european-union-co2-emissions-accounting for a description of the different accounting pespectives.

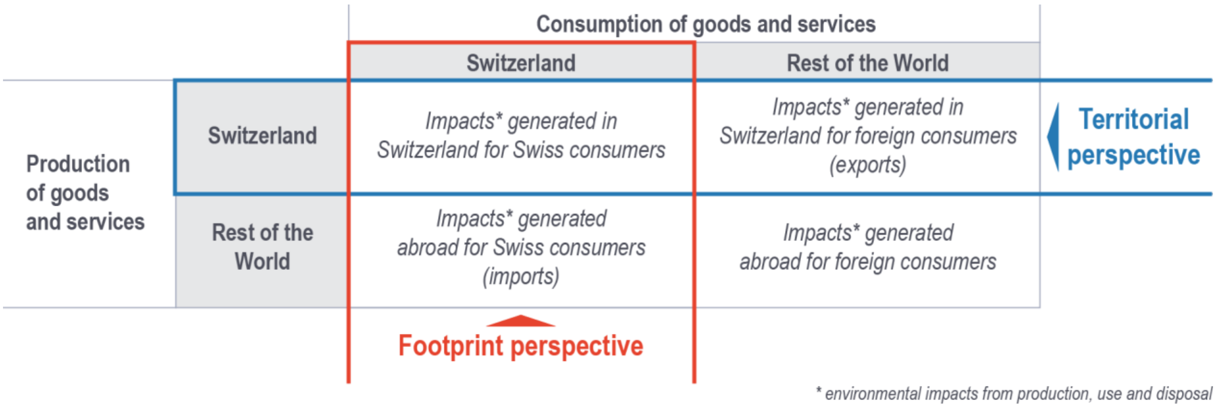

Figure 1. Swiss environmental impacts: territorial and footprint perspectives.

While these indicators are still recent, they are increasingly adopted, i.e. for environmental policies[2], the environmental assessment of goods[3] and of companies[4].

1.1.3. A new concept: the Planetary Boundaries

The concept of Planetary Boundaries was proposed by Rockström et al. in 2009 (Rockström et al., 2009b). The Planetary Boundaries are a set of physical and biological limits of the global Earth system that should be respected in order not to leave a "Safe Operating Space", and thereby put the planet's human-friendly living conditions into peril. The most known limit is Climate Change but others are considered like Ocean Acidification for example. As developed further in chapter 3, Planetary Boundaries are the most recent scientific framework to think about global environmental limits.

1.2. Current environmental situation and policy backgrounds

Footprint-based environmental targets are nowadays brought on the political agenda since it has become clear at both national and international levels that natural capital consumption and pollutions of the ecosystems must be lowered to naturally sustainable levels if the foundations of life are to be safeguarded for current and future generations.

1.2.1. A rising footprint in Switzerland and in the EU

More than half of the environmental impacts caused by Swiss consumption occur abroad (Jungbluth et al., 2011). This share has been rising from 1996 to 2011 (Frischknecht et al., 2014). The high share can be explained to a large extent by the fact that Switzerland is a growing small open economy with a high share of services relying on the production of goods, heavy industries and mining in other parts of the world. Tukker et al. (2014) show in the "Global Resource Footprint of Nations" that the EU is also relying on the rest of the world for its carbon, water and land footprints. Other countries like Brazil or China are, on the contrary, providing their resource base to other countries (Tukker et al., 2014).

1.2.2. Political background in Switzerland

In March 2013, the Swiss government adopted an Action Plan for a Green Economy to consider the fact that current patterns of consumption in industrialised countries, like

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[2] See, for instance, the EU Communication on Integrated Product Policy (COM (2003)302).
[3] E.g. the EU Product Environmental Footprint (PEF)
[4] E.g. the Corporate Value Chain (Scope 3) Accounting and Reporting Standard

Switzerland, are causing an over-exploitation of natural resources and are therefore not sustainable. The action plan involves a process of setting targets, monitoring and informing on progress. Currently, a legislative amendment for a Green Economy is being discussed in Switzerland. This amendment schedules, amongst others, a mechanism for target setting and reporting. This amendment is proposed as an alternative to the popular initiative[5] for a Green Economy,[6] which was submitted in 2012 by the Green Party of Switzerland. If accepted by the population, the target of an ecological footprint of one Earth for Switzerland (when extrapolated to world population) by 2050 would be stipulated in the Constitution. Switzerland's current environmental footprint corresponds to ~3 Earths.[7]

Furthermore, since June 2013 the Swiss government has adopted in its official "Swiss Position on a Framework for Sustainable Development Post-2015" that the Planetary Boundaries should be respected.

1.2.3. European and international backgrounds

In autumn 2013, the EU approved the 7th Environment Action Program, which will guide the environmental policy agenda up to 2020. Titled "Living well, within the limits of our planet",[8] the programme includes several direct references to the concept of Planetary Boundaries. Several European countries, including Finland, Germany and Belgium, have started research initiatives on the use of the concept of Planetary Boundaries for policy formulation.[9] An independent study has been recently published on South Africa (Cole et al., 2014).

The Swedish Riksdag (Parliament) adopted, in 2010 the so-called Generational Goal: "The overall goal of environmental policy is to hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden's borders." The goal should be achieved by 2020.[10] In 2013 the Swedish Environmental Protection Agency published a study "National Environmental Performance on Planetary Boundaries (Nykvist et al., 2013), the first attempt to downscale global limits to national limits and to perform a comparison with national footprints.

The relevance of Planetary Boundaries to national policies was also debated on January 23/24 2014 during an international expert workshop entitled "Safe Operating Space: Current State of Debate and Considerations for National Policies". This workshop was organised by the Network of European Environment and Sustainable Development Advisory Councils (EEAC) in collaboration with the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) as well as the Advisory Council for the Sustainable Development of Catalonia (CADS).[11]

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[5] A popular initiative is a direct-democratic instrument in Switzerland: Anyone can propose a constitutional amendment, pre-conditioned by the collection of 100'000 valid signatures, on which the population eventually has to vote on.

[6] http://www.gruene.ch/gruene/de/kampagnen/gruene_wirtschaft.html

[7] http://www.bfs.admin.ch/bfs/portal/en/index/themen/21/03/01.html

[8] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013D1386&from=EN

[9] See Pisano & Berger (2013) http://www.sd-network.eu/quarterly%20reports/report%20files/pdf/2013-October-Planetary_Boundaries_for_SD.pdf p. 22

[10] http://www.miljomal.se/Global/24_las_mer/broschyrer/Swedens-environmental-objectives.pdf

[11] http://www.eeac-net.org/working-groups/516-2014-eeac-bmub-international-workshop-on-safe-operating-space

2. Objectives

2.1. Swiss project: setting footprint limits for Switzerland

This study, commissioned by the Swiss Federal Office for the Environment (FOEN) to UNEP/GRID-Geneva and the University of Geneva in November 2013, has the aim to develop recommendations for a set of environmental limits for a Green Economy, by translating the limits of our planet to the context of Swiss demand.[12] If all these limits are respected by the proposed deadline, and assuming that countries around the world make comparable efforts, then the overall environmental impact could be considered managed and the Swiss consumption patterns could be fully sustained by nature on the long term. Thus, the limits can be interpreted as describing a sustainable level of resource consumption.

The mandate is to develop a set of measurable limits and footprints for Switzerland covering those Planetary Boundaries most relevant from a Swiss consumption perspective. This scientific contribution will contribute to the discussion on setting more operational targets and indicators through policy (Figure 2).

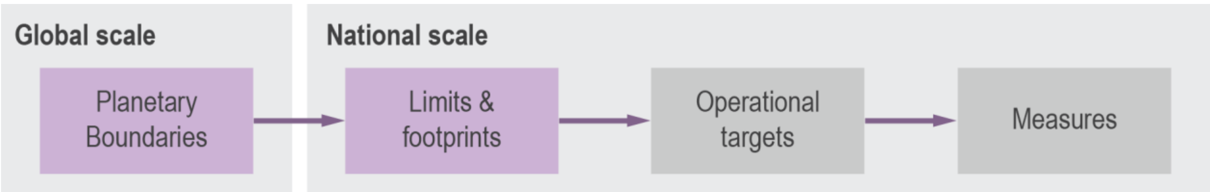

Figure 2. Scope of the project.

2.1.1. Characteristics of the Swiss limits and indicators

The Swiss limits and their related indicators must have the following characteristics:

- Be based on a sound scientific justification,
- Be quantitatively assessable,
- Be demand-based, i.e. adopting a footprint perspective including impacts generated abroad by the domestic consumption,
- Be expressed in absolute (total) and relative (per capita) terms,
- Be adapted to the expected future size of Swiss and world population.

They must have the highest practical feasibility, taking into consideration recent works on assessments and indicators at both international level (UNEP, 2012b, 2012c, 2012a; EEA; OECD, 2012; Mudgal & Tan, 2013) and Swiss national level (Jungbluth et al., 2011; Frischknecht & Büsser Knöpfel, 2013; Frischknecht et al., 2014; FOEN, 2013).

2.1.2. Expert workshop

A workshop was organised and held in Bern in 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

[12] Demand stands for final consumption and implies a footprinting approach.

into consideration the historical contribution of Switzerland. The list of participants is provided in the annex 2 of this study.

2.2. This report

This report aims at providing a complementary perspective to existing studies by Rockström et al. (2009) and by Nykvist et al. (2013) in order to enable a better understanding of the scientific aspects of the Planetary Boundaries concept, its downscaling to the national level, as well as to improve usability and communicability.

Building on these existing studies this report provides:

A. An understanding of the limits of our planet:

1. What are the Planetary Boundaries?
2. Are the Planetary Boundaries recognised global issues?
3. How do Planetary Boundaries differ from other sets of indicators?

B. Quantitative limits and footprints for the world and Switzerland:

4. What are the global quantitative limits and are they validated?
5. What is the current global performance and is there an overshoot?
6. What is the current Swiss footprint and performance?

C. Insights on the potential uses of the Planetary Boundaries with respect to current knowledge and the robustness of computed results:

7. What are the priorities for action?

2.3. Guiding principles

This study is based on four principles in recognition of the global nature of the Planetary Boundaries and the need for their adoption by a large number of countries to make action meaningful:

1. *An international perspective* that could be easily replicated rather than a purely Swiss perspective. This is an argument in favour of preferring international datasets rather than national ones even if the global datasets are usually less precise.

2. *A better understanding of the Planetary Boundaries by a large public* in addition to scientific proposals. This leads to the computation of performance ratios for dashboarding in order to enable a rapid grasp of the situation. This necessarily involves simplifications.

3. *Setting global and national priorities based on global and national performances as well as on the current knowledge status*. This leads to proposing three types of possible actions on the Planetary Boundaries: management, communication and/or knowledge development.

4. *An objective of complementarity with existing approaches at national and international levels.* This leads to not computing some of the Planetary Boundaries proposed by Rockström et al. (2009) for two reasons: a) because their global nature is not widely recognised, e.g. Freshwater Use or b) because adopting footprinting indicators does not seem to provide additional relevant information, e.g. Stratospheric Ozone Depletion.

3. Understanding the limits of our planet

Several concepts have already been developed to raise awareness about the limits of the planet. The Planetary Boundaries are the latest one and propose a new quantitative approach for identifying the thresholds to respect in order to avoid undesired effects on the global Earth system in the long run.

This concept appears in a period in which environmental aspects continue to be problematic in many parts of the world as well as globally. In the UNEP Global Environmental Outlook (UNEP 2012b), the review of progresses made since 1992 showed that the majority of environmental issues have even worsened between 1992 and 2012.

3.1. Awareness of global changes and limits

Global change

Current global environmental change is the consequence of interconnected causes occurring at a global scale: demographic growth (world population doubled from 1968 to 2011 (UNPD, 2011)), technological and economic development (real GDP tripled since 1980 (UNEP Environmental Data Explorer[13]), combined with insufficient environmental governance (the first agreements on the global environment date from the early 1970's, e.g. the RAMSAR convention in 1971).

The resulting increase in demand for natural resources and increase in releases into the environment has generated significant negative impacts on the physical and biological environment. The modification of the physico-chemical composition of the atmosphere leads to climate change, other processes lead to soil degradation, ecosystems decline and degradation, biodiversity loss, air and water pollution, to mention some of the main issues (UNEP, 2012c).

The 1970's as a turning point

This is far from new findings since such issues have already been studied since the 1950's, e.g. by Kenneth Boulding[14]. The view of a finite planet became prominent in the 1970's as exemplified by the first photo of planet Earth taken from Apollo 17. 1972 can be seen as a turning point with the first civil satellite monitoring the Earth's land cover (the Earth Resources Technology Satellite (ERTS-1), later renamed as Landsat) or the United Nations Conference on the Human Environment in Stockholm eventually leading to the creation of the United Nations Environment Programme (UNEP). The importance of the 1970's with respect to the global environment is also supported by the fact that it is the period in which human consumption of natural resources presumably reached the renewable capacity of the planet (as computed with the ecological footprint methodology) for the first time (WWF, 2014).

Natural resources are limited and limiting human development

In this context, Meadows and others applied a new approach for understanding the dynamic behaviour of complex systems with a simplified Earth model. They fed the model with

[13] http://ede.grid.unep.ch

[14] See the essay by K. Boulding (1966), The economics of the coming spaceship earth, http://dieoff.org/page160.htm

different inputs such as the accelerating industrialization, rapid population growth, widespread malnutrition, depletion of non-renewable resources, and a deteriorating environment. Their conclusions were published in "The Limits to Growth" (Meadows et al., 1972). The main argument of the report is that biosphere has a limited ability to absorb the impacts of human population and economic growth. They forecasted a global collapse at the latest in 2100, if humans do not achieve sustainability in their use of natural resources. These conclusions were heavily criticised by many economists for neglecting the theoretically unlimited growth potential of know-how, as well as technological progress, new discoveries of resources in the future, and market reactions. Yet, there were other economists who supported the need for zero growth. For example, Georgescu-Roegen (Georgescu-Roegen, 1971, 1979) applied Newton's laws of thermodynamics to economics in order to demonstrate the impossibility of continuous economic growth based on extraction of natural resources. Other mathematical models were used to criticise the neoclassical growth theory (Nelson & Winter, 1982).

Used by population biologists since the mid-twentieth century, the concept of "carrying capacity" is also addressing the idea of limited resources, focusing on the population (number of individual elements) that a given area can support in the long term.

In order to go beyond this neo-Malthusian model of demographic limits and fixed resources, Ehrlich et al. (1971) proposed the IPAT equation, which formalises the idea that impacts to 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) (Ehrlich & Holdren, 1971).

Sustainable development, global science

The sustainable development concept gained broad recognition in the late 80's, after the Brundtland Report (United Nations, 1987). The concept led to the development of sets of indicators that aimed at synthetically monitoring social and economic development as well as the quality of the environment, e.g. the CSD Indicators of Sustainable Development[15].

A new impetus for a global perspective emerged in the mid-1980s. The Chernobyl nuclear accident (1986) and the discovery of the ozone layer hole (and subsequent signing of the Montreal Protocol in 1987) contributed to global awareness 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, decline of biodiversity, are global and can threaten the ecosystems that sustain human well-being (Turner II et al., 1990).

In 1990, the Inter-Governmental Panel on Climate Change (IPCC) published its first report (IPCC, 1990) and in 1992 the United Nations Conference on Environment and Development (UNCED) was held in Rio. These events contributed to raising awareness of global environmental issues within governments and amongst the wider public, and led to the three main global conventions related to biological diversity, climate change and desertification.

Measuring the global environment: footprints and monitoring

In the early 1990, the ecological footprint methodology was developed (Rees, 1992; Wackernagel, 1994). The ecological footprint expresses 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 footprint is then

[15] www.un.org/esa/sustdev/natlinfo/indicators/factsheet.pdf

compared to the biocapacity of the Earth (the reference value, or the limit, in this case) to provide a very synthetic perspective of the number of Earths needed to sustain current lifestyle and consumption patterns.

While very powerful for communication, the approach was criticised by the scientific community (Fiala, 2008). The computation of the footprints based on the Planetary Boundaries concept can be seen as an extension of the ecological footprint original idea.

Environment in development policies

In 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 2000-201.[16] However, the environmental aspects were not sufficiently reflected and the aggregation of environmental aspects in one goal did not allow for its proper integration with the social and economic dimensions.

Based on a decision taken at the Rio+20 Conference[17] in 2012, the current discussion on the post-2015 agenda is aiming at setting Sustainable Development Goals (SDGs). The SDGs shall be universal in nature, they shall integrate social, economic and environmental aspects and look at how human development can continue in a sustainable manner. Related measurable targets are discussed along with the definition of goals. A concrete proposal from the so-called Open Working Group on SDGs is currently discussed and expected to be adopted at the UN Summit in New York in September 2015.

3.2. The concept of environmental limits

In view of the various concepts addressing the global environmental impacts and the limited capacities of the Earth system to absorb them, it is necessary to make a clear distinction between three categories of terms:

a) Limits (carrying capacity, limit to growth, Planetary Boundaries)
b) Policy targets (MDGs, SDGs, GEGs[18])
c) Footprints (carbon footprint, water footprint, land use footprints, etc.)

While the three categories are quantitative in nature and are measurable on the basis of quantitative indicators, they express different concepts and objectives.

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).

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[16] http://www.un.org/millenniumgoals/

[17] The conference is the third Earth Summit, following the 1992 Earth Summit in Rio de Janeiro and the 2002 Earth Summit in Johannesburg.

[18] GEGs are internationally agreed environmental goals and objectives drawn from existing international treaties and non-legally binding instruments (http://geg.informea.org/about).

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.

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.

Footprints

Footprint indicators are tools for measuring actual environmental impacts in a synthetic manner (Hoekstra & Wiedmann, 2014) going beyond the classical territorial perspective. 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) (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010)[19]. Data is however still scarce outside Europe and the aggregation of data into meaningful figures requires generally large amount of work.

3.3. The concept of Planetary Boundaries

3.3.1. Description of the concept

Physical limits of the global Earth system

The Planetary Boundaries, a concept proposed by Rockström et al. (2009), belong to the first category (i.e. limits) of the above-mentioned terms. The aim of the Planetary Boundaries concept is to identify a series of physical limits of the global Earth system.

Starting from the observation that the current geological era (the Holocene, from about 12’000 years) has been highly suitable for human development, Rockström et al. (2009) have attempted to synthesise the fundamental global environmental conditions favourable to further human development. The stability of the climate has, for example, been a key factor

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

for the diffusion of agriculture, which in turn profoundly transformed the world by converting large portions of natural land, and by supporting economic and demographic growth.

The Planetary Boundaries are a quantification of this “Safe Operating Space” circumscribed by nine limits. The original Planetary Boundaries are presented in annex 1.

Acceptable levels of impacts

A Planetary Boundary can be defined as a “human-determined acceptable level of a key global variable” (Carpenter & Bennett, 2011). The Planetary Boundaries concept is not about saving the Planet (life will continue after humanity), but is about limiting the adverse impacts of human activities to a level that still enables the system Earth providing the essential functions for humanity in the most predictable and stable manner possible.

Crossing the suggested limits would substantially change the way the Earth system is functioning. This would lead to a drastic change in human societies by disrupting some of the ecological bases underlying the current socio-economic system. According to Rockström & Sachs (2013) this would potentially lead to a significant reduction of the standard of living of the most developed countries, higher inequalities, instability and violence.

Not about material and energy resources

The Planetary Boundaries do not focus on resources in the sense of material and energy resources but on the functioning of the global Earth system. That is why some central aspects generally covered in sustainable development or environmental assessments, such as energy or material consumption, are not conceived explicitly as Planetary Boundaries. Only their impacts are taken into account in terms of global processes such as climate change or land cover change.

3.3.2. Overview of Earth System processes considered

The Earth System processes considered in this study are:

1. Climate Change
2. Ocean Acidification
3. Stratospheric Ozone Depletion
4. Nitrogen and Phosphorus Losses
5. Atmospheric Aerosol Loading
6. Freshwater Use
7. Land Cover Anthropisation (called “land use” in Rockström et al. (2009))
8. Biodiversity Loss
9. Chemical Pollution

The Earth System is an integrated system and the Planetary Boundaries are thus all related in a way or another. Some Planetary Boundaries are however more tightly linked. Climate Change and Ocean Acidification are both related to emissions of carbon dioxide (CO_2). Land Cover Anthropisation is related to Climate Change because it focuses on the stock of carbon within vegetation as well as on albedo. Land Cover Anthropisation is also related to

Biodiversity Loss because the type of land cover influences the biodiversity potential. Freshwater Use, the Nitrogen and Phosphorus Losses are all related to water. Atmospheric Aerosol Loading and Chemical Pollution are related to air pollution, by particulates and chemicals respectively. Chemical Pollution also concerns water, soil and the biosphere.

The separation in nine limits proposed by Rockström et al. (2009) is a simplification that can be adopted in this early stage of the quantification of the boundaries. But the known interrelations between the Planetary Boundaries call for a more holistic approach in the future.

Some of the limits proposed by Rockström et al. (2009) for these processes were first guesses and two Planetary Boundaries were not quantified (Chemical Pollution and Atmospheric Aerosol Loading). The level of uncertainties is high in terms of selecting the relevant indicators as well as of setting sound threshold values, by calculation or estimation. The linkages between the different Planetary Boundaries increase the uncertainties since crossing of one of the limits may drastically reduce the limit of the other Planetary Boundaries.

3.3.3. Differences with the classical themes of the Swiss environmental policy

The Planetary Boundaries do not cover all usual environmental themes of the Swiss environmental policy. The nine Planetary Boundaries are covering some of the classical themes of environmental assessments[20] (air, biodiversity, chemicals, climate, forest and wood, landscape, water). Other themes (such as biological safety, major accidents, natural hazards or noise) are however not covered because they are not directly related to the functioning of the global Earth System. For instance, noise is a problem for public health, but it does not jeopardise the natural environment on a global scale.

The definition of some Planetary Boundaries may also differ from the definition of themes existing at national level, even if the naming is similar. For instance, Land Cover Anthropisation is not about the management of forests or land use in Switzerland: it is about carbon sequestration, albedo and biodiversity at the global level.

[20] http://www.bafu.admin.ch/umwelt/indikatoren/index.html?lang=en, download: 28.10.2014

4. Distributional principles for defining the share of Switzerland

The Planetary Boundaries are limits at a global scale. Their respect or potential overshoot is the cumulative result of the actions of all countries and people on Earth wherever environmental impacts are generated.

The objective of setting limits per country from the global limits makes it necessary to identify the exclusive share of the planet allocated to each country, e.g. Switzerland. An exclusive share means that the shares allocated to all countries sum up to the global limit. It should be noted that, even if national limits are set, overshoots by some countries might still be compensated on the global level by undershoots in other countries.

An overview of potential principles and approaches for the allocation to countries is presented below.

4.1. General principles

Planetary Boundaries can be understood as the maximum quantity of resources that could be used. Resources are usually allocated through the application of legal right or economic transactions. Several entities can be the beneficiaries: countries, people as well a commercial and non-commercial organisations. There is however currently no recognised mechanism for the allocation of global resources nor for the allocation according to footprinting approaches.

In addition, once a so-called 'initial allocation' is performed, supplementary questions can be asked to identify the mechanisms for a so-called 'secondary allocation'. A secondary allocation would deal, for example, with questions related to the right of, and ways for, beneficiaries to trade the allocated shares, for example between countries or over time. In this study, the focus is on the initial allocation only.

4.2. Equal share per capita as starting point

The first conversion of the Planetary Boundaries to the national level has been done for Sweden. Nykvist et al. (2013) apply a so-called "equal share per capita". This means dividing the global limit by the global population: the same rights on natural resources are allocated to each inhabitant of Earth, i.e. anyone has the same share of resource use or rights for pollution.

This approach is easy to understand and to compute but has certain drawbacks:

1. The different needs of the inhabitants of Earth and the different amount of resources needed for the satisfaction of these needs is not considered. Living in Northern countries requires, for example, heating houses for a longer period than in Southern Europe. In addition, the perception of what is required varies in each culture.
2. Past emissions, respectively use of resources, are not considered while they differ to a great extent between countries.
3. The role of countries as the current main way to allocate resources between people is not considered.

4.3. Refined allocation approach

A broadly accepted way to go beyond the equal share per capita approach is currently lacking. This report adopts thus a pragmatic approach since justification for the allocation can be based on various grounds, e.g. ethical, political, economic or legal ones and the choice of the right rationales goes beyond this study.

The reader may refer, for more information on this issue, to the relevant literature on burden sharing, e.g. Shue (1999) or publications related to the Greenhouse Development Rights (GDR) Framework[21] and the Contraction & Convergence (C&C) model[22].

The approach applied in this report is based on the principles of Sustainable Development[23]: It assumes that past, current and future populations of Earth have, by definition, similar rights to resources. This approach adds thus a temporal dimension to the equal share per capita approach, taking into account historical and future resource use where feasible and relevant. A second distinction is introduced to consider the role played by countries in the allocation of resources. The approach is further developed in chapter 5.3.2.

[21] http://gdrights.org/publications/. GDR is a framework for defining effort sharing 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.

[22] http://www.gci.org.uk/. C&C 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).

[23] http://www.un-documents.net/ocf-ov.htm ("Our Common Future, From One Earth to One World", see chap I.3 Sustainable Development).

5. Approach

A three-stage approach is applied in order to a) better characterise the Planetary Boundaries and to understand which limits can effectively be currently quantified, b) to compute global and national limits as well as footprints, and c) to suggest priorities for action. The general approach of this study is summarised in Figure 3. Each one of the six steps is then described in a specific section of this chapter.

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

Figure 3. General approach of this study in six steps.

5.1. Identification of Planetary Boundaries with accepted global limits

Planetary Boundaries cover phenomena with varying spatial scopes. Applying a classification based on physical/biological aspects (unrelated to policy), some of the environmental aspects considered can be qualified as phenomena with a global scope: this is the case, for example, of climate change because it is the total amount of greenhouse gas emissions that is important, not their location. Some other phenomena are rather local or regional in scope: the local/regional conditions play a key role in the assessment of the environmental issue.[24]

While the existence of a global limit for Planetary Boundaries with a global scope is straightforward, the existence of a global limit for the environmental issues with a regional scale is much more debated. Planetary Boundaries can thus be classified in three groups:

1. *Global issues with global limits*: The described phenomenon is global by nature and a global limit exists by definition. This is the case for Climate Change, Ocean Acidification, and Stratospheric Ozone Depletion.
2. *Regional issues with a global limit*: The described phenomenon is at regional scale. A global limit can be identified because cumulated effects of the phenomenon have impacts on a global scale. This is the case for Nitrogen and Phosphorus Losses, Land Cover Anthropisation and Biodiversity Loss.
3. *Regional issues with a regional limit only*: According to current knowledge and data, the described phenomenon is at regional scale. A physical global limit cannot be identified at the time being. This is the case for Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution.

[24] The term 'regional' does not preclude that regional pollutants can travel or be transported (due to trade) over long distance and can be transboundary, i.e. being a global issue. This is for example the case for mercury. The regional nature nor precludes that action is not required from a global policy perspective. Some of these regional environmental issues are thus subject to international protocols like the Convention of 13 November 1979 on Long-Range Transboundary Air Pollution.

The classification of the nine Planetary Boundaries is presented in Table 1. For more information, refer to the detailed description per Planetary Boundary (chapter 6):

	Group	Scope	Limit
1. Climate Change	1	global	global
2. Ocean Acidification	1	global	global
3. Stratospheric Ozone Depletion	1	global	global
4. Nitrogen and Phosphorus Losses	2	*regional*	global
5. Atmospheric Aerosol Loading	3	*regional*	*regional*
6. Freshwater Use	3	*regional*	*regional*
7. Land Cover Anthropisation	2	*regional*	global
8. Biodiversity Loss	2	*regional*	global
9. Chemical Pollution	3	*regional*	*regional*

in bold : Planetary Boundaries quantified in this study

Table 1. Group, scope and type of limit of the Planetary Boundaries.

In the rest of this report, the Planetary Boundaries with a global limit will be further studied, except for the Planetary Boundary Stratospheric Ozone Depletion by the application of the fourth guiding principle, i.e. the objective of complementarity with existing approaches at national and international levels. Ozone depleting substances are currently phased out[25] by the Montreal Protocol signed by 197 countries. Only few countries are concerned for their production and there is thus no clear insight that a footprint-based approach could further improve the management of this issue.

Since, by definition, Planetary Boundaries are phenomena with a global limit, the Planetary Boundaries viewed as regional issues only, i.e. without any global limit will not be developed in this report:

- *Freshwater use*: The FOEN experts consider it as a regional issue with a regional limit only. There is a lack of sufficient information that a global limit does effectively exist outside of the framework of the Planetary Boundaries established by Rockström et al. (2009).[26]
- *Atmospheric Aerosol Loading* and *Chemical Pollution*: Rationales are currently lacking for setting a potential limit. This statement is similar to the conclusion in Rockström et al. (2009) and Nykvist et al. (2013).[27]

[25] Target value = 0.

[26] Should this Planetary Boundary be categorised as a global limit, a water scarcity indicator like the Water Stress Index (Pfister et al., 2009), relating water use to local conditions, would be a better proposal than a single indicator of total water use (Rockström et al., 2009a) or water withdrawal (Nykvist et al., 2013). A limit would be computable based on existing water scarcity scales, like the one proposed by OECD. (OECD, 2004)

[27] Should the scope of these Planetary Boundaries be considered as global in the future due to new findings, the global limit and footprints will be computable for atmospheric aerosols since indicators, e.g. PM10 and PM2.5, are well established and continuously monitored. With respect to chemical pollution and according to FOEN experts, the list of chemicals that could be included in the indicator is less clear. Some chemicals like POPs and mercury should probably be phased out in the long-term while for other heavy metals (e.g. cadmium and lead), an assessment based on the Planetary Boundaries concept could make sense.

5.2. Selection of indicators

Selecting the indicator representing a Planetary Boundary is a prerequisite to the computation of limits and footprints. During the selection process, three aspects are balanced, covering both the conceptual and empirical levels as shown in figure 4:

a. The representativity of the indicator with respect to the Planetary Boundary definition.
b. Data quality and availability for computing the global and national limits.
c. The possibility to compute national values through footprinting approaches.

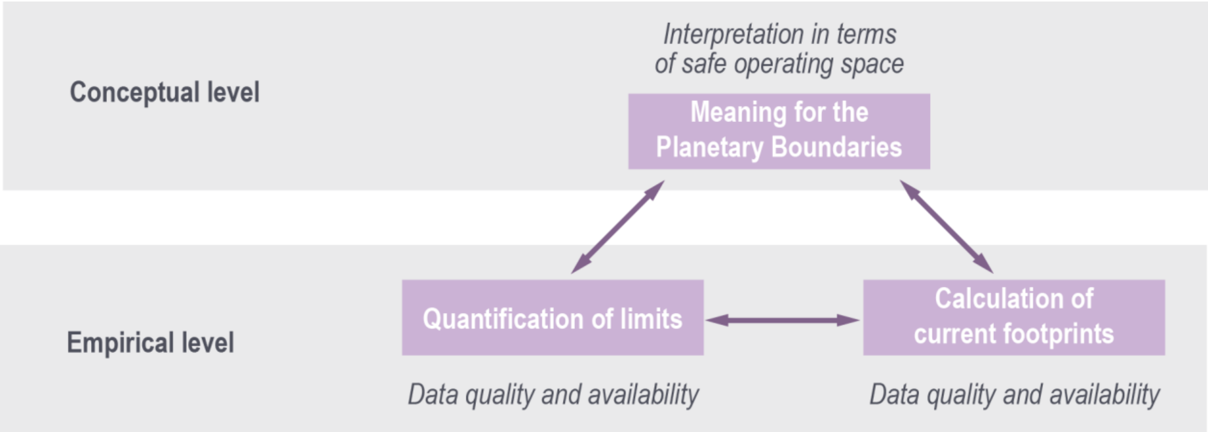


Figure 4. Conditions for the selection of indicators.

The level of representativity of the indicator with respect to the Planetary Boundary definition is assessed in a qualitative way with the help of the DPSIR framework (EEA, 2005). This framework provides a synthetic perspective to assess environmental processes and their relationship with human activities:

- *Driving Forces* (D) are the human activities generating the Pressures.
- *Pressure* (P) is the measure of the inflows or outflows modifying the State.
- *The State* (S) of the environment represents its status and quality.
- *Impacts* (I) are the consequences of changes of the State (e.g. health problems).
- *Responses* (R) are the modifications applied by society to modify the impacts.

An indicator at the State level seems the closest to the essence of a Planetary Boundary. Such kind of indicators are however not easy to monitor or compute for all Planetary Boundaries. In addition, the relationship between State(s) and Pressures as well as Driving Forces cannot be quantified for all of them. This is however essential to enable actions through Responses.

In this project the selected indicators are at the level of the State in the DPSIR framework unless a) data is lacking at this level, or b) scientifically valid rationales enable to go one (Pressures) or two (Driving-Forces) levels up the chain. An example related to climate change explaining the links between potential indicators is presented in Figure 5.

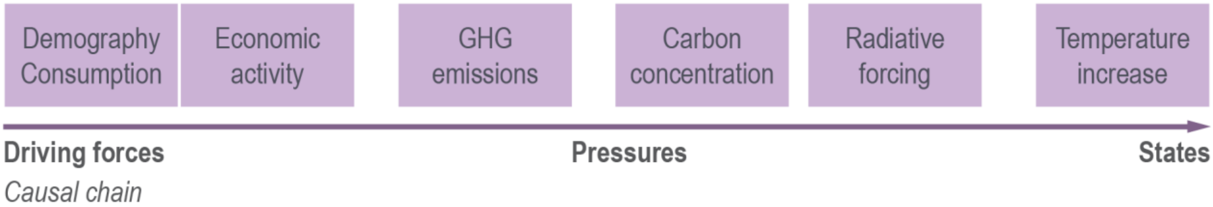


Figure 5. DPSIR framework: the example of climate change.

The indicators selected in this report are presented in Table 2, with information on their position in the DPSIR framework. The rationales for selecting these indicators are detailed per Planetary Boundary in the methodological parts of chapter 6.

	Indicator	DPSIR
1. Climate Change	GHG emissions (tCO_2 eq. per year)	Pressure
2. Ocean Acidification	Carbon dioxide emissions (tCO_2 per year)	Pressure
3. Stratospheric Ozone Depletion	-	-
4. Nitrogen Losses	Loss of reactive nitrogen to the environment (Kg N per y)	Pressure
Phosphorus Losses	Use of fertilizer with phosphorus (Kg P per y)	Driving-Force
5. Atmospheric Aerosol Loading	-	-
6. Freshwater Use	-	-
7. Land Cover Anthropisation	Share of anthropised land (%)	State
8. Biodiversity Loss	Average biodiversity damage potential (%)	State
9. Chemical Pollution	-	-

Table 2. Selected indicator per Planetary Boundary.

5.3. Computing the limits

Once a representative indicator is identified, two limits are to be computed per Planetary Boundary: the global limit and the country limit, i.e. the share of the global limit allocated to a particular country.

5.3.1. Global limits

Due to the different maturity of the issues covered by the Planetary Boundaries, several sources have been selected to identify the global limits. They are presented here by order of preference:

1. Value taken from the literature, widely recognised
2. Value computed based on information from an international agreement or an international policy process
3. Value not widely accepted, taken from - or computed based on – a limited number of references from the literature

The types of source per Planetary Boundary are summarised in Table 3:

	Source for the global limit
1. Climate Change	1
2. Ocean Acidification	3
3. Stratospheric Ozone Depletion	-
4. Nitrogen and Phosphorus Losses	3
5. Atmospheric Aerosol Loading	-
6. Freshwater Use	-
7. Land Cover Anthropisation	2
8. Biodiversity Loss	2
9. Chemical Pollution	-

Table 3. Type of source for the global limits.

5.3.2. Downscaling limits to countries through allocation

In this report, a pragmatic approach to downscaling is applied based on the principles of Sustainable Development (see chapter 4 for more information on the principles) and by providing answers to two questions having a strong influence on the allocation mechanism:

a) What is the object of the allocation: a yearly budget or a budget over time?
b) What are the entities considered as the beneficiaries of the allocation: countries or people?

5.3.2.1. Time perspective of the allocation

The selected indicators are modelled in two possible ways: either as yearly budgets or as budgets over time. The selection of one or the other way is purely related to the selected indicator and not to any other rationales: all Planetary Boundaries could be modelled in both ways.

Yearly budget

In the case of an indicator representing a yearly budget, the same amount is available every year as long as the capital generating this flow is preserved. This is the case, for instance, for the Planetary Boundary Nitrogen and Phosphorus Losses. This case can be viewed as a situation of steady state: each year can be considered independently. The yearly flow is totally allocated to the yearly total number of beneficiaries: neither the past nor the future is taken into account because the use of the flow cannot be delayed to a later period.

Budget over time

In the case of an indicator representing a budget over time, a finite amount is shared among past, current and future beneficiaries. The rate of use of the budget is key since the budget cannot be renewed: it can be used rapidly or delayed but when the whole budget has been used, the resource cannot be used anymore. Time is a key variable in this case since:

- The size of the budget is determined by setting a starting date (the reference year).
- The period of availability (and thus the average yearly rate of use) is determined by setting an end date.

By setting a starting date in the past, the historical use of the budget can be accounted for. By setting an end date in the future, the use of the budget can consider present and future beneficiaries.

Considering the past and the future

In this study, the past is considered for those Planetary Boundaries for which at least one of the two following pre-requisites is met to define a reference year:[28]

- Rights have been entitled or responsibilities recognised in the past. This can have happened either explicitly, e.g. through an international agreement at a specific date, or implicitly, as the situation was such, that the need for action was clear.
- Widespread knowledge was available in the past.

To consider the future, two aspects are implemented:

- The end year, i.e. until when future entities are included in the calculations.
- An even allocation of the budget between beneficiaries over time.

For budgets over time, global yearly allowance can differ as long as the cumulative allowance, i.e. the total budget, is respected. Assumptions related to technology or affluence as in the I=PAT model[29], developed originally by Ehrlich et al. (1971), could be used to identify varying yearly allowances. Improving the efficiency of technology can, for example, lead to more stringent targets in the long run compared to the short run based on the assumption that cleaner technologies will be developed and that temporary overshoots and/or additional risks are acceptable, since such technology could be used for future massive reductions of resource use. In this report, there is no such assumption with regard to technology or to the type of reduction pathway. The only assumptions to model the future are based on the equal share per capita approach (for global limits) and the hybrid-allocation approach (for national limits), as described in the rest of this chapter.

Classification of the Planetary Boundaries with respect to the time perspective

The classification of the Planetary Boundaries with respect to the time perspective of the selected indicator is presented in Table 4.

	Type of indicator
1. Climate Change	budget over time
2. Ocean Acidification	budget over time
3. Stratospheric Ozone Depletion	-
4. Nitrogen and Phosphorus Losses	yearly budget
5. Atmospheric Aerosol Loading	-
6. Freshwater Use	-
7. Land Cover Anthropisation	yearly budget
8. Biodiversity Loss	yearly budget
9. Chemical Pollution	-

Table 4. Time perspective of the selected indicator per Planetary Boundary.

[28] A more comprehensive discussion on possible political and ethical rationales for setting a reference year is beyond the scope of this project.

[29] The I=PAT model explains environmental Impact (I) as a function of Population (P), Affluence (A) and Technology (T).

5.3.2.2. *Beneficiaries of the allocation*

People as final beneficiaries

People are ultimately the *final* beneficiaries of any possible allocation of resources. In the equal rights per capita approach, people are selected as the *direct* beneficiaries of the allocation.

Selecting people as the *direct* beneficiaries of the allocation has however a strong disadvantage: the evolution of the share per capita, and thus the share per country, is influenced by global demographics (Earth population). Over time, the national share of countries with high demographic growth will increase compared to countries with low demographic growth.

Selecting people as the *direct* beneficiaries is thus not considering the fact that a globally growing population is one of the key causes of the increased pressure on Earth. This approach also does not consider that indirect socio-economic allocation pathways, e.g. through countries, commercial and non-commercial organisations, are usually the rule.

Countries as indirect allocation pathway

When countries are considered as allocation pathways, resources are *indirectly* allocated to people through the intermediary of countries. This is the most usual case: countries are the classical actors in international relations and are the usual entities dealing with international agreements concerning global issues. Countries are autonomous with respect to internal affairs and are one of the main determinants of the economic, political and cultural evolutions of regions and people.

An *indirect* allocation to people through countries has two advantages.

- First, an *indirect* allocation through countries reduces the role played by global demographics in the allocation. The allocation per capita evolves according to the internal demographics of each country. Countries with high demographic growth, for example, will have a decreasing share per capita over time. With this approach, the per capita share is thus not equal in the long term among people of different countries unless internal demographics evolve similarly.
- Second, an *indirect* allocation through countries enables considering the past (for the allocation of budgets over time). By fixing a country share at a past date, this enables the computation of the share of the budget over time already use by the people of a country.

An *indirect* allocation to people through countries allows thus reducing the second and third drawbacks (see chapter 4.2) of the equal share per capita approach. An *indirect* allocation can thus result in a largely different allocation than a direct one.

Considering the influence of age on needs

To reduce the first drawback (see chapter 4.2) of the equal share per capita approach, an approach considering the different needs of humans has been explored in a simple way. Applying a principle used in economic studies, the population has been split in two age groups: children and adults. Using economic information from the OECD equivalence scales (i.e. the proportional resources needed for each additional member of a household), children have been considered to have an economic demand that is equivalent to 50 % of the demand of adults in terms of expenses (OECD, 2013). Extending this reasoning to nonfinancial resources, the need of children for resources can be set as half the needs of an adult. In this approach, the allocation is thus shifted away from countries with a large children base compared to the equal share per capita approach.

Since the age structure of the Swiss population (proportion of children: 15% in 2015, 19% in 2050) is increasingly similar to the age structure of the world population (proportion of children: 26% in 2015, 21% in 2050), the interest of this approach is however low for Switzerland compared to the added complexity. This approach has thus not been implemented in this report. Further research should however be performed to better understand the influence of this proposal for other countries over the long run.

5.3.3. Downscaling approaches applied in this report

Two approaches

Two downscaling approaches are applied in this report to compute the national limits:

1. An *equal share per capita* approach, representing a direct allocation of the global limit to people.
2. A so-called *"hybrid-allocation"* approach, representing an indirect allocation of the global limit by allocating the global limit to countries first (based on a ratio calculated for a fixed reference year), then to people, per country.

   The hybrid-allocation approach recognises that:

   - People are the ultimate beneficiaries of global resources.
   - Countries are the primary allocation mechanism of resources in the current international political system.
   - Global demographics play a key role for respecting the limits of the Planet.

The equal share per capita approach

The equal share per capita is equivalent to the global limit per capita. This global limit per capita is computed differently for yearly budgets and budgets over time.

For indicators considered as *yearly budgets* (e.g. the area of anthropised land), the global limit per capita is computed by dividing the global limit by the yearly global population.

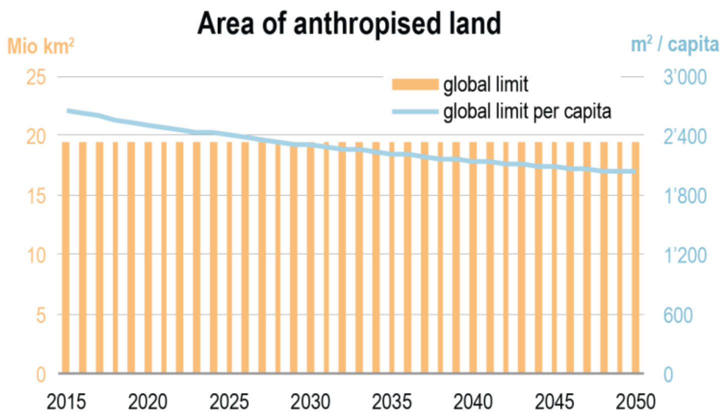


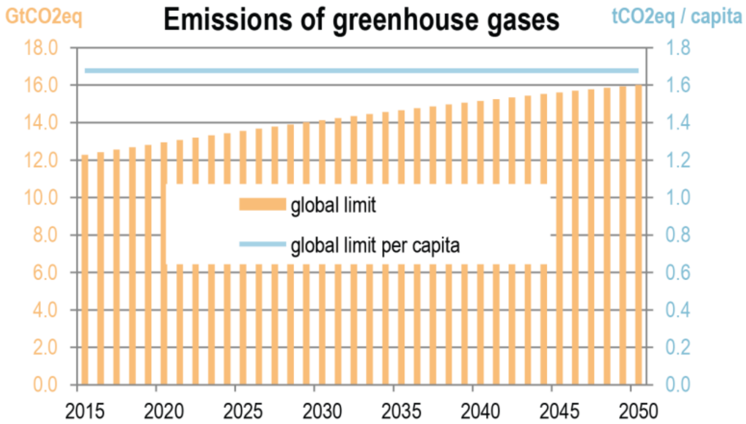
Figure 6. Yearly budgets: global limit and limit per capita.

The global limit is thus identical every year.

The limit per capita evolves each year according to the yearly global population [30] (a higher global population reduces the limit per capita).

[30] Population data sources: United Nations Population Division (UNPD, 2011), estimation of the world and country population until 2050, then a stable population is assumed until 2100.

For indicators considered as *budgets over time* (e.g. emissions of greenhouse gases), the global per capita limit is computed by distributing the remaining budget in 2015 evenly among all inhabitants of Earth until 2100. The budget is thus assumed exhausted in 2100. The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2011) 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. Then the global limit for each year is computed by multiplying the limit per capita (constant over the period) by the yearly global population.



The global limit per capita accounts for the use of the budget by present and future populations: the global limit per capita is fixed over the period, i.e. it is identical every year.

Consequently, the global limit varies each year, according to the yearly global population.

Figure 7. Budgets over time: global limit and limit per capita.

The hybrid-allocation approach

The hybrid-allocation approach is computed in the following way:

- The *country share of a Planetary Boundary* is defined as the share of the country population relatively to the global population at a reference date. The share of the resources available per country is fixed at this date.
- For *yearly budgets*, the yearly limit per capita is computed by dividing the previously fixed country resources by the yearly population of the country. The yearly limit per capita varies thus each year while the limit per country is fixed.
- For *budgets over time*, the yearly limit per capita is computed once by allocating the previously fixed country resources evenly between all the inhabitants of a country until 2100. The yearly country limit is computed as the sum of the limits per capita of the country. The yearly country limit varies thus each year while the per capita limit is fixed.

At the reference date, the limit per capita computed with the hybrid-allocation approach is thus similar to the per capita value obtained with the equal share per capita approach. For the following years, the limit per capita computed with the hybrid-allocation approach evolves per country, according to internal demographics. It can thus differ from the equal share (global limit per capita) value.

To consider past knowledge/rights/responsibilities, a reference date is selected in the past when possible to compute the country share.

For Switzerland, applying the hybrid approach to indicators considered as *budgets over time*, the remaining Swiss budget over time in 2015 is allocated evenly between all inhabitants of Switzerland until 2100. The Swiss limit per capita is thus fixed over time and the Swiss limit varies according to the Swiss yearly population. For *yearly budgets*, the Swiss limit is constant over time and the Swiss per capita limit varies according to the Swiss yearly population.

Demographic scenarios

The demographic scenarios applied for the computation of the national shares and the evolution of the per capita values is based on UN data. The United Nations World Population Prospects 2012 scenario “medium” is selected (UNPD, 2013) since it is the most probable scenario according to the United Nations and it is comparable to the Swiss Federal Statistical Office scenario “B-00-2010 high” (OFS, 2010). The different scenarios for the Swiss and World population, as well as the share of Switzerland in the World population, are presented in Table 5.

"Medium" scenario	1990	2000	2010	2020	2030	2040	2050
Switzerland (mio inhabitants)	6.7	7.2	7.8	8.6	9.5	10.2	11
World (mio inhabitants)	5 320.8	6 127.7	6 916.2	7 716.7	8 424.9	9 038.7	9 550.9
Swiss share (% of World population)	0.13%	0.12%	0.11%	0.11%	0.11%	0.11%	0.11%

Table 5. UN World Population Prospects, the 2012 Revision – “medium” scenario.

5.4. Computing the footprints

Global footprints

At a global scale, the territorial and footprint perspectives sum up, by definition, to the same total value. Since an allocation is not needed for global footprints, they can be computed with the same global data as the data used for computing the limits.

National footprints are based on models

At national scale, the territorial and footprint perspectives differ. Specific footprinting approaches, based on Life Cycle Thinking[31], are needed. Several methods exist, mainly based on bottom-up approaches, i.e. Process Life Cycle Assessment (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) or top-down approaches, e.g. Environmentally Extended Input-Output Analysis (Sue, 2009).

Data for computing the footprints

The Swiss footprints computed in this study are based on:

- The FOEN proprietary database[32] to compute the inventory of resources and emissions. The database combines officially published Swiss environmental data according to a territorial perspective with modelled environmental data for imports and exports. The environmental values for exports and imports have been computed for representative sub-sets of products and services by using ecoinvent 2.0 data (www.ecoinvent.org). The territorial values have been transformed into residential values when feasible.

[31] http://www.lifecycleinitiative.org/

[32] Available in SimaPro 7.3 CSV export/import format. The database is fully described in Frischknecht et al. (2013 and 2014).

- Life Cycle Impact Assessment approaches to convert this inventory into values compatible with the computed limits. These approaches are described in the detailed descriptions per Planetary Boundary (chapter 6).

Other data sources than the FOEN database could have been used for computing the inventory of resources and emissions: Process Life Cycle Inventory databases or multi-regional environmentally extended input-output (MRIO) models like the exiobase (www.exiobase.eu).

5.5. Assessing the performances

Taking into account overshoots, uncertainties and trends

The objective of setting performance indicators is to deliver a clear message per Planetary Boundary and enable dashboarding. Planetary Boundaries are classified into one of four categories from a categorical scale of performance according to a semi-quantitative process considering:

- *A quantitative score* computed as the ratio of a footprint over a limit.
- *A qualitative evaluation of the uncertainty* of the quantitative results for the limits and footprints. The uncertainties of the results are rather large due to a) the use of global data sets with medium accuracy in comparison with data generally used at country level, and b) the process of setting limits based on expert advices and/or policy decisions.
- *A qualitative evaluation of the trends* (past and future) of the footprint. A rapidly deteriorating situation expresses that the situation is evolving in a matter of years while a slow evolution expresses an evolution in terms of several decades.

Categories of performance

The four categories of performance are shown in Figure 7:

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
Cleary Safe	No overshoot	High	Slow evolution

Figure 8. A performance defined with four categories.

5.6. Principles for setting priorities

The short existence of the Planetary Boundaries concept implies that they have different levels of maturity. In recognition of these differences, the global nature of Planetary Boundaries as well as the Swiss international environmental policy, three possible actions are proposed:

Priority 1: a Planetary Boundary with a Clearly Unsafe or Unsafe performance at global scale should be managed.

Switzerland should promote international discussions and scientific developments on these issues even if it is not overshooting them on its own. In the case of national overshooting, national action should be taken, respectively intensified to reduce the Swiss footprint.

Priority 2: a Planetary Boundary for which the performance of Switzerland is Unsafe but a with a Safe situation at global level should be better understood to identify potential risks of a future global overshoot.

If a global overshoot is not foreseen, the Planetary Boundaries framework does not provide a justification[33] for reductions of the national footprints. In the case of a probable global future overshoot, Switzerland should devote resources to inform other countries and potentially prepare a national reduction plan.

Priority 3: a Planetary Boundary for which a limit cannot be identified yet should be set on the research agenda.

A better understanding of the potential existence of a global limit and the current global footprint as well as of the Swiss performance is required to decide if managing the Planetary Boundary is needed.

In this report, the following position is taken on the performance of the Planetary Boundaries without identified limits: the lack of currently widely recognised scientific information on a limit and its potential overshoot very probably means that this limit is currently not overshoot. This does not preclude however anything about a future potential overshoot and the speed of evolution.

[33] This does not contradict that action could be needed for other reasons, e.g. the need to respect local thresholds.

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

6.1. 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).

6.1.1. 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*.

6.1.2. Methodology

6.1.2.1. 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; Rockström et al., 2009b) 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:

a) It enables building an indicator compatible with the existing indicators applied for climate policies in Switzerland.
b) Selecting a more stringent objective 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).[34] 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.

6.1.2.2. 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 6. These values represent cumulative emissions of CO_2 equivalent and can be considered as a budget over time.

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

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

Source: IPCC, 2013

Table 6. 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*[35] *to stay below a 2°C increase by 2100 compared with pre-industrial level*, remaining emissions are 305 GtC, corresponding[36] 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[37] 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 requests 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 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

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

[36] 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).

[37] The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2011) 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.

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[38] resulting in a <u>Swiss per capita yearly limit of 0.6 tCO_2eq</u>. The Swiss per capita value is fixed over time but the yearly Swiss limit varies according to the yearly Swiss population. The resulting <u>limit for Switzerland is 4.8 $MtCO_2eq$ for 2015</u>. The value is smaller than the yearly average since the Swiss population will be larger in the future.

[38] The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2011) estimation of the Swiss population until 2050, then assuming a stable population until 2100. The sum equals 896 million people-year.

Data sources & evaluation of the indicator

The data sources for the limits and the global footprint are presented in Table 7.

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 7. Climate Change: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 8. 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 (Rockström et al 2009).
Coherence / comparability	+	
Availability of information	++	
Timely	++	

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

Table 8. Climate Change: quality assessment.

6.1.2.3. Computing current footprints

The general description of the computation of the footprints is presented in chapter 5. The specificities for Climate Change are presented here.

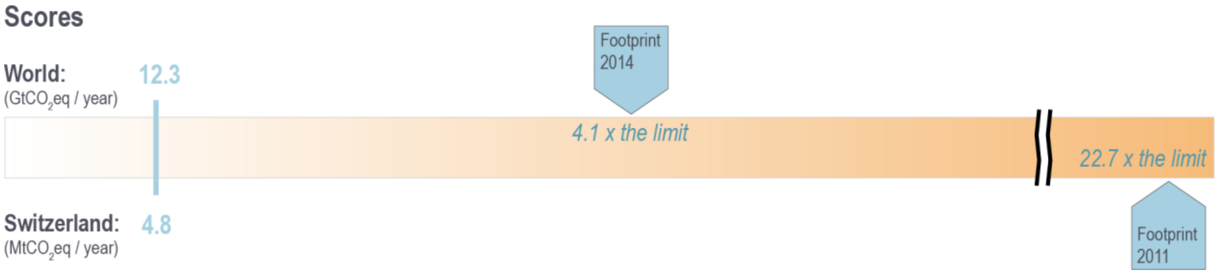
The global emissions (equivalent to the global footprint) are based on the EDGAR database (2011). Data is extrapolated for 2011 based on the average growth rate for 2006-2010.

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).

6.1.3. 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[39] are presented for 2015 limits and for current footprints (global: 2014, Switzerland: 2011) in Figure 9. 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 9. 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 of 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 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 of 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 of 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 of 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 $MtCO_2eq$.

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

- *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 $MtCO_2eq$.

6.1.4. 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 10 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.

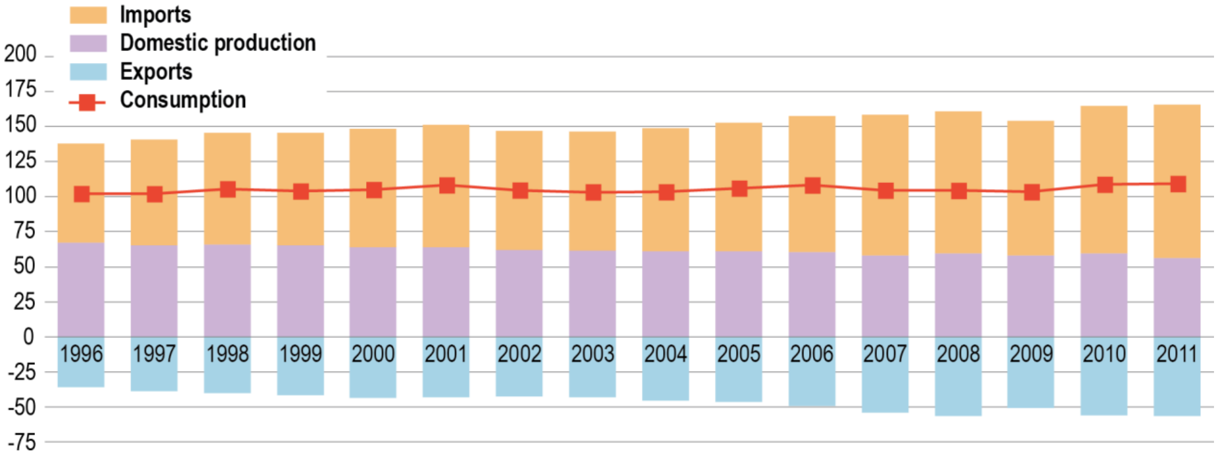


Figure 10. GHG emissions (in $MtCO_2eq.$) induced by the Swiss consumption.

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 & 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).

6.2. 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.

6.2.1. 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.

6.2.2. Methodology

6.2.2.1. 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.[40] Depending on scenarios, the pH is expected to be reduced[41] 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[42] at 450 ppm (McNeil & 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”.

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

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

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

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.

6.2.2.2. *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.[43] 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.

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

Where,

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.

[43] 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).

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[44] results in a global yearly limit per capita[45] 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 chapter 5: the Swiss share of the global CO_2 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 Ocean Acidification, this reference date is 2005 since it is the turning point in term of awareness.[46]

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

[44] The sum of inhabitants over the years is computed using United Nations Population Division (UNPD, 2011) 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.

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

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

emissions 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[47] 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.

Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are presented in Table 9. 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 AR5 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 9. Ocean Acidification: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 10. 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 10. Ocean Acidification: quality assessment.

[47] The sum of inhabitants over the years is computed using the United Nations Population Division (UNPD, 2011) estimation of the Swiss population until 2050, then assuming a stable population until 2100. The sum = 896 million people-year.

6.2.2.3. Computing footprints

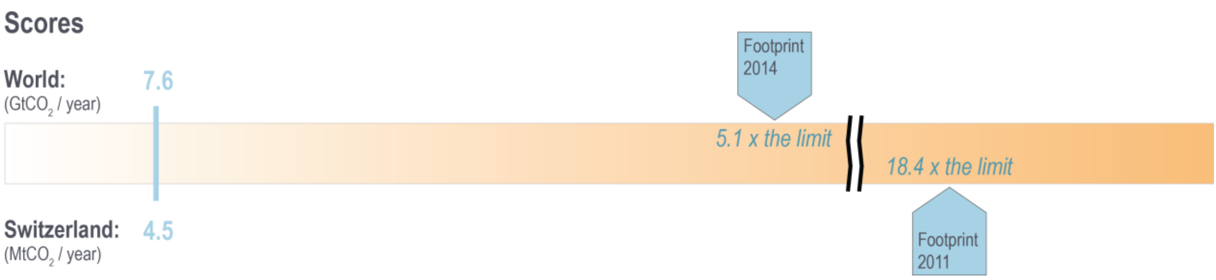
The general description of the computation of the footprints is presented in chapter 5. The specificities for Ocean Acidification are presented here.

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.

6.2.3. 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 11. 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.



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

Figure 11. 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 1.0 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 of 5.1 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 4.5 $MtCO_2$ 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 10.5 tCO_2 (Frischknecht et al. 2014), this limit is <u>exceeded for Switzerland by a factor of 18.4 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 of 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 $MtCO_2$.

6.2.4. 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 (Rockström et al., 2009b).

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.

6.3. 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[48] (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).[49]

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 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 (Carpenter & Bennett, 2011; Cordell et al., 2009; Bouwman et al., 2013; Seitzinger et al., 2010). The situation varies according to regions (Potter et al., 2010).

6.3.1. 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.

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

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

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.*

6.3.2. Methodology

6.3.2.1. 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[50], 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 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.

6.3.2.2. Selected indicators

For the Nitrogen Losses Planetary Boundary, the preference[51] 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.

6.3.2.3. 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

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[50] 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.

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

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 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[52] 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:[53]

- Atmospheric NH_3 concentrations in view of adverse biodiversity effects[54] (1-3 mg per m^3).
- Dissolved inorganic N concentrations (1-2.5 mg per liter) related to eutrophication or acidification.
- Radiative Forcing[55] (1-2.6 W per m^2).

The related computed losses and N fixations are presented in Table 11.

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

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

[52] 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.

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

[54] 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).

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

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.[56]

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[57] 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%.

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).

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

[57] 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.

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.[58] 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 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[59] (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. [60]

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

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

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

[60] 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.

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:

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

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

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

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[61] by de Vries et al. (2013), but nevertheless a

[61] 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).

key[62] 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[63] using the same dataset as by Vries et al. (2013) to compute N fixation. According to Bouwman et al. (2013) 175 Tg[64] 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 12. 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 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 & 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 12. 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[65] of losses to limits computed by de Vries et al. (2013). The global limit for agricultural N losses equal to 47.6 Tg.

6.3.2.4. Setting the global limit for Phosphorus

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}.

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

[63] 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.

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

[65] 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}).

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 scenarios are based on IAASTD[66] 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. Benett et al. (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.

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 report.

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[67] 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

[66] 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.

[67] 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.

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 report 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.

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 (de Vries et al., 2013) and (Bouwman et al., 2013, 2009) for N and (Bouwman et al., 2013, 2009) as well as (Rockström et al., 2009a) for P.

The evaluation of the indicators with respect to eight criteria is presented in Table 15 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 13. Nitrogen and Phosphorus Losses: quality assessment.

6.3.2.5. 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[68] to compute values in term of N. Footprints are computed for the years 1996-2011.

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.

6.3.3. 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 12. 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 12. 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, <u>the global footprint is 17% above the limit in 2000</u>.

[68] 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.

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.

6.3.4. 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 13 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.

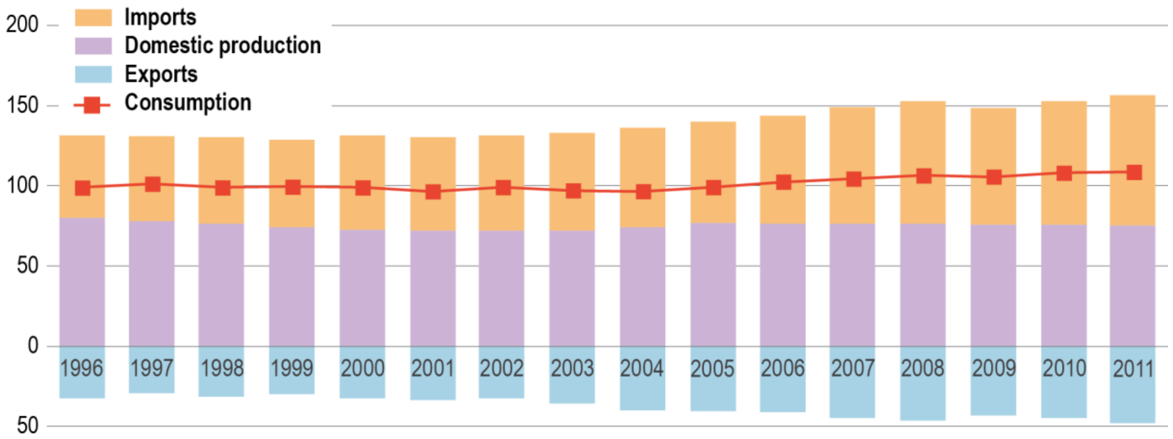

Figure 13. Nitrogen Losses (in kilotons) induced by the Swiss consumption.

The limit for the Phosphorus Losses is much less drastic (by a factor of 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.

6.4. 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).

6.4.1. 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, 2012c) 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)*.

6.4.2. Methodology

6.4.2.1. 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.[69]

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.[70]

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.

6.4.2.2. 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.

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 report. 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.

6.4.2.3. 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 report 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

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[69] 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.

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

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 report: 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[71] at 15% of the global land cover, which happens to be a value similar to Rockström proposal (based on changes in the albedo effect). <u>The global limit is equivalent to 19'362'000 km^2</u>. <u>For 2010, the global limit per capita is 2'800 m^2</u>.

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 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 <u>yearly limit for Switzerland is 21'900 km^2</u>. <u>The Swiss per capita limit is 2'770 m^2 in 2011</u>, which is very close to the global limit of <u>2'800 m^2 per capita.</u>

[71] 13% + 0.8% + 1% = 14.8%

Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are presented in Table 14. 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 14. Land Cover Anthropisation: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 15. 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).[72]

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 15. Land Cover Anthrophisation: quality assessment.

6.4.2.4. 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.

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

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, 2011) 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.

6.4.3. 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.

Results are presented for yearly limits and yearly footprints computed for 2010 (global) and 2011 (Switzerland) in Figure 14. 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 14. 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 14 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.

6.4.4. 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 15.[73] 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.

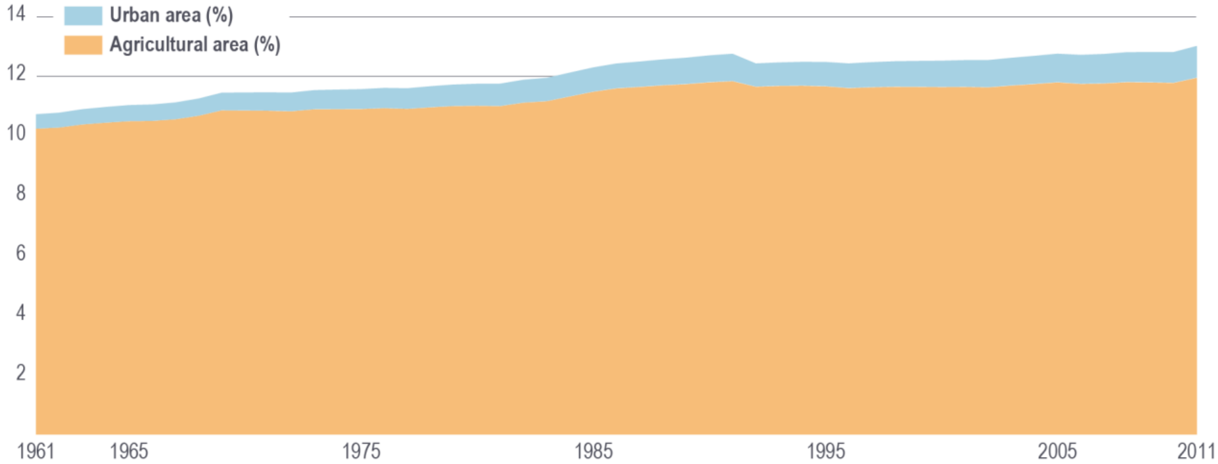


Figure 15. Anthropised Land Cover (in % of of global area w/o ice and snow) - global footprint.

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 16). The size of the footprint due to import is more than twice as large as the part of the footprint[74] 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.

[73] 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.

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

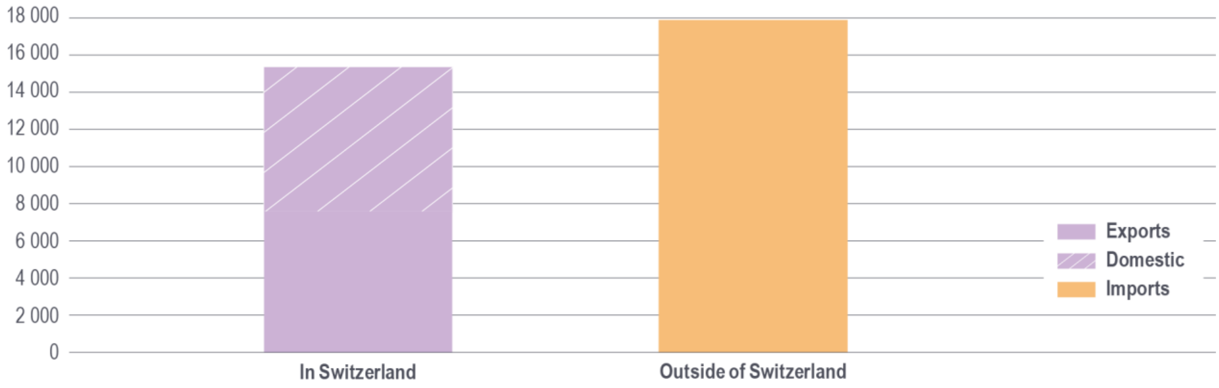


Figure 16. Anthropised Land Cover (in km²) - Swiss footprint.

In Figure 17, 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.

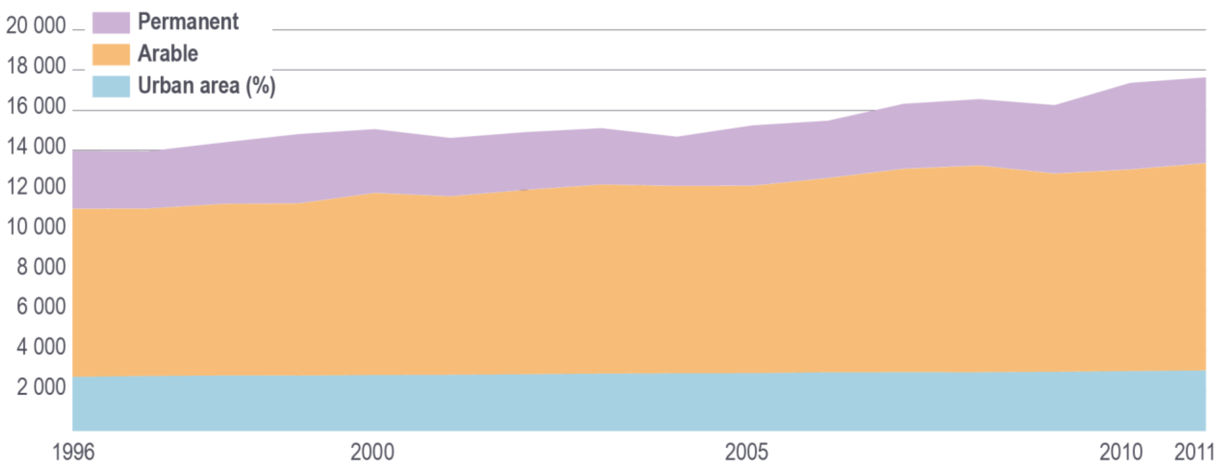


Figure 17. Anthropised Land Cover (in km²) - Swiss footprint: share per type of area.

6.5. 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).

6.5.1. 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; Hooper et al., 2005; Estes et al., 2011).

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*.

6.5.2. Methodology

6.5.2.1. 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.[75] 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).

[75] 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.

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) 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).

6.5.2.2. Setting limits

The global limit is an index (a relative value), i.e. it is not an absolute quantity (a total) that can be shared between countries and people. Therefore the same relative value is used for the global, the Swiss and the per capita limits.

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)[76] were selected:

- "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."

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

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 report and in research.

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 18.[77]

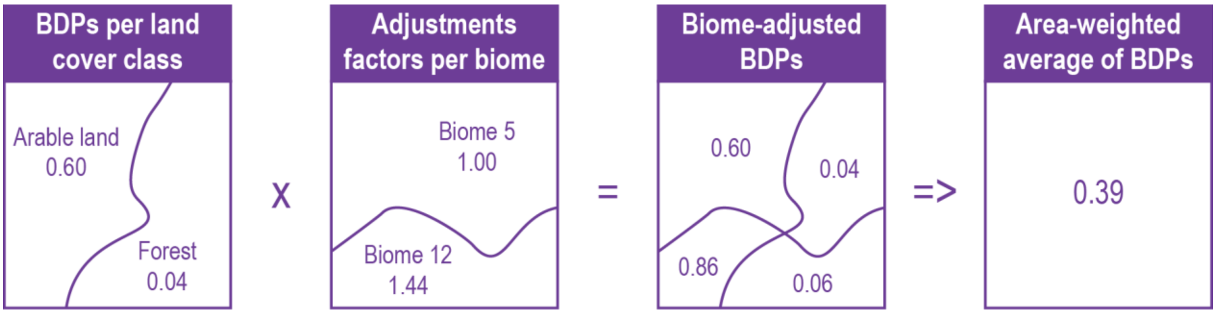


Figure 18. Biodiversity Damage Potential: schematic description.

<u>The computed current (2009) global average Biodiversity Damage Potential is 0.2</u>. 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:

[77] 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.

- 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 16, 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

Table 16. 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[78] 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.

Mace et al. (2014) propose other alternatives but data is not available yet.

[78] 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.

Data sources & evaluation of the indicator

The data sources concerning the limits and the global footprint are presented in Table 17.

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 17. Biodiversity Loss: data sources for global values.

The evaluation of the indicator with respect to eight criteria is presented in Table 18. 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 18. Biodiversity Loss: quality assessment.

6.5.2.3. *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.[79]

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.[80]

6.5.3. 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 19.

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

Figure 19. 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.

[79] The computed BDP for imports varies in a range of 0.24 to 0.27.
[80] The average BDP varies by only 1% when considering them or not.

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.

6.5.4. 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[81] 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 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.

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

- 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.

7. Synthetic results for Switzerland and the world

The summary of the global and Swiss performances for five (Climate Change, Ocean Acidification, Nitrogen and Phosphorus Losses, Land Cover Anthropisation and Biodiversity Loss) of the nine Planetary Boundaries originally defined by Rockström et al. (2009) are presented in this chapter. Priorities are then proposed based on this assessment.

The categories of performances obtained in this study are described in Figure 20. They have been built to enable delivering a clear message per Planetary Boundary (see chapter 5.5 for more information).

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

Figure 20. Performances observed in this study.

7.1. Global limits, footprints and performances

From a *global* perspective three of the six computed performances show a Clearly Unsafe situation either because of a large overshoot (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 Planetary Boundaries. While further research is needed to identify their performance, there is no evidence in the literature that the limits of these Planetary Boundaries are currently crossed.

As a result, we conclude that the **global limits are crossed for four out of nine Planetary Boundaries, with a Clearly Unsafe situation for three of them (Climate Change, Ocean Acidification and Biodiversity Loss)**, as shown in Table 19:

Performance	Planetary Boundary	Units	Limit	Current footprint	Confidence	Trend
Clearly unsafe						
	Climate Change	$GtCO_2$ eq	12.3	50.8	high	rapidly deteriorating
	Ocean Acidification	$GtCO_2$	7.6	38.6	high	rapidly deteriorating
	Biodiversity Loss	*no units*	0.16	0.2	low	rapidly deteriorating
Unsafe						
	Nitrogen Losses	Tg	47.6	55.6	low	slow evolution
Safe						
	Land Cover Anthropisation	km^2	19 362 000	16 669 000	medium	slow evolution
	Phosphorus Losses	Tg	38.5	31	low	slow evolution

Footprints values for 2011 except for biodiversity (2009)

Table 19. Summary table of global performances, limits and footprints.

The selected limits for Climate Change and Ocean Acidification are set with the notion of a budget over time representing the remaining emissions until a physical limit is reached. The selected limits express a yearly maximum rate of emissions to ensure that the limits will only be achieved in 2100, i.e. zero emissions globally from this date. The global limits consider the future but not the past.

For Climate Change, the theoretically correct physical limit to stay in a “Safe Operating Space” has been set by (Hansen et al., 2013; Rockström et al., 2009b) at 350 ppm. This limit is currently overshot. Since it is extremely unlikely (Stocker et al., 2013) to come back to this limit, another limit has been set based on a potentially (50% chance) achievable objective, a 2°C target. Converting this physical limit into the remaining global GHG emissions budget over time shows that, at the current yearly rate of GHG emissions, the global budget will be exhausted in four to five years. Applying this budget over time to set the limit applied in this study, i.e. the yearly maximum GHG emissions accounting for current and future populations until 2100, shows that the yearly limit is currently overshoot by a factor of 4.3. The results are compatible with other studies and current preoccupations about the risks of Climate Change (Stocker et al., 2013). These results show however a large difference with current Climate Change policies with respect to the urgency of the situation and the range of efforts required for respecting the computed limit.

The physical limit for Ocean Acidification will be attained in around twenty years at the current global rate of yearly CO_2 emissions. Computing the limit applied in this study, i.e. the yearly maximum CO_2 emissions accounting for current and future populations until 2100 shows that the yearly limit is currently overshoot by a factor of 5.6. Due to the slow reaction with respect to the overshoot of the Climate Change limit and the medium-term crossing (in a Business as Usual scenario) of the limit for Ocean Acidification, it seems totally meaningful to consider Ocean acidification has a boundary on its own even if the underlying causes are really close to the Planetary Boundary Climate Change.

The limits for the Planetary Boundaries Nitrogen and Phosphorus Losses, Land Cover Anthropisation and Biodiversity Loss are set with the notion of a yearly budget.

The limit for Biodiversity Loss considers the potential damages to biodiversity per land cover types accounting for the level of biodiversity per biome. The limit has been set based on international policy objectives for reducing biodiversity loss (Aichi targets). While the score for Biodiversity Loss does not show a large overshoot, the Planetary Boundary is estimated Cleary Unsafe in this study due to the rapidity of the changes. Due to the lack of historical datasets, this study cannot show any historical values: The situation is however expected to degrade rapidly in due to the rapid rate of land cover changes and destruction of habitats combined with slow rehabilitation efforts. In addition, the limit will probably be set more drastically in coming years, when the influence of biodiversity on global and regional processes will be better understood.

The limit for Land Cover Anthropisation is set in terms of the surface of anthropised land, i.e. agricultural and urbanized land, as percentage of ice-free land (water bodies excluded) to consider aspects related to albedo and carbon stocks in vegetation. The limit is based on political objectives and not on scientific ones. The limit is currently respected (- 14%): this is consistent with the way the limit has been set, i.e. limiting future deforestation and urban settlements based on international policy targets. Over the period from 1961 to 2011, the global footprint has increased by around 21%. At the global average rate of the last 15 years, the limit will be reached in 45 years. From a scientific point of view it could be discussed if this limit is strict enough given its relevance for the Climate Change and the Ocean Acidification Planetary Boundaries which are largely overshot.

The limits for Nitrogen and Phosphorus Losses are set in terms of agricultural N-losses and P-fertilisers based on local values averaged at global scale. While the situation is critical in many locations, the overall assessment shows an overshoot for Nitrogen Losses. The resulting combined performance for the Planetary Boundary is thus qualified as Unsafe because of the slow evolution of the situation.

7.2. Swiss limits, footprints and performances

From a *Swiss* perspective, the situation for Switzerland is similar to the global situation for most of the Planetary Boundaries considered in this study: the situation is however worse for Nitrogen Losses (large overshoot), i.e. a Clearly Unsafe situation, as well as for Land Cover Anthropisation, i.e. an Unsafe situation, because of a rapidly evolving situation), as shown in Table 20.[82]

Performance	Planetary Boundary	Units	Limit	Current footprint	Confidence	Trend
Clearly unsafe						
	Climate Change	$MtCO_2$ eq	4.8	109	high	rapidly deteriorating
	Ocean Acidification	$MtCO_2$	4.5	82.8	high	rapidly deteriorating
	Biodiversity Loss	*no units*	0.16	0.3	low	rapidly deteriorating
	Nitrogen Losses	Kt	53.8	108.6	low	slow evolution
Unsafe						
	Land Cover Anthropisation	km^2	21 900	17 600	medium	rapidly deteriorating
Missing data						
	Phosphorus Losses	kt	43.6	*no data*	low	slow evolution

Table 20. Summary table of Swiss performances, limits and footprints.

[82] The Swiss limits for the two Planetary Boundaries computed with budgets over time (Climate Change and Ocean Acidification) differ from the global limits by also considering the past in the computations.

7.3. Thinking ahead with Business As Usual scenarios

Considering the projections of the future Swiss and global populations, the evolution of the global and Swiss per capita limits for the Planetary Boundaries based on a yearly budget (Nitrogen and Phosphorus Losses, Land Cover Anthropisation and Biodiversity Loss) is shown in Figure 21.

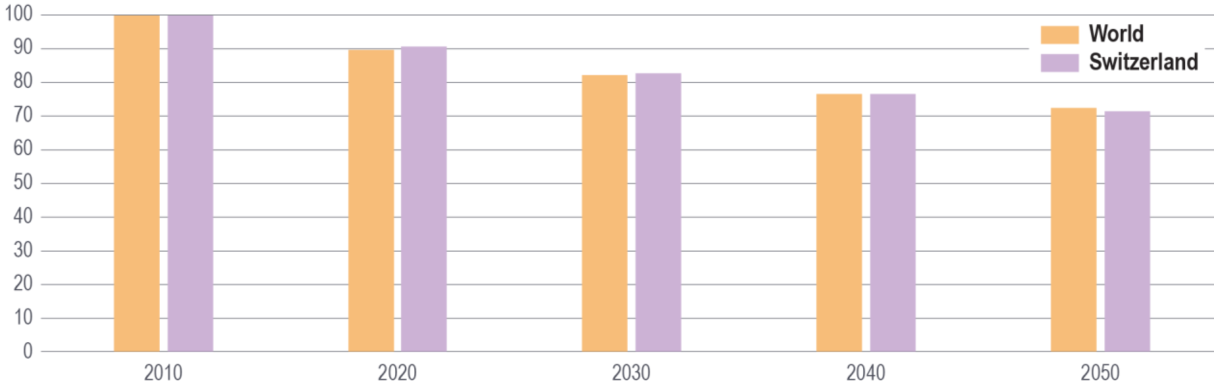


Figure 21. Evolution of the global and Swiss per capita limits based on population projections for 2010-2050 (Index 100 = 2010).

For Planetary Boundaries with indicators considered as yearly budgets, the global and Swiss per capita limits evolve similarly, resulting in a reduction of the limits per capita of around 10% in 2020, 18% in 2030 and 29% in 2050. Since the yearly limits are similar every year, maintaining the same global and Swiss performances in the future requires thus reducing over time the per capita footprints. The required reduction is, for example, of 10% in 2020 compared to 2010 values. Assuming a Business as Usual scenario, i.e. a constant per capita footprint, the limit will be attained for all Planetary Boundaries before 20 years, due to population growth.

For Planetary Boundaries with indicators considered as budgets over time, the evolution of the future population is already accounted for in the indicator. Assuming a Business as Usual scenario, i.e. a constant per capita footprint, the limit will be attained for Climate Change in 4.8 years (Switzerland) and 26 years (globally). For Switzerland, a sustainable pathway would require an ongoing yearly reduction of 17.5%. For Ocean Acidification, the limit will be attained in 6 years (Switzerland) and 20 years (globally). For Switzerland, a sustainable pathway would require an ongoing yearly reduction of 15%.

Despite this critical situation Switzerland has already done quite some successful efforts as shown by the relative decoupling between the evolution of the Swiss consumption (GDP in constant CHF) and the evolution of the footprints. For respecting the limits in the future, domestic efforts should be intensified and reduction efforts on impacts of Swiss imports should be started.

7.4. Priorities

Potential use of the computed indicators

The resulting indicators are an indication of the ecological sustainability of the impacts induced by the Swiss consumption in a long-term global perspective, assuming that past, current and future populations on Earth have, by definition, similar rights to the resources. The resulting indicators are thus not to be understood as (policy) targets. The results from this study contribute to the scientific knowledge that will be needed for potentially setting policy targets and measures.

It should be kept in mind that the generated values are based on modelling. Since, by definition, modelling 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 three potential uses of the limits and footprint indicators proposed in this report are to:

a) Raise awareness
b) Set priorities among the Planetary Boundaries,
c) Identify large overshoots and analyse long-term trends, i.e. relative differences over 5-10 years periods, of aggregated values.

The generated indicators and values are *not* adequate to:

d) Monitor precise values,
e) Identify small overshoots, and monitor small variations (e.g. 10%) over short periods (e.g. yearly variations).

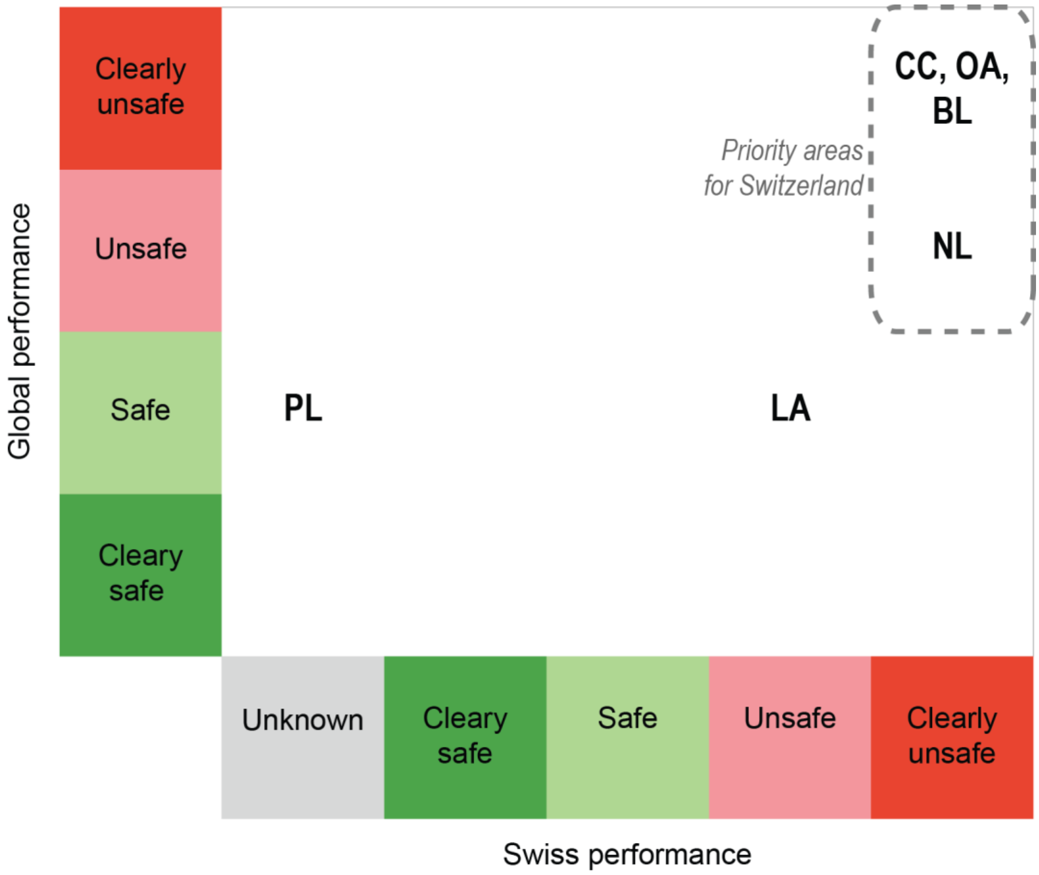
The indicators are thus not appropriate to set operational target values linked to the importation of a specific product, e.g. palm oil. More disaggregated data or models, a more narrow focus on specific products, and a focus on Driving-Forces, should be used for these purposes. However the Planetary Boundaries can be envisaged as an alternative to the Ecological Footprint.

Setting priorities

From the above assessment it can be recommended that **Climate Change**, **Ocean Acidification**, **Biodiversity Loss and Nitrogen Losses** are the first priorities (Figure 22): these Planetary Boundaries with a Clearly Unsafe or Unsafe performance at global scale should be managed. Current footprints are above an ecologically sustainable level, both globally and for Switzerland. International discussions and scientific developments on these issues should be promoted. National action should be taken, respectively intensified to reduce the Swiss footprints.

Land Cover Anthropisation and Phosphorus Losses are priorities of second rank: these Planetary Boundaries for which the performance of Switzerland is (potentially for Phosphorus) Unsafe, but with a Safe situation at global level should be better understood to identify potential risks of a future global overshoot. This report shows that the global situations are evolving slowly: currently the Planetary Boundaries framework does not provide a justification for the reduction of the national footprints. However the approach to allocate shares to countries shows that Switzerland is rapidly approaching its national limits. In the case it is assumed that national limits should be respected in all countries, Switzerland should then engage into reduction efforts.

Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution are priorities of third rank: these Planetary Boundaries for which a limit cannot be identified yet should be set on the research agenda.



BL: Biodiversity Loss, **CC**: Climate Change, **LA**: Land Cover Anthropisation, **NL**: Nitrogen Losses, **OA**: Ocean Acidification, **PL**: Phosphorus Losses (Swiss performance unknown due to lack of data).
For the four other Planetary Boundaries - Stratospheric Ozone Depletion, Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution - there is no evidence of global overshoots, their global performances are considered in the green zones. The Swiss performances of these Planetary Boundaries have not been assessed.

Figure 22. Priority Planetary Boundaries, based on Global and Swiss performances

8. Conclusion

8.1. Lessons learned

This report confirms the already well-known importance of acting to manage Climate Change and Biodiversity Loss. This report adds Ocean Acidification and Nitrogen Losses to the list of the key topics.

The interest of the applied approach - combining Planetary Boundaries and footprinting as a *complementary* perspective to existing analyses - is in providing:

a) A multi-criteria assessment going beyond the current focus on Climate Change.
b) Global priorities that can be applied at various scales, e.g. countries, sub-countries or cities, as well as at the levels of corporations, products or technologies.
c) Absolute limit values against which performances can be benchmarked.

Eventually, it should be emphasized that this report focuses only on global environmental processes. The regional nature of other environmental issues does not preclude that action is not required from a global policy perspective. Regional pollutants can travel or be transported (due to trade) over long distance and can be transboundary, i.e. requiring potentially a global approach. Some of these regional environmental issues are thus subject to international protocols like the Convention of 13 November 1979 on Long-Range Transboundary Air Pollution. In addition, issues not mentioned as first priority from this specific analysis may be of high priority for other reasons like being a key input for the agro-industrial system, e.g. phosphorus, or for local health, e.g. mercury.

8.2. Recommendations for further research

This exploratory work shows the interest of - as well as limits of the current understanding of the Planetary Boundaries concept and outlines the need for further developments.

- First of all, indicators and limits are still to be identified for three Planetary Boundaries (Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution). Stratospheric Ozone Depletion is left out since current international agreements seem enough to phase out the ozone depleting substances and to have a positive impact on the ozone concentrations.
- Secondly, a large number of approximations are performed 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 Planetary Boundaries.
- 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 more in details the quantitative differences induced by the existing distributional concepts.
- Finally questions of technical and economic feasibility of future reductions of the Swiss footprints should be addressed. Potentials to reduce Carbon, Biodiversity and Nitrogen Footprints should be evaluated for different domains of consumption and production.

8.3. A new way of thinking

Countries as part of a larger system

With the concept of Planetary Boundaries and environmental footprints, a perspective complementary to the classical territorial perspective can be applied on the environmental impacts induced by a country and its inhabitants. A perspective considering a country as an element of a larger whole (the system Earth), in which the impacts are accounted wherever they occur, and for which maximum allowed impacts are identified.

The importance of indicators providing information on the environmental impacts induced by Swiss citizens outside the boundaries of Switzerland is confirmed. Such indicators are needed because the foreign part of the environmental impacts is large due to the current global economic system relying on the economic specialisation of countries and international trade.

Considering countries and people, as well as temporal dimensions

The downscaling of the global limits to the national scale is based on two different types of indicators, yearly budgets or budgets over time to consider the future when required. The application of a hybrid-allocation approach enables considering the role of countries, the past when required and considering people as the final beneficiaries of the allocation. This approach enables extending the basic equal share approach by considering past and future populations in addition to present ones.

Changing the focus

Planetary Boundaries are not straightforward to grasp because they require to think differently: in terms of spatial scope first (the global Earth system versus the national territory), and then because their focus may differ from the national preoccupations for the same environmental issues: e.g. the Planetary Boundary Land Cover Anthropisation is primarily about global carbon sequestration and albedo, it is 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 definitely has potential to change the way we practice environmental assessments and environmental policies both at the global and national levels.

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Annex 1. 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 CO2 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 CO2 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 (Ωarag).	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 O3 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 N2 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 N2 to 35 Mt N yr-1, which is ~ 25% of the total amount of N2 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, km3 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 km3 yr-1 (4,000 - 6,000 km3 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 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/21/research/research-programmes/planetary-boundaries/planetary-boundaries/about-the-research/quantitative-evolution-of-boundaries.html

Note : An update of the Planetary Boundaries was published in January 2015 (Steffen et al., 2015), after the present study was completed.

Annex 2. Participants of the Worskhop of 17.3.2014

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