Global Environmental Change 52 (2018) 49–57

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

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

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ARTICLE INFO

Keywords:
Planetary Boundaries
Green economy
National footprints
Switzerland

ABSTRACT

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

1. Introduction

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

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

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

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

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https://doi.org/10.1016/j.gloenvcha.2018.06.005
Received 16 October 2017; Received in revised form 28 May 2018; Accepted 7 June 2018
0959-3780/

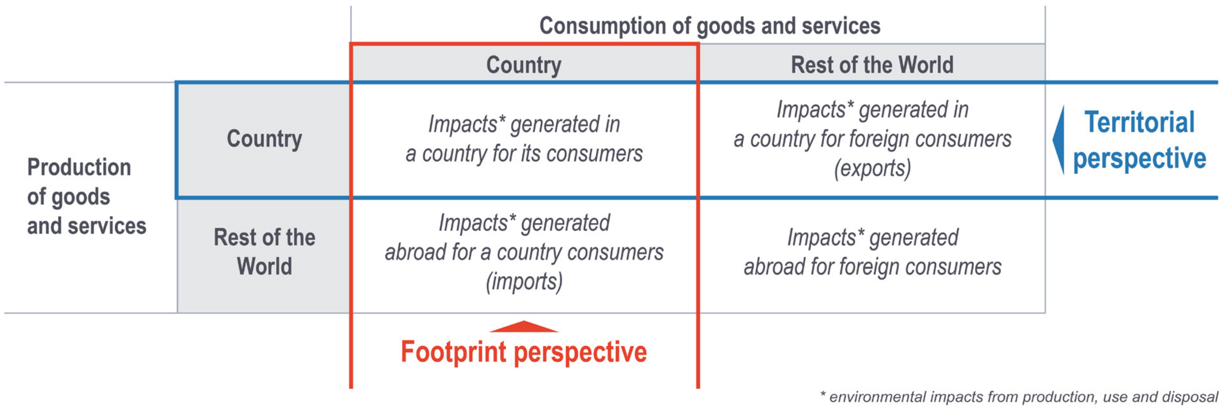

Fig. 1. Territorial versus Footprint (or consumption) approach.

Many environmental indicators are already produced by countries as part of their reporting obligations to international agreements. These indicators at national scale are in their vast majority examining the environment from a territorial perspective; e.g., reporting on domestic greenhouse gas emissions under the Kyoto Protocol. Footprints, or consumption-based indicators applying a Life Cycle Perspective, provide a complementary approach to the Sustainable Development Goals and other sustainability monitoring particularly relevant for the evaluation of the performance of countries with respect to global issues.

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

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

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

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

Our present research was developed with the aim that the downscaling of Planetary Boundaries and the quantification of the impacts of consumption can be replicated for any country or territory.

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

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

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

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

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

2.1. Evolution of the international awareness

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

In the early 1970s, the report from the Club of Rome "The Limits to Growth" (Meadows et al., 1972), using dynamic models, and Georgescu Roegen, who applied the laws of thermodynamics to the economy (Georgescu-Roegen, 1979, 1971), both denounced the impossibility of continuous economic growth based on natural resources. During this same time, international recognition of the importance of the environment took off. For example, the Ramsar Convention on Wetlands was signed in 1971, and the United Nations Conference on the Human Environment was held in 1972 in Stockholm, leading to the creation of the United Nations Environment Programme (UNEP) the same year.

During these years, the concept of "carrying capacity" was applied to estimate how large a population could be supported by a given area in the long term. Then, to go beyond this neo-Malthusian model of demographic limits and fixed resources, the IPAT equation (Ehrlich and Holdren, 1971) has been proposed. The impacts on the environment (I) are not only a function of population size (P), but also of affluence (A), i.e. consumption per capita, and technology (T).

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

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

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

2.2. Multiple concepts to address the limits of the planet

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

a) Limits (limit to growth, carrying capacity).
b) Policy targets (MDGs, SDGs, internationally agreed environmental goals drawn from existing international treaties and non-legally binding instruments (http://geg.informea.org/about)).
c) Footprints based on a Life Cycle Perspective (carbon footprint, water footprint, biodiversity footprint, land use footprint, et al.).

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

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

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

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

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

In September 2016, a constitutional amendment (proposed by a popular initiative validated by 112'098 signatures), aiming to set in the Constitution a target of an "Ecological Footprint" of one Earth for Switzerland (when extrapolated to world population) by 2050 (against the current Switzerland's Ecological Footprint of ~3 Earths), was rejected in a public vote (63.6% against). The vote stimulated a public debate on the question as to whether current patterns of consumption are sustainable in the future and confirmed the interest of the Swiss Federal Office for the Environment to assess how to apply the PBs for Switzerland.

3. Data and methods

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

3.1. Identification of the Planetary Boundaries and selection of indicators

The selection of the Planetary Boundaries is based on an in-depth review and consultation of experts. Five PBs have been selected for this study: Climate Change, Ocean Acidification, Land Cover Anthropisation, Biodiversity Loss, Nitrogen and Phosphorus Losses (two different computations, but considered by Rockström et al. (2009) as one PB). The original names of some PBs (Rockström et al., 2009; Steffen et al., 2015b) have been modified in order to be closer to the selected socio-economic related indicators. For example, the indicator provided by Rockström et al., 2009) for climate change (CO2 concentration in the atmosphere: 350 ppm and radiative forcing: 1 W m^{-2}) is a "state" indicator (see DPSIR classification in Kristensen, 2004). To assess the contribution (or the share) of a specific country, one needs to look at what led to this "state" which is the result of GHG emissions. GHG emissions is a "pressure" indicator and can be attributed to specific countries.

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

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

1 The global systemic changes include local sources of changes leading to (a) global effect(s) and with a global limit. This is the case for Climate Change, Ocean Acidification and Stratospheric Ozone Depletion.
2 The global cumulative changes include multiple transformations having local impacts, but which can nevertheless be considered global because they are occurring on a worldwide scale and can have global consequences. This is the case for Nitrogen and Phosphorus Losses, Land Cover Anthropisation and Biodiversity Loss.
3 The third PB category includes issues that, according to current knowledge and data, are at regional scale only: a global limit cannot be identified at the time being. This is the case for Atmospheric Aerosol Loading, Freshwater Use and Chemical Pollution. The term 'regional' does not preclude that regional pollutants can travel or be transported (due to trade) over long distances and can be transboundary, i.e. become a global issue. Rockström et al. (2009) did not characterise Atmospheric Aerosol Loading and Chemical Pollution but Steffen et al. (2015b) proposed indicators. For Freshwater Use, the overuse and/or pollution of freshwater can have significant impacts locally (or regionally, i.e. downstream watersheds), but without compromising other regions outside the watersheds, except maybe for oceans, e.g. the case of plastic/marine litter, which is not (yet) a PB and beyond the scope of this study.

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

For each of the PBs, the selection of an indicator is then based on three main criteria listed below. Selecting a different indicator than the one proposed by Rockström et al. (2009) and Steffen et al. (2015b) is required in order to enable linking a PB described in biophysical terms to the socio-economic activities inducing it, i.e. to compute a footprint. While Rockström et al. (2009) and Steffen et al. (2015b) assessed which boundaries are crossed at the current point in time, the indicators selected in this study consider whether current yearly footprints are respecting these boundaries. The criteria are:

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

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

3.2. Computing the limits

3.2.1. Global limits

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

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

3.2.2. Distributional principles for defining a country's share

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

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

1) The different needs of the inhabitants of Earth and the different amount of resources needed to satisfy these needs are not always considered. For example, living in Northern European countries requires heating houses for a longer period than in Southern Europe. In addition, the perception of what is required varies in each culture, a factor not easy to take into account.
2) Past emissions and use of resources are not considered, while they differ to a great extent between countries/regions of the world.
3) The role of countries, being the current main way of allocating resources between people, is not considered.

However, any broadly accepted way of going beyond the "equal share per capita" approach is currently lacking. So-called “ethical approaches” have been applied to climate change in the literature on burden sharing (Shue, 1999; Höhne et al., 2014). For instance, the Greenhouse Development Rights (GDR) Framework (Baer et al., 2009) defines sharing efforts in climate change mitigation, based on justice principles. Starting from the postulate of a right to development, GDR proposes a quantification of responsibilities and capacities to be equally shared between people, once a certain development threshold is attained. The Contraction and Convergence (C&C) model (Meyer and Bruges, 2000) is a framework for defining and negotiating differentiated paths of greenhouse gases reduction (contraction), until per capita emissions reach a level that is equal for all countries (convergence). The Science-Based Targets initiative (http://sciencebasedtargets.org/) allocates carbon budgets to companies

Table 1
Selection of indicators.

Planetary Boundary	Description of the indicators	Units	Type
Climate Change	Remaining cumulative GHG emissions (including land cover changes) for a 50% chance to stay below a 2 °C increase by 2100 compared with pre-industrial level.	$GtCO_2eq$/year	Pressure
Ocean Acidification	Remaining cumulative emissions of carbon dioxide (CO_2) from human activities to maintain an acceptable calcium carbonate saturation state Ω.	$GtCO_2$/year	Pressure
Nitrogen (N) and Phosphorus (P) Losses	N: Loss of reactive N into the environment. Considering losses into soil, water (NO_3-) and air (partially, i.e. NH_3 but not NOx). P: Use of fertilizers with Phosphorus.	N: Tg N/year P: Tg P/year	N: Pressure P: Driving-force
Land Cover Anthropisation	Surface of anthropised land, i.e. agricultural and urbanised (sealed) land, as percentage of ice-free land (water bodies excluded).	km^2	State
Biodiversity Loss	Potential damages to biodiversity per land cover types accounting for the level of biodiversity per biome	unitless	State

based on so-called “proportional approaches”, considering economy-wide emissions based on IPCC scenarios or so-called “technological approaches” estimating the remediation capabilities of technologies based on long-term International Energy Agency (IEA) scenarios.

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

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

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

3.2.3. PBs with yearly budgets

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

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

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

Equation 1. Yearly budget

$$Lc = \frac{Pc_y}{Pw_y} \bullet Lw_y \tag{1}$$

Where:

Lc = Country limit
Lw_y = World limit at reference year
Pw_y = World population at reference year
Pc_y = Country population at reference year

3.2.4. PBs with budget over time

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

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

Equation 2. Budget over time

$$Lc_{2010\,2100} = \frac{Pc_{1990}}{Pw_{1990}} \bullet Lw_{1990\,2100} - Uc_{1990\,2010} \tag{2}$$

Where:

Lc_{2010_2100} = Country budget remaining for 2015–2100
Pc_{1990} = Country population 1990
Pw_{1990} = World population 1990
Lw_{1990_2100} = World limit 1990–2100, total budget over the period
Uc_{1990_2100} = Country resource use 1990 to 2014

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

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

Table 2 presents the global and Swiss limits used in this study.

3.3. Computing country footprints

The footprints are the current use of resources (or the cumulative use of resources, if the PB is of a budget type). To stay within planetary boundaries, the footprints should be smaller than the PBs. Footprint indicators are tools for measuring actual environmental impacts in a synthetic manner (Hoekstra and Wiedmann, 2014) going beyond the

Table 2
Limits used at Global and Swiss levels.

Planetary Boundaries	Global Limit	Swiss limit
Climate Change	12.3 GtCO2eq	4.8 MtCO2eq
Ocean Acidification	7.6 GtCO2	5.7 MtCO2
Biodiversity Loss	0.16 (unitless)	0.16 (unitless)
Nitrogen Losses	47.6 Tg	53.8 t
Phosphorus Losses	31 Tg	43.6 Kt
Landcover Anthropisation	1,936,200 km2	21,900 km2

classical territorial perspective. Footprints quantify environmental impacts occurring in- and outside a country due to domestic consumption. Footprints are based on scientifically validated rationales and apply an approach called Life Cycle Thinking.

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

3.4. Performance and priority assessment

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

3.5. Principles for setting priorities

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

3.5.1. PBs to be considered as a priority

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

Table 3
A performance defined with four categories.

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

3.5.2. PBs that are not a priority

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

4. Results

4.1. Limits, current footprints and performances

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

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

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

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

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

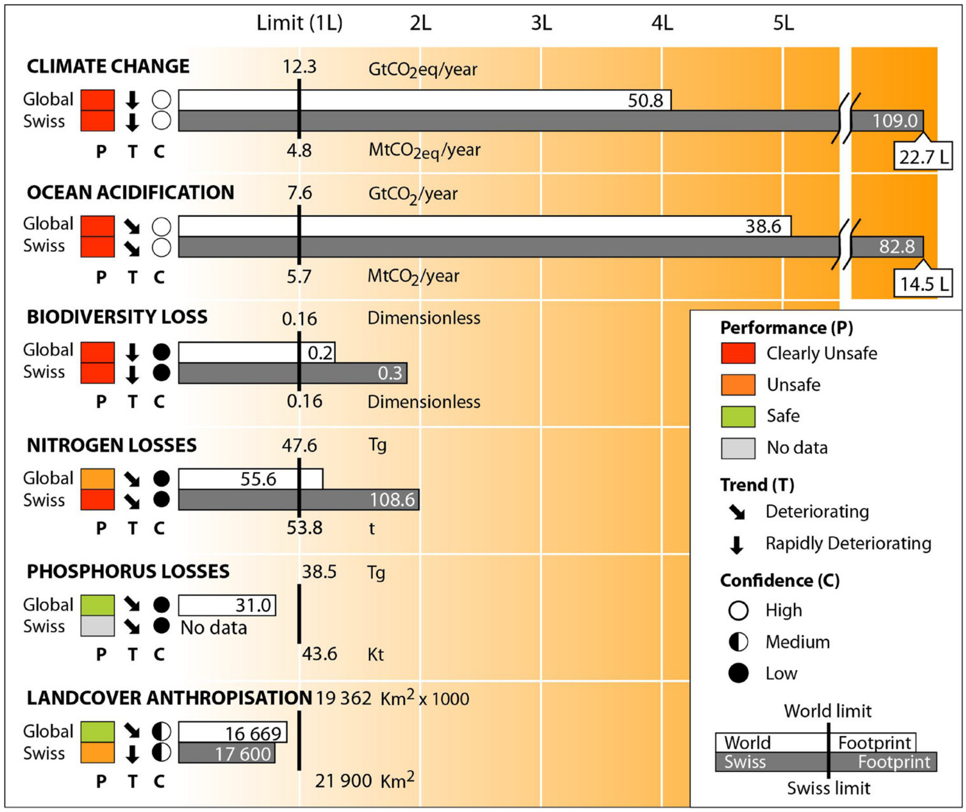

Fig. 2. Summary of the results.

World and 22.7 for Switzerland.

4.2. Thinking ahead with business as usual scenarios

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

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

4.3. Priority assessment

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

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

5. Discussion

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

The generated indicators and values are adequate to identify large overshoots, orders of magnitude and analyse long-term trends, i.e. relative differences over 5 to10 year periods of aggregated values. They are not adequate to monitor precise values nor for identifying small overshoots, and monitor small variations (e.g. 10%) over short periods (e.g. yearly variations). The indicators are thus not appropriate to set operational target values linked to the importation of a specific product, e.g. palm oil. More disaggregated data or models, a narrower focus on specific products and a focus on Driving Forces should be used for these purposes.

5.1. Allocation

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

5.2. Historical contributions

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

5.3. Limits for climate change: political values

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

5.4. Linkages between PBs

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

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

6. Conclusions

6.1. Added-value of the approach

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

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

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

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

6.2. Lesson learned: a new way of thinking

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

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

6.3. Recommendations for further research

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

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

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

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

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

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

Funding

This work was supported by the Swiss Federal Office for the Environment [Research Contract No 12.0042.PJ/M455-0302].

Acknowledgements

We would like to thank FOEN for funding the research and for facilitating access to data and to experts. Our special thanks to Andreas Hauser and Loa Buchli (FOEN). Their critical review and facilitation in contacting FOEN experts have greatly helped in the success and quality of this research.

The authors also express their thanks to the members of the Advisory group convened by FOEN, to individual experts consulted, as well as to the participants of the workshop held in Bern for their inputs (see list of individual names in Supplementary material).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.06.005.

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