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Planetary Boundaries: designing (fair?) limits to assess performance at the country level

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The Planetary Boundaries framework, published in 2009 and updated in 2015 and 2023, proposes limits for nine environmental processes, which should not be transgressed to maintain the stability and resilience of the Earth system. To operationalize the Planetary Boundaries, these must be translated to lower scales, such as countries, suitable for action. This article reviews the allocation principles and methods enabling the quantification of fair limits and ultimately the assessment of performance at the country level. Based on a literature review, we synthesize six steps and six allocation principles applicable to translating the Planetary Boundaries at a country scale. We conclude that computing national shares based on multiple allocation principles for Planetary Boundaries remains a considerable challenge that does not preclude, however, discussions about the insights gained in terms of possible priorities. In its current status, the quantification of limits can and should support transparent political discussions on concrete and urgent commitments to maintain a well-functioning Earth system for humankind.

KEYWORDS

Planetary Boundaries, operationalization, translation, allocation principles, national scale, fair shares, right and duties

1 Introduction

1.1 Planetary Boundaries and their operationalization

The Planetary Boundaries (PBs) framework emerged in 2009 in the context of the "Great Acceleration"[1] of various human and biophysical processes since the 1950s, which puts the stability and resilience of the Earth system under pressure. The framework defines global biophysical boundaries in nine environmental domains, which, if transgressed, put the stability of the Earth system's functioning and related benefits for humankind at risk (Rockström et al., 2009; Steffen et al., 2015). This framework not only complements—but also competes with—other frameworks already in place, such as the Essential Climate Variables, the Sustainable Development Goals, and the Internationally Agreed Environmental Goals.

The PBs framework and the risk-driven call for action it conveys have attracted great interest from the research, policy, and business communities, and mainstreaming PBs is thus underway in multiple sciences (e.g., Earth system science, Earth system justice

1 From the "Great Acceleration" graphs first published in 2004 in the International Geosphere-Biosphere Programme (IGBP) publication "Global Change and the Earth System: A Planet Under Pressure," updated in 2015.

and governance, economic thinking, and sustainable development research; Rockström et al., 2024).[2] This seems to be needed because, according to the latest PBs assessment (Richardson et al., 2023), six of nine PBs have been crossed.

To be operationalized—a necessary step to gain further adoption—the PBs must be translated to lower scales (e.g., country, region, city, company, or product). This means going from a global biophysical perspective to a perspective linking environmental aspects to human beings to allow for identifying actor-specific objectives and monitoring their performance. This downscaling can be achieved in multiple ways, each with specific challenges.

1.2 Focus of the article: translation of Earth-systems limits to the national scale

In this article, we focus on translating the biophysical limits of the PBs at the national scale to support assessing countries' environmental performances. The national scale is chosen for its precedence in the PBs' translation literature (Nykvist et al., 2013) and its necessity for PBs' operationalization in international and local policies.

After introducing a general framework to further specify the scope of analysis, we review the different ways PBs have been translated to country scale in the literature, as well as how fairness is approached and the main challenges that are to be faced. Based on the literature review, we synthesize the main steps needed for translating PBs at the country scale. We conclude with the implications, remaining challenges, and benefits of translating global limits at the national level.

2 From global biophysical limits to country-specific performance evaluation

Translating global biophysical limits to country scale—and assessing performance—can be described as a six-step process presented in Figure 1: (1) the selection of an **indicator** that is representative of a PB and can link environmental processes with human activities, (2) the selection of a **translation approach** (bottom-up individual objectives setting or top-down integrated objectives settings), (3) the selection of an **allocation principle** to serve as the basis on which to share a global PBs limit, (4) the **implementation** (computation of a country limit using the available data on the past, present, and future situations), (5) the selection of an **accounting approach** to represent the current environmental impact of a country (territorial vs. footprint perspective) to compare the computed limit with, and, eventually (6) the **performance evaluation** combining the country impact and country limit.

2 A Google Scholar search (29 Nov. 2024) for Planetary Boundaries returns 2,620,000 results with no less than 1,150 references with the terms explicitly in the title.

2.1 Selection of an indicator to represent the environment–human linkages

2.1.1 Budget-based socioeconomic indicators

The PBs' indicators are expressed in terms of biophysical control variables that have an influence on the potential perturbation of the Earth system. For instance, climate change, as characterized by global temperature differences since the preindustrial era, has two PB control variables: atmospheric carbon dioxide (CO_2) concentration (ppmCO_2) and total anthropogenic radiative forcing at the top of the atmosphere (Wm^{-2}). Identifying the upstream socioeconomic indicators driving these variables is possible using approaches like the Driver–Pressure–State–Impact–Response (DPSIR) framework.[3] This framework helps categorize indicators into driving forces (e.g., demography and consumption), pressures on the environment (emissions of CO_2), consequences (climate change and its related impacts), and actions (public and private responses). For each of these indicators, a maximum budget to split among actors, for example, the maximum carbon emissions required to remain below a determined increase in global temperature, can then be computed. Two types of budgets are possible: a fixed budget over time and a recurring budget (e.g., yearly budgets). Both views, depending on their usage, can be valid for any PB. In climate negotiations, the remaining global budgets (calculated by science as fixed over time) are converted into annual emissions targets and pathways to discuss country commitments. An additional requirement is that indicators should also be measurable with footprint data to provide a realistic picture of the impacts from countries (see Section 2.5).

2.1.2 From Earth-system resilience to human wellbeing

Several approaches to linking PBs with social dimensions have been proposed, such as the doughnut "safe and just space for humanity" delimited by the ecological ceiling of the PBs and a foundation of social minima (Raworth, 2017), the "sustainable development target space" (van Vuuren et al., 2022) streamlining development indicators with science-based frameworks such as the PBs, or the "safe and just Earth system boundaries" (Rammelt et al., 2023; Rockström et al., 2023), which proposes setting more stringent PB values based on 31 justice criteria that "minimize human exposure to significant harm [no significant harm (NSH)] (Rockström et al., 2023)." These approaches go further than the PB framework, aiming to ensure adequate conditions for humanity, by objectively integrating an assessment of human wellbeing.

Such combined PBs and social approaches have been translated at sub-global levels (Gómez-Alvarez Díaz et al., 2024; Fanning et al., 2021; Dearing et al., 2014; Hickel, 2019; Turner and Wills, 2022; O'Neill et al., 2018). The translation of the Earth system's limits to the national scale as proposed in this article also applies to the PBs' part of these proposals integrating social dimensions. Socioeconomic aspects are, however, here considered for the purpose of splitting global budgets among countries, not for assessing wellbeing.

3 https://www.eea.europa.eu/publications/TEC25

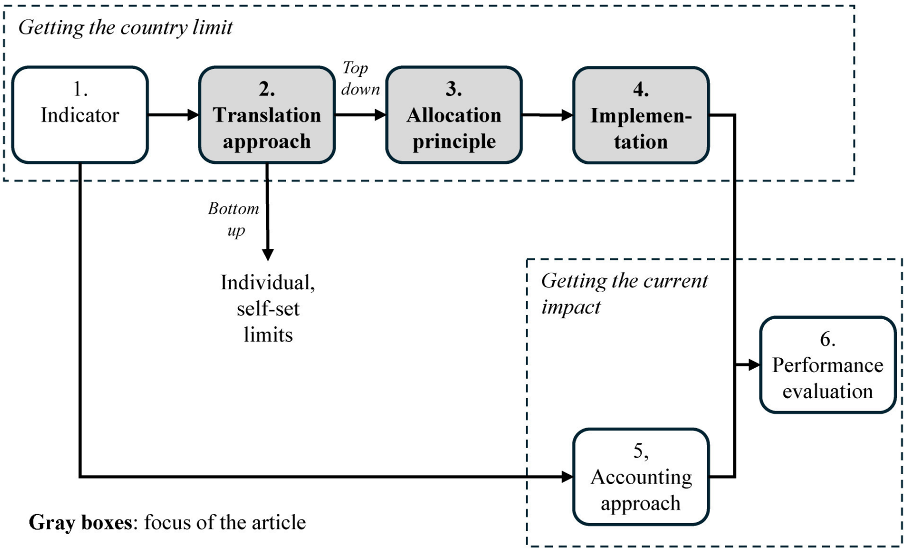

FIGURE 1
Six steps from Planetary Boundaries to country-specific performance evaluation.

2.2 Selection of a translation approach (top down or bottom up)

In the literature, the main approach to translating PBs to the country scale is top-down. A top-down approach applies a sharing scheme to split a global limit among countries according to specified criteria (e.g., population size and consumption levels; Häyhä et al., 2016; Parsonsova and Machar, 2021).

Such a top-down approach differs from a bottom-up one based on utility (e.g., the functional approach in a life-cycle assessment) or efficiency (cost-effectiveness). A bottom-up approach is mainly applied for assessing individual products, companies, and reduction or adaptation approaches regarding global limits (Bjorn et al., 2020; Sandin et al., 2015; Li et al., 2019; Ryberg et al., 2016). The Science Based Target Initiative is another example of a bottom-up approach helping companies transition toward net-zero greenhouse gases (GHG) emissions in their field of activities (Bjørn et al., 2022).

It should be noted that a bottom-up approach could also be applied at the country scale. The UNFCCC Nationally Determined Contributions, that is, the main tool in international negotiations on climate change, can be considered a bottom-up approach, taking into account principles, such as responsibility, capacity, and right to development, within a collective top-down process. Cole et al. (2014) propose limits for South Africa based on national goals. Mixed approaches are also possible. The Triptych approach (Phylipsen et al., 1998), has been, for example, used to support decision-making on nationally differentiated emissions targets before and after the Kyoto conference.

2.3 Selection of an allocation principle for the sharing scheme

In a top-down approach, the first step is to select an allocation principle for the sharing scheme. Adopting a sharing scheme is based on the idea that in the context of the PBs framework, keeping human activity within the PBs can be considered a global, public, and common good.[4,5,6] Common goods have the particularity of being rivalrous yet non-excludable, and they need to be protected for their conservation. International common goods are mainly protected through international coordination (e.g., international discussions on climate and biodiversity) and legal and economic instruments at the country scale (e.g., water regulations or taxation of environmental externalities of energy products).

2.3.1 Sharing schemes are mainly discussed in the literature on climate change

Discussions on the principles and rules underlying the allocation of limits to countries are surprisingly scarce in the literature on PBs. Few studies provide initial insights on the allocation of PBs (Nykvist et al., 2013; Hoff et al., 2014; Häyhä et al., 2016; Dao et al., 2018), and meta-discussions have been conducted (Sabag Muñoz and Gladek, 2017). Only two studies, however, propose a broad selection of allocation rationales for PBs and discuss their consequences (Friot and Dao, 2019; EEA/FOEN, 2020; Bai et al., 2024). This contrasts with the climate change literature and the current international discussions on climate change, clearly oriented toward notions of equity and fairness (Civil Society Review, 2015; Mbeva and Pauw, 2016; Pelz et al., 2024).

4 "A commons is a tract of land or water owned or used jointly by the members of a community. The global commons includes those parts of the earth's surface beyond national jurisdictions - notably the open ocean and the living resources found there - or held in common - notably the atmosphere" (IUCN, UNEP, and WWF, 1980).

5 Beyond Global Commons, the new concept of Planetary Commons (Rockström et al., 2024), defines specific biophysical systems critical for the Earth system, such as the Amazon forest.

6 See, for example, Harris and Roach (2018) for a discussion of public goods and global commons.

Following den Elzen et al. (2003) and Fleurbaey et al. (2014), sharing schemes can be based on two overarching logics: rights to use (resource sharing) and duties to conserve (effort sharing). As shown in EEA/FOEN (2020), due to the nature and current knowledge of the PBs, resource sharing is more adequate for global limits, which are not overshot, while effort sharing applies more easily to overshot PBs evaluated with the help of a remaining budget over time (e.g., climate change).

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

Since the 1990s, more than 40 studies have proposed quantitative operationalizations of this central principle to compute sharing schemes, GHG emissions allowances, or reductions at national or regional levels in a fair and equitable way (Höhne et al., 2014), considering specific aspects, for example, historical trajectories of countries/regions, development needs, responsibility, capacity, equality, sovereignty, or efficiency.

Häyhä et al. (2016) introduce examples of equity principles developed in the climate change domain potentially relevant for sharing the PBs. The study by EEA/FOEN (2020) presents the first synthetic classification of principles applicable to the PBs along with a systematic exploration of their quantification. Parsonsova and Machar (2021) further reviewed methods and indicators for downscaling PBs to the national level. Bai et al. (2024) present the newest version of a classification extended to 10 "translation principles" and their related "enacting metrics," along with a detailed translation protocol, including scale, and time dimensions.

2.3.2 Going beyond the basic per capita equality principle

Beyond the usual per capita equality principle applied in the literature on PBs' translation, two types of actors, people and countries, can be considered recipients of the rights or duties. The main allocation principles found in the literature applicable to the PBs are classified by type of approach in Figure 2. Taking people as recipients, an allocation can be considered with respect to equality (per capita for a current year or over time to respect the concept of sustainable development), satisfying basic needs, and the right to development. Taking countries as recipients, an allocation can be considered with respect to a country's sovereignty over its own territory, responsibility for past actions, and financial capacity to support other countries.

People/countries allocation principles can be summarized as follows:

Equality: People have equal rights to resources, resulting in an equal share per capita. Equality can be envisaged between people living in a particular year or between people over time.

Needs: People have differentiated resource needs. This could be due to their age, the size of the household they live in, or their location.

Right to development: People have the right to a decent life (e.g., the right to cover basic needs). In the long term, a convergence of welfare among people could be envisaged. People in countries with lower development levels could thus be allocated more resources or contribute less to mitigation efforts to meet development objectives.

Sovereignty: Excepted from engagements from international treaties, countries are managed based on internal policy rules. Countries have a legal right to use their own territory as they decide. In addition, countries have different levels of economic wealth and environmental impact. This situation is accepted as a starting point for allocating the global budget at the national scale (e.g., by grandfathering).

Capability: Countries have different levels of economic wealth. Countries with higher financial capabilities could contribute proportionally more to mitigation efforts or use less than their allocated share of resources because their ability to pay is higher.

Responsibility: Countries have already used resources in the past. Considering a date in the past to compute the remaining current rights is thus possible.

Going beyond the basic per capita equality principle opens a new type of question regarding the comparison of the possible allocation principles in terms of fairness and justice. This discussion is outside the scope of this article.

2.4 Implementation: computation of country shares

Once an allocation principle has been chosen, its implementation requires the definition of three elements:

1. An allocation key, that is, a variable representing the allocation principle [e.g., Gross domestic product (GDP) for capability];
2. A transformation function to express the relation between the variable and the allocation principle (e.g., linear/exponential or direct/inverse); and
3. A time reference, defining the start and end of the period considered.

2.5 Accounting approach: territorial or footprint

Environmental accounting and reporting are usually done on a territorial basis, that is, considering the impacts within national borders (e.g., in the Kyoto Protocol), based on well-established methodologies. Footprint indicators are tools for measuring actual environmental impacts in a synthetic manner (Rees and Wackernagel, 2023; Hoekstra and Wiedmann, 2014; Graedel, 2019) from a consumption-based perspective. Based on life-cycle thinking and material flow accounting, they allow for the assessment of the impacts over the supply chains of the goods

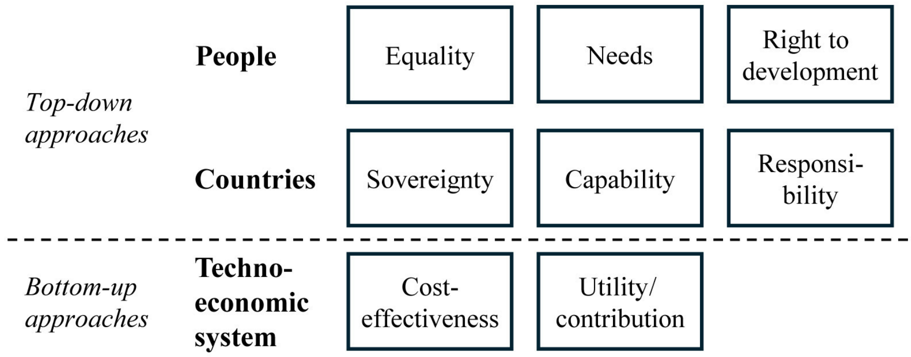

FIGURE 2
Main approaches and allocation principles for the translation of Planetary Boundaries. Certain bottom-up mechanisms can also be used as part of a broader top-down country allocation process such as the Nationally Determined Contributions in international climate negotiations.

and services consumed by residents of a given country within and outside national borders.

2.6 Performance evaluation: comparing limits and impacts

2.6.1 Limits or targets?

Making a clear distinction between limits and targets is important. Limits refer to threshold values (e.g., levels of CO_2 concentration in the atmosphere) beyond which unacceptable impacts are likely to occur. Such threshold values should be determined by science, based on the evaluation of impacts on ecosystems or humans.

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, which do not exclude scientific considerations, to support achievable objectives.

2.6.2 How to assess performance?

There are multiple ways to quantify and visualize situations regarding defined limits and among countries. Quantifying a discrepancy between a limit and an observed impact may seem simple, for example, by calculating a ratio, which has the advantage of putting all PBs on the same measurement units. But several challenges rapidly emerge: choice of the numerator and denominator ("impact/limit" indicates exceedance, where the higher the value, the worse the situation; "limit/impact" shows the opposite) and interpretation of values tending toward infinity when the limit or impact is close to zero. Visual representations, such as the well-known target-like PBs graphs[7] or sliders (Dao et al., 2018; EEA/FOEN, 2020), are powerful communication vehicles, but they are not exempt from difficulties in representing quantifications in a precise (e.g., symbols truly proportional to values) and simplified manner.

7 https://www.stockholmresilience.org/research/planetary-boundaries.html

3 Discussion

3.1 Calculations challenges

Operationalizing allocation principles aims at generating quantitative results, that is, "enabling metrics and data" (Bai et al., 2024). A large number of computation methods, including various data sets, parameters, and assumptions, have been implemented and described in the literature, in particular on climate change, for which two computation methods have mainly been applied to evaluate the needed mitigation efforts:

1. Convergence approaches, that is, the achievement of a common level of GHG emissions per capita at a future date through differentiated pathways.
2. A budget over time, that is, knowing how much greenhouse gas can still be emitted, before attaining the global biophysical limit.

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

The PBs framework sets new challenges for implementing the allocation principles (EEA/FOEN, 2020). The measure of complex processes, such as chemical pollution or biodiversity and linkages of states, causes and consequences (e.g., on ecosystem resilience and food provision) along DSPIR causal chains, is not as well established for PBs other than climate change.

The PBs indicators linking human and environmental aspects also differ in their temporality. Some, such as water consumption, are yearly budgets (possible recurrent resource use), while others, such as global carbon budgets, are budgets over time. Future pathways of resource use are only modeled for a selection of PBs (e.g., Intergovernmental Panel on Climate Change (IPCC) or International Energy Agency (IEA) pathways and trajectories for climate change) currently limiting the possible options for setting budgets over time.

Concerning calculations, parameters influence the resulting country shares:

- Allocation key: Multiple criteria and indicators can be chosen to perform the allocation for a given principle (e.g., age or nutrition for "Needs"). Choosing, and, if necessary, weighting, indicators to measure principles that are often multidimensional in nature is a complex endeavor requiring proper rationales.

- Transformation function: Indicators may be transformed to modify their relative influence on shares, for example, logarithmic transformations to reduce the effects of extreme values or saturation levels applied to set poverty or luxury min/max thresholds.
- Time: The reference year (for yearly budgets) or period (for budget over time) is considered for computing the allocation key, for example, 1990 in the Kyoto Protocol or 2050 and 2100 in IPCC reports.

3.2 Impact on resulting country shares

Existing studies in the climate change literature have shown how assumptions and parameters can influence results. Höhne et al. (2014) conclude that, for GHG-sharing schemes, the possible differences resulting from the modifying parameters when computing shares with a specific allocation principle can be as large as when switching between allocation principles.

To our knowledge, in the PBs literature, only one study provides results for multiple allocation principles and implementation methods (EEA/FOEN, 2020). In this study, 36 calculations following 15 methods for 6 allocation principles have been produced for 2 European areas (in 2018): the European Union (28 countries) and the European Environment Agency (33 countries).[8]

They show that applying the different methods results for all principles in a lower European share than when considering the equal share per capita approach (i.e., the most used allocation method in PBs studies at the country level) except for sovereignty (which is a consideration of the current situation). Considering the median values for each principle's results, this means a European share between 4.1% and 12.5% compared to 9.2% for the equal share per capita approach. This might be considered a narrow range in light of the variety of approaches and data sets used, even if the more stringent climatic scenario (e.g., 1.5° at 66%) (see footnote[8]) shows a negative share of −3.9% and the sovereignty principle produces a maximum share of 21%.

Discussing uncertainties (while not providing a quantified evaluation), they conclude that, based on their experience, the choice of a reference share for a country is more a decision of an ethical or political nature than a scientific one. The parameters' sensitivity (e.g., reference dates, weighting, etc.) clearly needs to be better analyzed, as does the ethics of the criteria choices.

4 Conclusion

Few studies related to PBs have researched the question of translating the framework to the country scale. Far from being a straightforward conversion, such as an equal per capita computation often seen in the PB literature, this translation requires multiple steps, including ethical considerations and quantitative assumptions with potentially large consequences. The idea of having a limit at the country scale can even be questioned. However, very little research has been performed on this topic outside the climate change literature. Beyond PBs' specific weaknesses in properly capturing the environmental process at stake, the PBs framework remains a siloed approach that does not currently fully address the interactions between each domain (Argüello Velazquez and Negrutiu, 2019). Also, the relevance of setting global thresholds for some PBs (not only the aforementioned biodiversity and chemical pollution thresholds but also those for freshwater or land use) has been questioned from the start (Nykvist et al., 2013).

We believe that further research on translating PBs at actionable scales, such as countries, is clearly needed in view of the current difficulties in current international discussions to finance costs of climate change losses and damages or actions for biodiversity. More generally, allocation and implementation frameworks deserve considerable focus and development. A shared representation of the rights and duties related to past, present, and future emissions seems crucial to solving the current climate crisis, and there seems to be no reason to believe that the situation would be different for any other PB discussed at the international level.

Beyond their uncertainties, as well as conceptual and operationalization limitations, PBs' translations can provide reliable orders of magnitude about country duties/rights and impacts. They are a means for actors to discuss priorities for action and concrete implications in a shared, transparent, and actionable manner, which is, every day, more urgent to maintain a well-functioning Earth system for humankind.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

8 Although the results for the climate change and ocean acidification PBs are not presented in the EEA/FOEN (2020) report, they are available in the background report by Friot and Dao (2019), http://pb.unepgrid.ch.

Publisher's note

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