



HAL
open science

Downscaling Planetary Boundaries: How Does the Framework's Localization Hinder the Concept's Operationalization?

Damien Rieutor, Gwendoline de Oliveira-Neves, Guillaume Mandil, Cecilia Bertozzi

► To cite this version:

Damien Rieutor, Gwendoline de Oliveira-Neves, Guillaume Mandil, Cecilia Bertozzi. Downscaling Planetary Boundaries: How Does the Framework's Localization Hinder the Concept's Operationalization?. *World*, 2025, 6 (3), pp.96. <10.3390/world6030096>. <hal-05160148>

HAL Id: hal-05160148

<https://inria.hal.science/hal-05160148v1>

Submitted on 16 Jul 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.





L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

Review

Downscaling Planetary Boundaries: How Does the Framework's Localization Hinder the Concept's Operationalization?

Damien Rieutor ^{1,*} , Gwendoline De Oliveira-Neves ² , Guillaume Mandil ^{1,*}  and Cecilia Bertozzi ³ ¹ Univ. Grenoble Alpes, CNRS, Inria, Grenoble INP, LJK, 38000 Grenoble, France² Department of Geography, History and Philosophy, Pablo de Olavide University, 41013 Sevilla, Spain; gсарoli@upo.es³ European Commission, Joint Research Centre (JRC), 41092 Seville, Spain; cecilia.bertozzi@ec.europa.eu

* Correspondence: damien.rieutor@univ-grenoble-alpes.fr (D.R.);

guillaume.mandil@univ-grenoble-alpes.fr (G.M.)

Abstract

This article investigates issues in the local operationalization of the Planetary Boundaries concept (PBC), crucial for assessing human impacts on the Earth system and guiding sustainable development policies. Originally designed for the global scale, this concept requires local adaptation to align territorial actions with global environmental goals. Following a qualitative analysis of 34 review articles, a systematic categorization method is employed to identify recurrent localization and operationalization issues. Their analysis provides three main contributions that improve the understanding of PBC downscaling mechanisms. First, it identifies a prevalent quantification-based localization approach. Second, it categorizes local operationalization constraints into three distinct groups. Third, it reveals underlying patterns demonstrating that the prevalent approach, despite ensuring scientific rigor, generates methodological and practical constraints to effective local operationalization. This “operational paradox” reveals fundamental tensions between the PBC’s biophysical interpretation, localization by quantification, and local operationalization, contrasting measurement or meaning, precision or participation, and standardized solutions or locally adapted responses. For future research, the analysis of the interactions between these contributions suggests operating a paradigm shift based on a socio-biophysical interpretation of the PBC and the contextualization of the resulting components. This alternative approach could prioritize territorial anchoring, stakeholder inclusion, and the co-construction of sustainability trajectories.

Keywords: Planetary Boundaries framework; Planetary Boundaries concept; downscaling; operationalization; localization; quantification; contextualization; local governance



Academic Editor: Manfred Max Bergman

Received: 13 May 2025

Revised: 1 July 2025

Accepted: 2 July 2025

Published: 8 July 2025

Citation: Rieutor, D.; De Oliveira-Neves, G.; Mandil, G.; Bertozzi, C. Downscaling Planetary Boundaries: How Does the Framework's Localization Hinder the Concept's Operationalization? *World* **2025**, *6*, 96. <https://doi.org/10.3390/world6030096>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

1.1. Context

Since Rockström et al. [1] introduced the Planetary Boundaries concept (PBC) in their seminal 2009 article ‘Planetary Boundaries: Exploring the Safe Operating Space for Humanity’, this concept has emerged as a cornerstone reference in the research on global environmental sustainability. Its theoretical framework (PBF) provides a quantitative basis for assessing the possibility of a change in the state of the Earth system that could profoundly and irreversibly disrupt the environmental conditions of the planet. To this end, it aims to quantify the boundary values of global biophysical processes beyond which the Earth’s habitability is threatened [2].

Stemming from Earth system science and building on environmental sciences [3], the Planetary Boundaries concept (PbC) has been developed mainly through the detailed description of its biophysical framework (PbF) and its components [4]: system, reference state, processes, control variables, thresholds, boundaries, and state of processes. However, since its first introduction, the social and anthropological significance of the PbC was equally recognized by its authors. Indeed, they already explained the disastrous societal consequences of crossing the boundary values as a result of industrialized societies' activities [1]. In 2015, the concept of the "Planetary Boundary Approach" [5] reinforced the importance of maintaining the Earth in its "Holocene" habitable state to ensure the development and prosperity of human societies. Despite this conceptual connection with social sciences and humanities, practical applications of Planetary Boundaries have developed around its biophysical components only, particularly in the case of downscaling attempts.

Although the PbC's relevance for assessing global environmental sustainability is widely acknowledged, its adoption by sub-global authorities has become crucial to meeting the defined global objectives [6–10]. The downscaling of the concept has highlighted the importance of localizing Planetary Boundaries. Indeed, the localization, or adaptation to the other scales, is a central step that precedes the local operationalization, i.e., the development of realistic responses that are context-appropriate and aligned with the global aims of the PbF. However, efforts to make the PbC effective at the local level have often been hindered by multiple obstacles, as demonstrated by the limited operational success of various localization initiatives documented in the recent literature [7,8].

In this context, this article aims to provide a robust and detailed diagnosis of the obstacles encountered in the local operationalization of the PbC, as well as their root causes. To this end, the analysis goes far beyond technical considerations relating to the parameters of a given localization method. It questions not only the approach chosen to localize PbC but also the underlying interpretation of this concept, on which the whole downscaling process is ultimately founded.

1.2. Research Gaps and Relevance of This Study

The analysis of the current literature reveals three major conceptual and methodological shortcomings, hindering the effective operationalization of the Planetary Boundaries concept. First, technically sophisticated methodologies for local quantification have been developed. However, empirical evidence reveals a persistent disconnection between these technical advances and their translation into concrete policy measures. This gap questions the effectiveness of the prevalent quantification-based localization approach. Second, the existing literature reveals an essentially technical approach to localization issues. This approach treats them as parametric challenges requiring better data or methods. It fails to examine how fundamental choices—conceptual interpretation and methodological approach—influence operational outcomes. Third, as a consequence, the analysis of the theoretical interconnectedness between the conceptual interpretation of the Planetary Boundary concept, the methodologies for its localization, and its operational success remains insufficiently developed. In light of these shortcomings, this study proposes a systematic analysis of the links between conceptual interpretation, localization methodology, and operational effectiveness. This analysis is based on a multidisciplinary approach that articulates reflections on a territorial scale with the analysis of context-specific transformations of scientific knowledge, and critiques of a strictly technocratic vision of sustainability.

1.3. Theoretical Framework, Objectives, and Research Hypotheses

This analytical framework integrates insights from three distinct yet complementary fields. First, environmental governance scholarship, which illuminates tensions between

scientific universalism and territorial particularism. Second, science and technology studies, which elucidates how scientific concepts undergo transformation across contexts. Third, critical sustainability studies, which examines how depoliticized frameworks may jeopardize transformative action.

This article addresses the following research question: does the biophysical dimension of the Planetary Boundaries framework (PBf) hinder the local operationalization of the Planetary Boundaries concept (PBc)? More specifically, it aims to better understand the origins of the operational issues of the PBc by identifying and analyzing the connections with the approach applied for localization and how the concept is interpreted in the first place.

We formulate three hypotheses. First, a purely biophysical interpretation of the PBc favors localization that focuses solely on quantifying the numerical components of the PBf. Second, this quantitative approach hinders local operationalization in two ways: it fails to overcome downscaling challenges and generates additional obstacles. Third, the initial interpretation of the PBc directly influences the ability to design and implement effective local actions. These hypotheses structure the overall analysis through the identification of prevalent localization approaches, the categorization of operational obstacles, and the conceptualization of the operational paradox.

1.4. Article Structure

This article develops its reasoning through six analytical steps. Firstly, it introduces the methodology adopted for selecting review articles (Section 2). Secondly, it analyzes the characteristics of the studied corpus from both an interdisciplinary and international perspective (Section 3). Thirdly, it describes the qualitative analysis method employed to identify issues related to localization and the local operationalization of the PBc (Section 4). The empirical findings are then presented in a structured format (Section 5), followed by in-depth analysis to extract theoretical contributions (Section 6). Finally, this article tests initial hypotheses of potential solutions against the obtained results, discussing their implications and proposing directions for future research (Section 7).

1.5. Main Theoretical Contributions and Societal Implications

This article clarifies the main steps for downscaling the Planetary Boundaries concept (PBc): interpretation, localization, and local operationalization. Moreover, it offers three main contributions to a deeper understanding of the interactions between these steps. First, it unveils a prevalent approach to PBc localization: the top-down local quantification of the numerical components of the biophysical framework of Planetary Boundaries (PBf). Second, it describes the links between this prevalent approach and the issues of the local operationalization of the PBc, thus identifying an “operational paradox.” Finally, it discusses how the initial interpretation of the Planetary Boundaries concept has influenced the emergence of a prevalent approach to localization. This allows us to show how a focus restrained to the biophysical components can hinder the local operationalization of the PBc.

In doing so, this study contributes to the current debate on the downscaling of Planetary Boundaries concept. Its contributions suggest the need not only to change the mainstream approach to localization, but also to develop new perspectives on the overall concept, going beyond the strictly biophysical dimension of the PBf to encompass other fundamental dimensions that are present in the founding concept. These proposals seem to hold promising capacity in unlocking effective responses to the identified operational issues hindering PBc localization, thus contributing to the development of a local governance of environmental sustainability that is aligned with the global scope of the Planetary Boundaries concept.

2. Materials

2.1. Initial Corpus Selection Methodology

The selection methodology is based on a systematic and rigorous analysis of a corpus of the interdisciplinary and international literature addressing issues of localization and local operationalization of the Planetary Boundaries concept (PBc).

The analyzed literature spans from January 2015 to December 2023. It begins in 2015 because the first fundamental update of the PBc, published that year (Steffen et al., 2015) [5], catalyzed localization efforts by explicitly emphasizing the importance of local action, marking a turning point in the field, as documented by Biermann and Kim (2020) [11]. It ends in 2023 because the systematic review was conducted by the authors in 2024, thus marking December 2023 as a natural endpoint for comprehensive coverage.

The focus on review articles serves three principal purposes. First, it enables the development of a general analysis of the challenges of PBc downscaling challenges, rather than a list of detailed issues influenced by the biophysical processes and characteristics of the territories studied in research articles. Second, it provides a disciplinary and critical perspective on these issues, facilitating comparison of different analytical viewpoints. Finally, this methodological choice ensures a relevant and consistent selection of review articles, that represent key advances related to the issues addressed, while maintaining a manageable corpus size. Indeed, opting for primary research articles would have generated an excessive corpus, compromising the feasibility of rigorous qualitative content analysis.

To build the corpus, the following three sources were used: Google Scholar, ScienceDirect, and previous aligned research work of the authors. Google Scholar served as the primary source for its comprehensive interdisciplinary coverage, essential to address a trans-disciplinary topic spanning across environmental and social sciences. The resulting corpus was compared with ScienceDirect's robust collection of environmental science articles—the primary domain in Planetary Boundaries research—to assess its quality. The overlap between databases confirmed the selection strategy's robustness (all filtered ScienceDirect articles were already in Google Scholar results). Finally, the authors' own bibliography ensured the inclusion of key texts potentially overlooked by database indexing limitations.

For internet sources, in addition to activating the "review articles" option, the following choices were made to obtain results relevant to the research question:

- Using a structured request with the following terms: "planetary boundaries"; "planetary boundary"; "safe and just space"; "safe operating space"; and "safe and just operating space." In doing so, the Doughnut Economics framework (the concept of "safe and just operating space") was included in this search because it is rooted in the Planetary Boundaries framework and has been very successful among local authorities.
- For Google Scholar, adding restrictions ("-layer-protein-chemistry") was conducted to remove articles that were not relevant to this analysis and to limit the number of articles to be filtered. The term "layer" associated with "planetary boundaries" refers to computer modeling unrelated to the concept we are studying. The terms "protein" and "chemistry" refer to applications of the concept of "planetary boundaries" linked to a specific sector of activity. This does not correspond to the present research, which studies the territorial application of Planetary Boundaries.

These three sources resulted in an initial corpus of over 2000 review articles. This corpus was subsequently filtered, to extract relevant results.

2.2. Corpus Refinement

To ensure scientific rigor and relevance, four specific filters were applied to the initial corpus (Table 1).

Table 1. Literature review selection process and results.

Number of Review Articles	Google Scholar	Science Direct	Previous Research	Total
Initial results	1980	77	17	2074
→ Filter A: Alignment with the territorial application of PB	54	61	17	132
→ Filter B: Substantial commitment to PB	42	18	16	76
→ Filter C: Peer-reviewed journals, Q1	36	18	13	67
→ Filter D: Relevance for localization and operationalization	31	12	13	56
→ Final corpus, number of review articles selected:				34

Source: Author's own elaboration.

Filter A: Alignment with the research field

The title, keywords, and abstract were analyzed to eliminate articles whose main aim was not related to the territorial application of the PBc. Articles focusing on the alignment of economic sectors, companies, or products with the PBc were therefore excluded. To maintain a global overview of the issues related to the downscaling of Planetary Boundaries concept, the selection deliberately focused on articles addressing the concept as a whole, rather than studies focusing on a single biophysical process (except two review articles, one on biosphere integrity and the other on water).

Filter B: Substantial consideration of the PBc

An analysis of keyword frequency ensured that the PBc was not merely contextual but was analyzed in the body of the article. Keywords used are as follows: "Planetary Boundaries", "Safe Operating Space", "SOS", "Safe and Just Operating Space", "SJOS", "Doughnut", and "planetary boundar*".

Filter C: Quality and impact of journals

Only peer-reviewed review articles were selected. This ensures the scientific soundness of the selected corpus and results. Priority was also given to journals ranked Q1 at the time of publication. On this last point, two exceptions were made for reasons of relevance; however, the journals from which these two exceptions were taken obtained a Q1 ranking in the year following the article publication:

- Shao (2020), «Paving Ways for a Sustainable Future: A Literature Review» (Environmental Science and Pollution Research) [12];
- Hossain and Ifejika Speranza (2019), «Challenges and Opportunities for Operationalizing the Safe and Just Operating Space Concept at Regional Scale» (International Journal of Sustainable Development & World Ecology) [13].

Filter D: Relevance for localization and local operationalization of the PBc

Only studies providing an overview of practical advances and obstacles to the local operationalization of the PBc were selected.

2.3. Final Selection

Following this rigorous PB selection process, 34 review articles were selected. The final corpus is detailed in Table 2.

Table 2. Final corpus.

Ref.	Title	1st Author	Year
[11]	The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a “Safe Operating Space” for Humanity	Biermann F.	2020
[14]	Review of life-cycle based methods for absolute environmental sustainability assessment and their applications	Bjørn A.	2020
[15]	Global environmental change II: Planetary boundaries—A safe operating space for human geographers?	Brown K.	2016
[16]	Revisiting the application and methodological extensions of the planetary boundaries for sustainability assessment	Chen X.	2021
[17]	Dwelling in the biosphere: exploring an embodied human–environment connection in resilience thinking	Cooke B.	2016
[18]	Significance of environmental footprints for evaluating sustainability and security of development	Čuček L.	2015
[19]	A development of intergenerational sustainability indicators and thresholds for mobility system provisioning: A socio-ecological framework in the context of strong sustainability	Dillman K.J.	2023
[20]	Matching scope, purpose and uses of planetary boundaries science	Downing A.S.	2019
[21]	The double negative approach to sustainability	Feitelson E.	2023
[8]	Planetary Boundaries and the Doughnut frameworks: A review of their local operability	Ferretto A.	2022
[22]	Defining the “Positive Impact” of socio-technical systems for absolute sustainability: a literature review based on the identification of system design principles and management functions	Gebler M.	2022
[23]	Benchmarking urban performance against absolute measures of sustainability—A review	Goodwin K.	2021
[24]	Earth system justice needed to identify and live within Earth system boundaries	Gupta J.	2023
[25]	Review of Quantitative Applications of the Concept of the Water Planetary Boundary at Different Spatial Scales	Han S.	2023
[13]	Challenges and opportunities for operationalizing the safe and just operating space concept at regional scale	Hossain M.S.	2019
[26]	The uptake of the biosphere integrity planetary boundary concept into national and international environmental policy	Hurley I.	2020
[27]	For an accounting translation of the Anthropocene: fuelling the debate on planetary boundaries	Jabot R.	2023
[28]	Potentials and limitations of footprints for gauging environmental sustainability	Laurent A.	2017
[9]	The role of planetary boundaries in assessing absolute environmental sustainability across scales	Li M.	2021
[29]	A review of collaborative planning approaches for transformative change towards a sustainable future	Linnenluecke M.K.	2016
[30]	Assessing and enhancing environmental sustainability—a conceptual review	Little J.C.	2016
[31]	What is a footprint? A conceptual analysis of environmental footprint indicators	Matušík J.	2021
[32]	A safe and just operating space for human identity: a systems perspective	Oliver T.H.	2022
[6]	Downscaling the planetary boundaries in absolute environmental sustainability assessments—A review	Ryberg M.W.	2020

Table 2. Cont.

Ref.	Title	1st Author	Year
[12]	Paving ways for a sustainable future: a literature review	Shao Q.	2020
[33]	How to conceptualize and operationalize resilience in socio-ecological systems?	Sterk M.	2017
[34]	Policy design for the Anthropocene	Sterner T.	2019
[7]	Downscaling doughnut economics for sustainability governance	Turner R.A.	2022
[35]	Horses for courses: analytical tools to explore planetary boundaries	Van Vuuren D.P.	2016
[36]	Environmental footprint family to address local to planetary sustainability and deliver on the SDGs	Vanham D.	2019
[37]	Framework to define environmental sustainability boundaries and a review of current approaches	Vea E.B.	2020
[10]	City footprints and SDGs provide untapped potential for assessing city sustainability	Wiedmann T.	2021
[38]	A planetary boundary-based environmental footprint family: From impacts to boundaries	Wu L.	2021
[39]	The Progress and Prospects in the Scenario Simulation Research on the Sustainability of Regional Ecosystem Services Based on a “Safe Operating Space”	Zhang X.	2023

Source: Author’s own elaboration.

3. Characteristics of the Selected Corpus

3.1. Interdisciplinarity

To assess the interdisciplinarity of the corpus, we analyzed the terms used in the title of the organizations represented by the authors of the selected articles. The IramuTeQ software helped to determine the occurrence of terms, while the disciplinary classification of terms was based on the European Research Council’s categorization [40]. This method provides a qualitative assessment of the primary field to which terms with an occurrence of more than 1% referred. It should be noted that the classification of terms is considered independently of the content of the article. This classification is therefore qualitative and cannot be considered quantitative information.

The most frequent terms are related to physical and engineering sciences, but social sciences, humanities, and life sciences are also represented (Figure 1).



Figure 1. Representation of scientific fields addressing Planetary Boundaries. Legend: the colors refer to scientific fields according to the European Research Council’s categorization: green for “Physical Sciences and Engineering”; orange for “Social Sciences and Humanities”; and purple for “Life Sciences”. Source: Author’s own elaboration.

3.2. Geographical Distribution

The geographical scope of the corpus was assessed by listing the countries where the organizations represented by the authors of the selected articles are based. When an author contributed to several articles, the country of the institution represented was counted as many times as necessary. All continents are represented (Figure 2).

Geographical distribution of the countries where the organizations represented by the authors of the selected articles are based

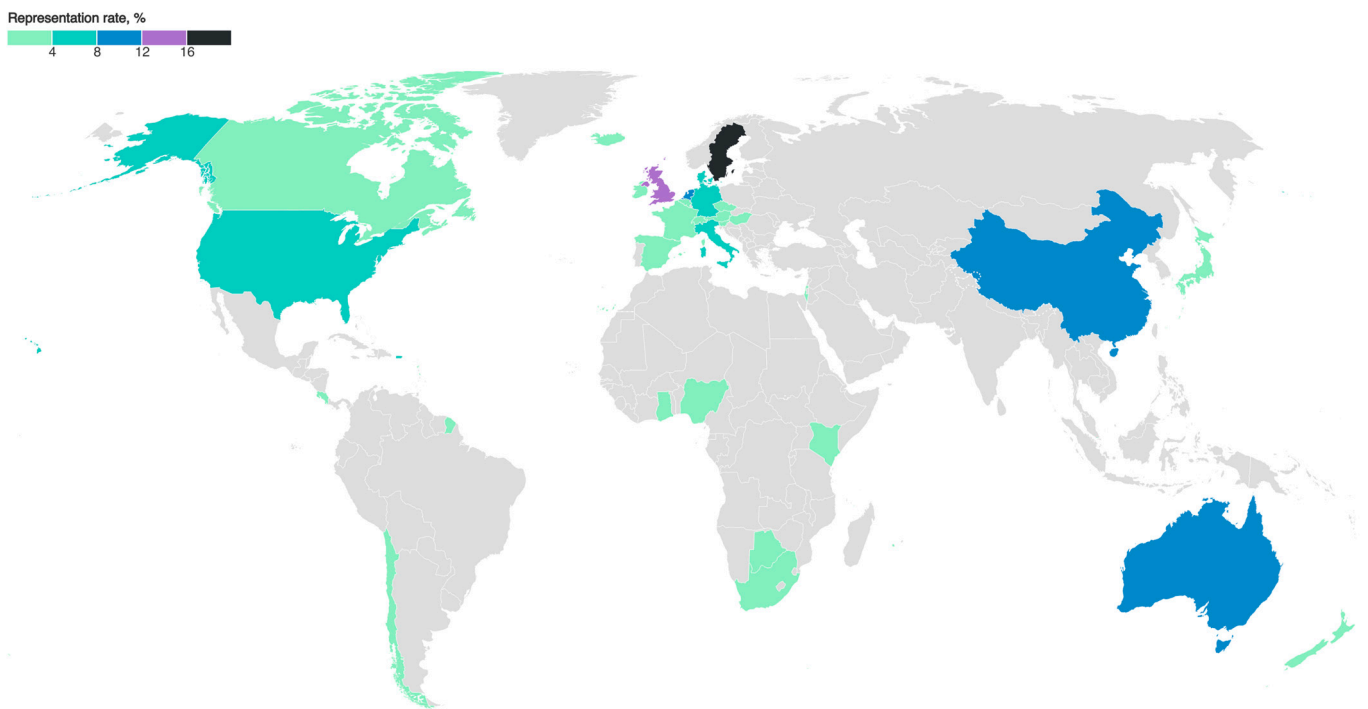


Figure 2. Geographical distribution of the countries where the organizations represented by the authors of the selected articles are based, in terms of frequency. Source: Author's own elaboration.

The analysis shows an unequal geopolitical distribution, with a strong predominance of OECD countries (88%). This regional imbalance reflects broader structural disparities in global sustainability research, where high-income countries dominate scientific output production. Nevertheless, the inclusion of studies from all continents provides a relatively diverse set of perspectives, which is essential for analyzing the downscaling of Planetary Boundaries concept across various social and environmental contexts.

3.3. A Critical Perspective on Planetary Boundaries

In addition to its interdisciplinary nature and international scope, the selected corpus is open to other concepts, frameworks, and analytical tools:

- In total, 29% of the corpus deals with the following: footprints; life cycle assessment, and absolute environmental sustainability assessment (AESA).
- In total, 26%: Sustainable development goals and the concept of sustainability.
- In total, 24%: Doughnut economics.
- In total, 12%: Systems analysis (SES, socio-technical systems) and systemic modeling; putting the PBC into perspective with environmental policies, types of governance, and participatory approaches.

In conclusion, the interdisciplinary nature and geographical diversity of the selected corpus minimizes disciplinary and cultural biases and ensures a broad and inclusive assessment of the localization and local operationalization of the Planetary Boundaries concept. Furthermore, comparing this concept with other frameworks, tools, and concepts reduces intellectual silos and opens up new perspectives.

By founding this study on this corpus, the authors aim to better understand the main issues related to the downscaling of the PBC.

4. Method for Identifying Issues Related to the Downscaling of Planetary Boundaries Concept

As detailed in the previous sections, the methodology employed for the selection of the review articles was meticulously defined, and the characteristics of the resulting corpus were ascertained. The corpus exhibits four defining characteristics: international scope, multidisciplinary breadth, scientific rigor, and comprehensive and critical approach both for the Planetary Boundaries concept (PBC) and the issues associated with its downscaling. This corpus and its characteristics thus constitute a substantial empirical basis for corroborating the data collected during the review of the 34 articles.

To ensure the rigorous extraction of relevant data, a four-step methodology was implemented. This systematic approach enables the identification, organization, and presentation of the challenges inherent in the localization and local operationalization of the PBC, as illustrated in Figure 3.

FLOWCHART FOR SELECTING AND CLASSIFYING ISSUES RELATED TO THE PROCESS OF DOWNSCALING PLANETARY BOUNDARIES

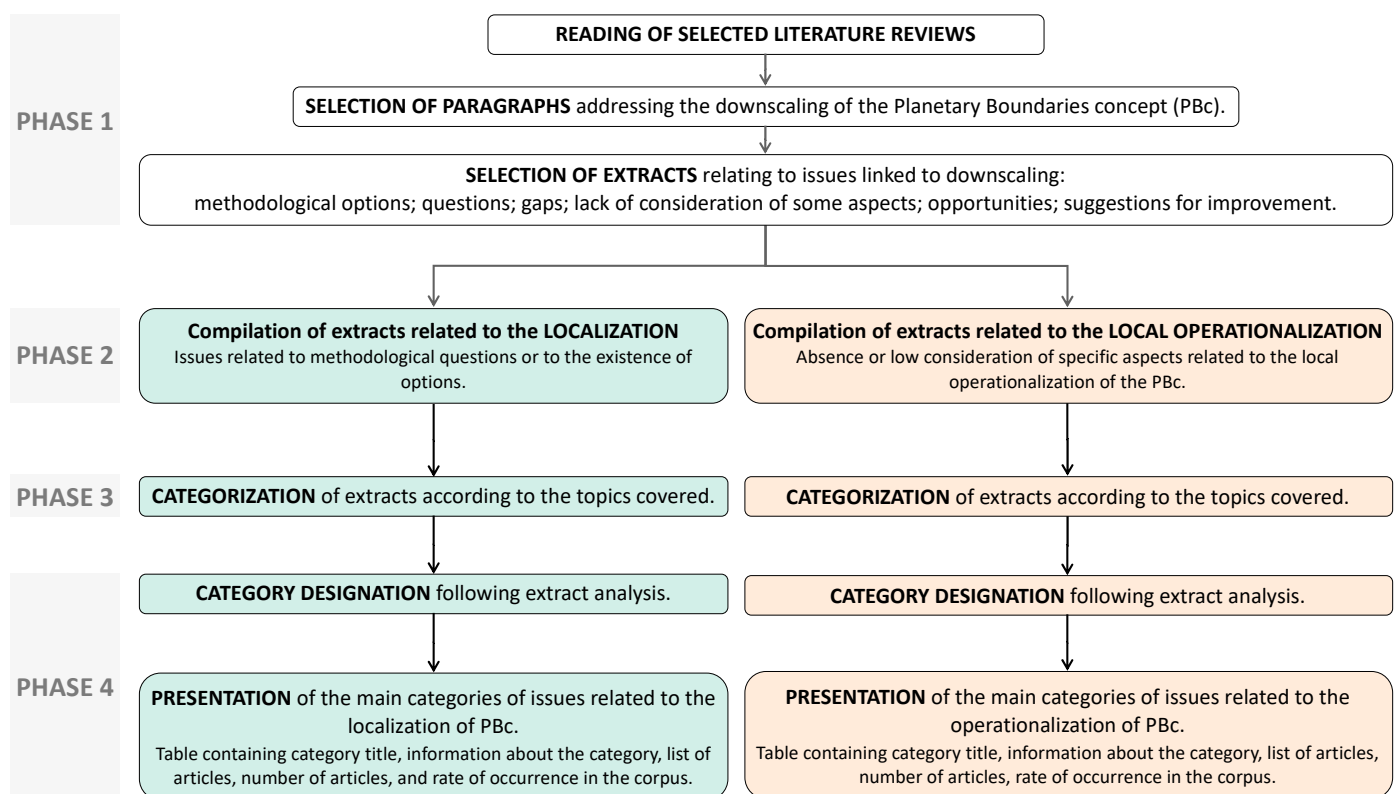


Figure 3. Methodological flowchart for the analysis of selected articles. Source: Author's own elaboration.

4.1. Phase 1: Data Collection

The first phase consisted of an exhaustive review of the selected corpus to identify paragraphs addressing the challenges of downscaling Planetary Boundaries. Through paragraph analysis, we identified recurring challenges including methodological options, theoretical questions, knowledge gaps, research suggestions, and emerging approaches.

4.2. Phase 2: Localization or Local Operationalization

The extracts obtained in phase one were separated into two groups: the localization (local representation or adaptation) and the local operationalization (local actions aligned with the global concept).

The extracts related to localization mainly discussed questions, divergences, or options. They refer to technical parameters related to methods used for representing the PBc locally.

The extracts on local operationalization address the difficulties in developing actions or decision making aligned with the PBc. The extracts mainly refer to the absence or low consideration of aspects that are necessary or useful for this aim.

4.3. Phase 3: Categorization

In this phase, each of the issues was organized and classified according to specific themes, based on a qualitative analysis of the selected extracts. This approach allowed us to generate themes in an evolutionary way, adjusting and refining the categories as the analysis progressed. This dynamic process provides an accurate and nuanced representation of the issues at stake.

4.4. Phase 4: Presentation

After organizing the extracts, titles were assigned to each theme: in the form of a question for those related to localization, and of a gap for those related to local operationalization.

This phase resulted in two structured tables showing the challenges of localization and local operationalization of the PBc. For each theme, the tables give the reference and number of review articles that cover it, as well as its frequency in the corpus.

4.5. Examples

Here are two representative examples illustrating the method:

- “This demonstrates that a scale for localized planetary boundaries needs to be chosen that makes absolute sustainability assessment meaningful and comparable.” (Wiedmann and Allen, 2021) [10]. This extract addresses a choice related to localization (“localized planetary boundaries”) and concerns the theme of scale.
- “For this reason, measuring urban environmental boundaries should take into account the threshold behaviors as well as social priorities within various forms of cities.” (Chen et al., 2021) [16]. In this extract, we identify a suggestion for improving operationalization: “take into account threshold behaviors as well as social priorities.” This fits into a theme related to better consideration of local stakeholders and the social context.

5. Results

Through the systematic analysis of the corpus, this section presents the empirical findings, listing the issues related to the downscaling of the Planetary Boundaries concept, their category, and their occurrence.

The analysis of 34 review articles identified a wide range of issues related to the downscaling of the Planetary Boundaries concept (PBc), which can be divided into two main groups: methodological issues of localization and gaps hindering the local operability of the PBc.

5.1. The Questions About Localization

Methodological issues (Table 3) focus on how to adapt the PBc to local contexts or how to produce localized representations of them while maintaining their global relevance.

Table 3. Classification of the main issues in the localization of the Planetary Boundaries concept.

IL n°	Key Issues in the Localization of the Planetary Boundaries Concept Available Options (Non-Exhaustive list) or Additional Information	Review Articles		
		List	Total	%
1	What is the right scale? What geographical scope? Global, continental, national, subnational? Multiregional, cross-border?	[6–8,10,11,13–17,20,21,25,26,30,33–36,38,39]	21	62
2	What are the characteristics of this method?	[7–11,14–16,19–23,25,27,31–34,37,39]	21	62
2.a	Methodology: Bottom-up, top-down, or mixed?	[7–11,14,16,20–22,25,31–33,37,39]	16	47
2.b	Other characteristics of the method: - General or specific, fixed or adaptable? - Integrated? Systemic? - Analysis based on consumption or production? - Technocratic or democratic development and application?	[7–10,15,19–21,23,27,34]	11	32
3	How to determine local boundary values? - How should limits be shared? - How should the level of responsibility be assessed? - What ethical principles should guide the calculation of sharing? For which processes? - What denominators should be used to share limits? - What time scope should be considered? How should changes in global boundaries be considered? - What are the criteria for determining the boundary value for each process?	[6–11,13–16,20,21,23,27,28,31,36,38]	18	53
4	How can consistency be maintained between the global concept, its local representations, and the local context? - How can the global concept be made relevant at all levels? How can its global scope be linked to the countless specific features of local contexts? - How can local specificities be respected when downscaling the global framework? - How can the issues and constraints of local governance be linked to global challenges?	[7,8,11,13,15,16,20,21,25,27,30,33–35,38]	15	44
5	Which indicators? True to the local context or identical to the originals? Aggregated or not?	[7,8,10,13,14,16,18,19,21,23,25,27,36,38]	14	41
6	What type of area should be assessed? Administrative, natural, or mixed areas?	[8,11,13–15,20,21,26,33–36,39]	13	38
7	Should a standardized method be developed?	[6,8–10,13,14,20,28,34,37]	10	29
8	What are the qualities of data to prioritize? Availability; traceability; levels of uncertainty; democratic quality; accessibility?	[7,10,13,14,16,19,25]	7	21
9	Should new biophysical processes or environmental issues be added? Materials; food production; issues specific to the area studied. . .	[7,9,11,21]	4	12
10	How can time be integrated into the method?	[13,25,35]	3	9

Source: Author's own elaboration.

The first issue raised, discussed in 62% of the review articles selected, concerns the scale at which the PBC should be applied. Its localization requires in-depth reflection on the most appropriate administrative scale, whether national, regional, or local, and on how to spatialize data to adapt the boundaries to local realities.

Another major challenge, also addressed in 62% of the corpus, focuses on the methodological characteristics of the localization approach. Among these challenges, the first concerns the direction of the method (50%): should we favor a bottom-up approach, which considers the realities of local stakeholders, or a top-down approach, based on global policies and the global framework of Planetary Boundaries (PBf)? The second set of questions (32%) concerns other possible characteristics of the methods used. Should a fixed method be favored, identical regardless of the scale or territory studied, or should methods be adapted to local specificities? This question addresses the approach's nature: should experts dominate (technocratic), or should local stakeholders participate (participatory)? The choice between consumption-based and production-based analysis represents another central element.

These reflections are accompanied, in 53% of the corpus, by ethical and practical issues, mainly related to the sharing of the global boundary values of the PBf between local entities. This raises necessary questions about the responsibility, at various time scales, of local stakeholders in exceeding the boundary values and about the ethical principles to be followed to ensure a fair distribution of constraints.

In this context, maintaining consistency between the global and local scales, highlighted in 44% of publications, is a key challenge, as it is linked to most of the other challenges listed in Table 3, particularly those relating to the relevant scale, processes, indicators, the direction of the method, and the nature of the area being assessed. This issue therefore calls into question the ability to establish consistency between local characteristics, the local representation of PBc, and the relevance of the global framework.

In line with the previous challenge, 41% of articles address a point of tension concerning the choice of which indicators to prioritize: should global indicators be retained, even though they may be too general and lack consistency with the local context, or should they be adapted to better reflect local specificities but lose their link with the global framework?

Similarly, 38% of articles link this consideration to the question of the preferred type of scale: administrative (municipal, regional) or natural (ecosystem, biological unit, watershed)?

In 29% of articles, the standardization of methods for localizing the PBc is identified as a major challenge. Although a standardized method ensures data consistency, it may not take local specificities into account.

In relation to the question of indicators, 21% of articles question the quality of the data used to measure the PBf locally. The availability of data, its accessibility, its monitoring over time, and the associated uncertainty are essential elements in ensuring a reliable local assessment of the PBf.

For 12% of the corpus, the issue raised by the choice of indicators also applies to the choice of biophysical processes. Indeed, it may be relevant to integrate new issues specific to each territory, whether or not they are related to the global processes of the PBf.

Finally, some articles (9%) raise questions about the temporal continuity of the down-scaling of the PBc.

In conclusion, Table 3 shows that there are numerous methodological issues surrounding the localization of the PBc. They focus on 10 major themes: the right scale; the technical characteristics of the method; the sharing of boundary values; the consistency between scales; the choice of indicators; the nature of space; the standardization; the data quality; the environmental issues; and the integration of future developments. Ultimately, most of the challenges associated with localizing the PBc are related to maintaining consistency among scales, as mentioned in the article by Ferretto [8]. This challenge is central to the localization of planetary boundaries but also to their local operationalization. It influences

the local relevance of these global challenges and, in doing so, affects their uptake by local stakeholders.

5.2. Gaps in the Local Operationalization of Planetary Boundaries

In the process of downscaling the Planetary Boundaries concept (PBC), we suggest that its localization is a prerequisite for its local operationalization, i.e., the development of local responses aligned with the global challenges of this concept. Following the localization issues, we have therefore categorized the major issues related to the local operationalization of the PBC (Table 4).

Table 4. List of gaps for better local operationalization of Planetary Boundaries.

OI n ^o	Issues in the Local Operationalization (OI) of the Planetary Boundaries Concept	Review Articles		
		List	Total	%
1	Local stakeholders (decision-makers, method users, citizens, residents) can be considered and mobilized.	[6–9,11–17,19–21,24,27,29,32,34,39]	20	59
2	Limited understanding of local socio-environmental dynamics.	[7,9,13,15–17,20,21,25,29,33,34,37]	13	38
3	Low legitimacy of the concept on a local scale: absence from legal texts; limited political support; lack of relevance on a local scale due to its global nature.	[7,10,11,13,15,19,20,24,34]	9	26
4	There is little consideration of the need to rethink governance within and between organizations and to implement appropriate policies.	[7,11,13,19,20,29,34]	7	21
5	No clearly defined aims for the context.	[7,19,20,29,34]	5	15
6	Underestimation of the resources required (financial, human, intellectual).	[7,10,19,34]	4	12
7	No consideration of how to maintain the approach over time.	[7,9,21]	3	9
8	Lack of transparency regarding the characteristics and uncertainties of the method.	[14,27]	2	6

Source: Author's own elaboration.

The literature reveals insufficient stakeholder engagement as the primary impediment (59% of corpus), encompassing decision-makers, citizens, and community representatives—constituencies whose involvement proves essential for the development and operationalization of responses.

Another key issue is the difficulty of adapting the PBC to local realities (38% of the corpus). Local socio-environmental dynamics vary considerably depending on geographical contexts. This diversity makes adapting the PBC to each context unique and particularly complex. This difficulty widens the gap between global aims and practical solutions at the local scale, thereby compromising their effectiveness.

A third major obstacle observed is the lack of legitimacy of the PBC for local stakeholders (26%). This can be deduced from the absence of legal obligations (e.g., there is no law requiring planetary boundaries to be assessed at the local scale), weak political support (e.g., the concept is not supported by politicians), and a perceived lack of relevance to the territory (e.g., it is a concept designed for the global scale and therefore disconnected from local specificities).

Another important gap is the need to rethink the governance and organization of local institutions (21%) to better integrate the PBC. These review articles highlight the importance of rethinking local governance structures. This involves reflecting on how local institutions can better collaborate and coordinate their actions to effectively integrate the PBC into local public policies and strategies.

It also appears that some practical issues need to be addressed to ensure the local success of the PBC. Among these, the lack of clear and appropriate goals (15%) can lead to scattered and ineffective efforts, as well as an underestimation of the resources (12%)—financial, human, and intellectual—needed for their effective operationalization at the local

scale. Furthermore, the sustainability of the approach remains uncertain. Nine percent of articles mention the lack of strategies to maintain this approach over time.

Finally, another challenge concerns transparency regarding the methods used to localize the PBC and the associated uncertainties (6% of the corpus). This raises doubts about the validity and impartiality of the process.

In summary, this study identifies several obstacles to the local operationalization of the planetary boundaries concept (PBC). The main obstacle is the low level of commitment among local stakeholders, partly due to the difficulty of adapting the concept to local contexts, to its lack of legitimacy, and to the inadequacy of governance structures. Added to this are the absence of clear goals, the lack of resources, the uncertainty about the durability of the approach over time, and a lack of transparency in the applied methods. Some of these issues have already been highlighted in the previous sections and compromise the effectiveness of PBC integration at the local scale.

In conclusion, by analyzing selected review articles, this study identifies and organizes the issues related to the adaptation or local representation of the PBC (Table 3), as well as the development of concrete actions aligned with this concept (Table 4).

6. Analysis of Results and Theoretical Contributions

Moving from description to interpretation, this section analyzes patterns deriving from the empirical results and describing the relationship between the localization approach used and the operational results achieved. In doing so, it develops three theoretical contributions that clarify the central question of this paper: does the biophysical dimension of the Planetary Boundaries framework (PBf) hinder the local operationalization of the Planetary Boundaries concept (PBC)?

In the first part, based on the issues raised by localization, we highlight the existence of a prevalent approach to PBC localization. In the second part, the challenges to operationalization are linked to three categories of constraints, which shed light on their underlying causes. In the third part, by linking these categories of constraints to the characteristics of the prevalent approach, we reveal an inherent contradiction: although designed to drive the local operationalization of the PBC, this localization approach tends, ultimately, to limit its effective operationalization. This concept is referred to as the “operational paradox” of the prevalent approach to PBC localization.

6.1. A Prevalent Approach to Localizing Planetary Boundaries Concept

In the introduction to this article, we emphasized the need to operationalize the PBC at the local scale. However, this cannot be achieved without adapting the concept to the specific local contexts (localization). This localization has two components: first, identifying the object to be localized—that will be represented locally—and second, transforming this object that is supra-local in nature into an object that has meaning in the local context.

In this study, an “object” refers to a concept or its components that will be measured, analyzed, or adapted during localization. For the PBC, this may correspond to the complete concept, or to some of its components, such as biophysical processes; boundary values of indicators; indicators; the system under study; or the notion of “Safe Operating Space for Humanity.” Considering the issues associated with the localization of the PBC, as described above (Table 3), the objects that appear to be most studied are indicators and boundaries (Table 5). These objects are among the seven key components of the PBf: system, reference state, biophysical processes, indicators, thresholds, boundaries, and state of processes. It is relevant to note that two components of this framework are not among the transformed objects: “system” and “reference state”. However, these components have the particularity

of not being described by numerical data. Consequently, we conclude that the quantified or quantifiable components of the PBf have been prioritized in localization efforts.

Table 5. Main objects and transformations used to locate Planetary Boundaries in relation to localization issues.

Key Issues in the Localization of Planetary Boundaries		Constituents of the Localization Process	
Available Options (Non-Exhaustive List) or Additional Information	%	Localized Object	Transformation Used to Locate the Object
What is the right scale? What geographical scope? Global, continental, national, subnational? Multiregional, cross-border?	62		The questions of scale and geographical scope seem to point towards spatialization .
What are the characteristics of this method?	62		
Methodology: Bottom-up, top-down, or mixed?	47	The boundary value of indicators.	Transformation is closely linked to the direction of the method: top-down implies sharing ; bottom-up favors contextualization .
Other characteristics of the method: - General or specific, fixed or adaptable? - Integrated? Systemic? - Analysis based on consumption or production? - Technocratic or democratic development and application?	32	These questions seem to focus on a numerical object (statistical data) .	The standardization of a method is often based on statistical data and therefore favors transformation through quantification .
How to determine local boundary values? - How should limits be shared? - How should the level of responsibility be assessed? - What ethical principles should guide the calculation of sharing? For which processes? - What denominators should be used to share limits? - What time scope should be considered? How should changes in global boundaries be considered? - What are the criteria for determining the boundary value for each process?	53	All the questions show the importance attached to the components of the biophysical framework of the Planetary Boundaries, and, in particular, the boundary values .	Sharing .
How can consistency be maintained between the global concept, its local representations, and the local context? - How can the global concept be made relevant at all levels? How can its global scope be linked to the countless specific features of local contexts? - How can local specificities be respected when downscaling the global framework? - How can the issues and constraints of local governance be linked to global challenges?	44	Planetary Boundaries framework; process boundary values	This question refers to the direction of the method: top-down implies sharing ; bottom-up favors contextualization .
Which indicators? True to the local context or identical to the originals? Aggregated or not?	41	Indicators	Should we give priority to the original indicator, with no transformation , or redefine it to take account of specific local environmental factors (contextualize the indicator)?
What type of area should be assessed? Administrative, natural, or mixed areas?	38		Spatialization
Should a standardized method be developed?	29		Standardization often requires quantified objects that involve local quantification as a transformation.
What are the qualities of data to prioritize? Availability; traceability; levels of uncertainty; democratic quality; accessibility?	21		The importance of issues related to the characteristics of numerical data confirms the importance of quantification .
Should new biophysical processes or environmental issues be added? Materials; food production; issues specific to the area studied. . .	12	Processes	Should priority be given to global biophysical processes, no transformation , or should they be redefined to take account of local environmental specificities (contextualization), or should additional processes be added (contextualization)?
How can time be integrated into the method?	9		

Source: Author's own elaboration.

The second component of the localization process, “transformation,” refers to the adjustments needed to adapt objects to the local context.

Table 5 presents the transformations associated with each localization issue. We identify four types:

- **Sharing:** Distributing numerical objects using local statistical data (quantification).
- **Contextualization:** Redefinition of the object in relation to the context.
- **Spatialization:** Cartographic representation of the object (quantification).
- **No Transformation:** The localized object is identical to the global object.

When seeking to adapt the Planetary Boundaries framework (PBf) to the local scale, objects can be transformed in different ways. Sharing and Spatialization are approaches that use the quantification of objects: for example, a global boundary value (such as a maximum amount of CO₂ emissions) can be distributed across a defined administrative scale. Contextualization, on the other hand, may also use numerical data, but it works differently. It does not simply apply a piece of data to a smaller scale; it seeks to rethink the global object in terms of local characteristics, whether environmental (type of ecosystem), social (inequalities, local uses), or cultural. In addition, the choice of transformation is also linked to the type of object being localized. If the object is already measured or measurable (such as a numerical boundary value defined in the PBf), quantification tends to be chosen because it is directly applicable. But if the object is more conceptual—such as the notions of “system” or “reference state”—then Contextualization appears more relevant, as it allows for finer adaptation to the local reality. In practice, however, it is primarily the quantified elements of the global framework that are subjected to localization. This explains why quantification is currently the most widely used form of transformation.

At the same time, from a methodological perspective, Contextualization requires a bottom-up method to question the relevance of the object in relation to the context being studied. Sharing mainly uses a top-down approach, allocating a share of the global object to each local context. Spatialization mainly uses a mixed method, as it mainly builds on the Sharing but also requires in-depth knowledge of some characteristics of the context.

For example, local boundary values are mainly obtained by sharing global boundary values. However, they can be contextualized by redefining a boundary value derived from local environmental constraints. Indicators and processes are either identical to those in the global framework (no transformation) or modified or created to take account of the local environmental context (contextualization).

The localization issues presented in Table 5 seem to indicate that all four transformations are being questioned. However, a standardized method cannot be bottom-up, given the countless particularities of local contexts. Furthermore, issues relating to the standardization of data characteristics highlight the importance of local, numerical, and harmonized objects, which also suggests the use of a top-down method. However, of the four transformations discussed in Table 5, only Sharing and Spatialization can adopt a top-down method. This analysis therefore suggests that local quantification is the most prevalent transformation.

In summary, objects are the elements to be adapted to the local context, while transformations refer to the processes through which these objects are adapted to local specificities. On this basis, the analysis of issues related to the localization of the Planetary Boundaries concept (Pbc) leads us to identify a privileged localization approach, which uses the quantification as a transformation, and the numerical components of the Planetary Boundaries biophysical framework (PBf) as objects (indicators, limits). We thus identify the local quantification of the biophysical PBf as the localization approach of the Pbc that prevails among the experiments conducted until December 2023.

6.2. Categories of Constraints in the Local Operationalization of the Planetary Boundaries Concept

An analysis of local Pbc operationalization issues reveals three main categories of constraints that shed light on the current boundaries of localization. Table 6 summarizes these constraints as follows: insufficient consideration of the local context, weak social anchoring of the concept, and limited uptake of the concept and localization methods by stakeholders. These three categories highlight both theoretical and practical limitations that hinder the effective operationalization of the Pbc on a local scale.

Table 6. Categories of constraints hindering the local operationalization of Planetary Boundaries.

Issues in the Local Operationalization (OI) of the Planetary Boundaries Concept (PBC)	%	Categories of Constraints		
		Consideration of the Local Context	Social Components of the PBC	Uptake by Local Stakeholders
Local stakeholders (decision-makers, method users, citizens, residents) can be considered and mobilized.	59			OI.1
Limited understanding of local socio-environmental dynamics.	38	OI.2		
Low legitimacy of the concept on a local scale: absence from legal texts; limited political support; lack of relevance on a local scale due to its global nature.	26	OI.3	OI.3	OI.3
There is little consideration of the need to rethink governance within and between organizations and to implement appropriate policies.	21		OI.4	
No clearly defined aims for the context.	15		OI.5	
Underestimation of the resources required (financial, human, intellectual).	12	OI.6		
No consideration of how to maintain the approach over time.	9	OI.7		
Lack of transparency regarding the characteristics and uncertainties of the method.	6			OI.8

Source: Author's own elaboration.

6.2.1. Full Consideration of the Local Context

From a conceptual perspective, a lack of consideration and understanding of local socio-environmental dynamics (OI.2, 38% of the corpus) is a major impediment to adapting global aims to local realities. This is also true for the weak institutional and political legitimacy of the PBC's downscaling approach (OI.3, 26%). Without good alignment between the proposed solutions and local contexts, application of the PBC becomes less relevant and less effective.

From a practical perspective, it is necessary to consider the resources required (OI.6, 12%), whether financial, human, or intellectual, to localize the Planetary Boundaries and ensure their effective operationalization at the local scale. This issue is further accentuated by the time dimension (OI.7, 9%): it is essential to ensure the sustainability of the approach by reassessing and updating it regularly and by developing long-term actions.

6.2.2. Development of Social Components Specific to the PBC

The issue of the concept's legitimacy (OI.3, 26%) requires making it more understandable and accessible to stakeholders, taking into account the specific characteristics of the territory. This issue stems from the lack of connection between the global concept and the social and societal aspects of the context. Indeed, this concept is largely absent from legal texts, receives little support from political stakeholders, and, due to its global nature and the prevalence of its biophysical dimension, is disconnected from local socio-environmental realities.

Moreover, local governance needs to be rethought (OI.4, 21%) to better integrate the PBC into public policies. It is therefore essential to review the organization of local institutions and develop appropriate policies to ensure that the PBC is effectively considered in local decisions.

Finally, several articles highlight the need to explain the aims of the PBC for the territory (OI.5, 15%). Clear goals are needed to effectively guide the actions to be taken and to improve stakeholders' understanding of the concept. Indeed, only the compliance with the boundary values of global biophysical processes is implemented in the PBC's scale

change approach. The integration of social objectives specific to the concept could give more meaning to this approach.

The local operationalization of the Pbc therefore suffers from the absence of social components specific to the concept that could connect it to the territories: regulatory integration; political support; impacts on governance; and social goals and consequences, including the social transformations necessary to respect the biophysical objectives of the Pbc.

6.2.3. Uptake of the Concept and Localization Method

One of the main issues in local operationalization is the underestimation of the role of key stakeholders such as decision-makers, residents, and all other actors that are supposed to use the method (OI.1, 59%). This lack of involvement and effective acknowledgement of local stakeholders has a direct impact on the effectiveness of Planetary Boundaries operationalization at the local scale. Indeed, without active mobilization, it is difficult to ensure the uptake of the Pbc by the local community, which ultimately hinders their integration into local practices.

Finally, the uptake of the Pbc and the downscaling process by local stakeholders is hindered by the low level of consideration and involvement of local stakeholders, their lack of legitimacy in the territory (OI.3, 26%), and a lack of transparency in the localization methods (OI.8, 6%). However, the previous categories of constraints also have consequences for uptake. Indeed, full consideration of the local context and the development of social components specific to the Pbc that are capable of connecting it to the context contributes to its uptake by local stakeholders, who are the main protagonists of the local operationalization of the Pbc.

This reflection on the lack of a social component in the localization of the Pbc echoes the analysis of the multidisciplinary nature of the selected corpus. Indeed, the apparent underrepresentation of explicit social science terminology in the selected corpus paradoxically validates our central argument. This pattern reveals how discourse on the localization of the Pbc often addresses social challenges through technical language—a ‘depoliticized’ framing that may itself contribute to operational failures by obscuring power relations and social conflicts inherent in sustainability transitions (Swyngedouw, 2010) [41]. The marginalization of social sciences in the Pbc literature—as confirmed by Downing et al. [20] who note that ‘human dimensions’ remain a major gap—illustrates the very problem we diagnose: the dominance of biophysical interpretation that hinders local operationalization.

6.3. *The Operational Paradox of the Prevalent Approach to the Localization of the Pbc*

The previous sections have provided two essential contributions. First, a critical interpretation of how the Planetary Boundaries concept is localized, showing that the prevalent approach is mainly based on the transposition to the local scale of numerical thresholds derived from the global biophysical framework. Second, an analysis of the structural obstacles to local operationalization, emphasizing how it remains hindered by a lack of consideration of territorial specificities, the absence of social components clearly integrated into the conceptual framework, and the lack of commitment or uptake by local stakeholders.

Connecting these two contributions reveals a critical link: emphasizing Pbc biophysical components during Pbc localization creates the constraint categories that hinder local operationalization. As a result, the emphasis on the purely biophysical dimension is directly correlated with the absence of social components specific to the Pbc. Furthermore, the decision to quantify the numerical components of the Pbc, using a top-down approach, allows the designer of the localization method to minimize the importance of the local

context, or even to carry out the localization solely “in the lab.” In these conditions, the local context is given very little consideration, and local stakeholders are rarely involved in the localization process, which hinders their uptake of the PBc and of the method used to localize it.

As a result, the prevalent localization approach appears to generate constraints to local operationalization, or at least fails to remove them. This contradicts the fundamental purpose of PBc localization: to stimulate the development of local actions aligned with the PBc. In conclusion, the third contribution of this article is to identify a paradox: “the operational paradox of the prevalent approach to localizing the concept of Planetary Boundaries.”

It is relevant to note that this operational paradox, conceptually defined in the present research, can also be identified in concrete documented localization attempts. Three experiments can illustrate this phenomenon:

1. Hossain and Ifejika Speranza (2019) [13], drawing on Häyhä et al. (2016) [42], highlight that “*Though the initial delineation of SOS and SJOS was derived by the scientific community, designing SJOS for SES is often an ethical and political choice, as making the SJOS operational entails the engagement of relevant actors who operate at national and regional scales.*” This example demonstrates that operationalizing the PB is fundamentally an ethical and political choice requiring local and regional stakeholder commitment. Top-down quantitative approaches minimize their roles in the design process, creating buy-in deficits that hinder local operationalization. In other words, this case study highlights how the technical sophistication of quantification, far from facilitating operationalization, can paradoxically hinder it by excluding those who should implement it on the ground.
2. Turner and Wills (2022) [7] report from Cornwall: “*Our involvement in this process of applying the doughnut framework in Cornwall has illuminated the challenges identified in the literature (. . .) Representing, understanding and responding to complex systems: identifying goals and monitoring progress is hampered by a lack of suitable data, targets and indicators at a county scale, as well as conflicting views among Leadership Board partners around which indicators are most appropriate. Many national datasets are unavailable locally, and for some domains, no appropriate available indicators could be identified. Available indicators predominantly assess relative progress rather than change in relation to goals or limits, for which locally appropriate values are difficult to determine.*” The Cornwall experience provides a concrete example of the mismatch between the technical ambitions of the Planetary Boundaries framework and local operational realities. The lack of appropriate data, the absence of relevant indicators at the territorial scale, and disagreements among partners on the choice of metrics reveal that the focus on quantification creates practical obstacles. The pursuit of technical precision (locally appropriate boundary values) becomes counterproductive in the face of complex local systems; thus, an approach based solely on quantified indicators can hinder its own operationalization.
3. Hossain and Ifejika Speranza (2019) [13] illustrate how universal indicators can have contradictory meanings across territorial contexts by demonstrating how shrimp farming simultaneously represents environmental degradation in mangrove regions and essential livelihood provision in highly saline areas. This duality reveals the impossibility of applying universal indicators without considering the territorial and social context. The example demonstrates that a purely biophysical approach, by ignoring the specific social dimensions of territories, can generate contradictions that make operationalization not only difficult but conceptually impossible in some contexts.

These examples reveal the mechanism of the operational paradox. The technical sophistication increases the precision of results but reduces accessibility to the method. It creates scientifically robust metrics, which might be misaligned with governance in-

struments, and generates harmonized indicators that could obscure local meanings and overshadow the specificities of local contexts. This operational paradox also reflects deeper tensions within contemporary environmental governance: between scientific legitimacy and democratic legitimacy, between universal knowledge and localized knowledge, between technical solutions and social dynamics. This is not linked to a poor implementation but to fundamental assumptions about how global frameworks should guide local action: assumptions that prioritize measurement over meaning, precision over participation, and standardized solutions over locally tailored responses. Recognizing these tensions calls for a rethinking of policy frameworks, with a greater emphasis on territorial anchoring, stakeholder inclusion, and the co-construction of sustainability trajectories.

7. Discussion

This section summarizes the main results of this research and the theoretical insights that emerge from them. It organizes the key elements of the analysis in a summary diagram (Figure 4) and offers concrete suggestions to overcome the identified obstacles to local operationalization of the Planetary Boundaries concept (PBc). By connecting the currently prevalent localization approach—based on top-down quantification of the numerical components of the biophysical framework (PBf)—with the main obstacles encountered in the operationalization attempts, this section paves the way for three complementary proposals. These invite us to reconsider not only the objects and the transformation modalities chosen for localization but also the very interpretation of the Planetary Boundaries concept itself. This last point requires to make explicit the social dimension inherent to the PBc, and to detail its components in order to integrate them into the objects to be localized on equal footing with the biophysical components. Together, these proposals outline an innovative orientation for future research work on the local operationalization of the PBc.

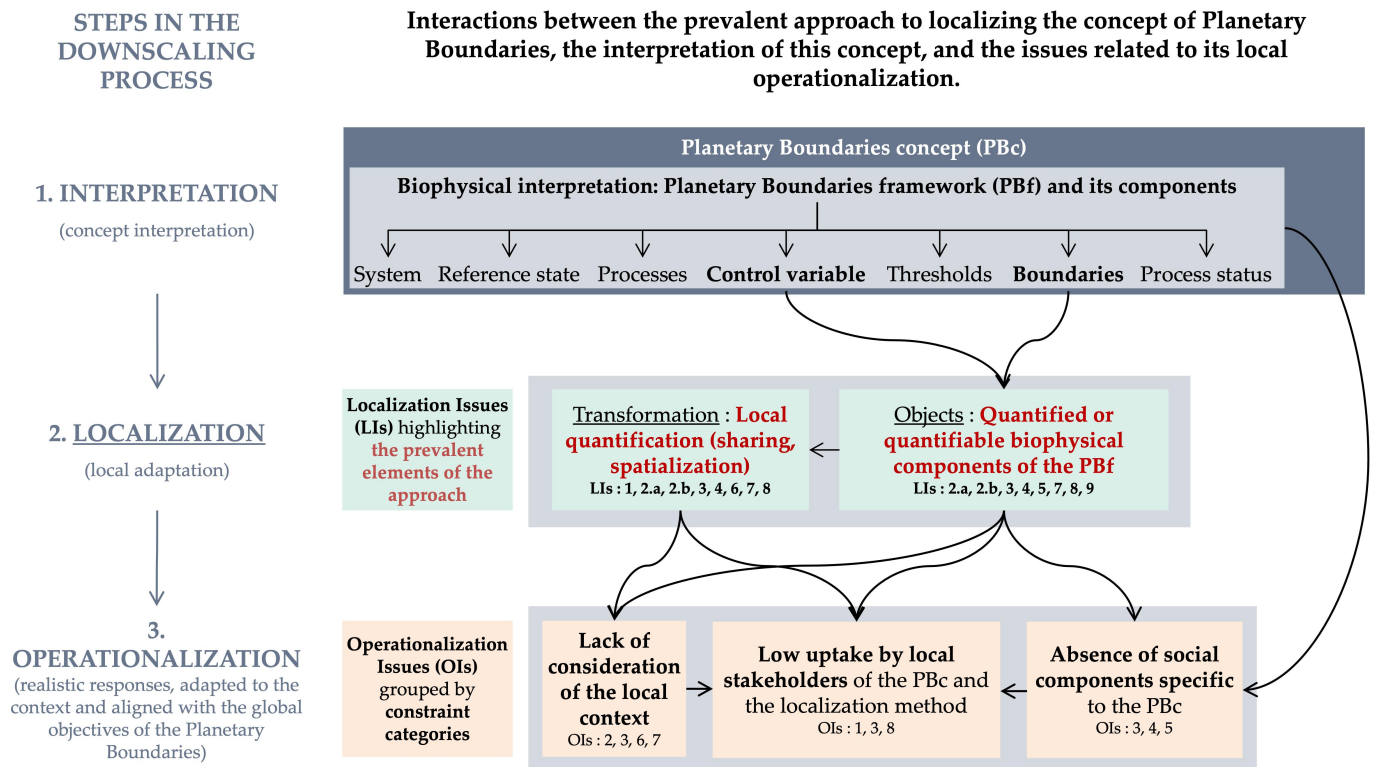


Figure 4. Interactions between the prevalent approach to localizing the Planetary Boundaries concept, its interpretation, and the issues related to its local operationalization. Source: Author’s own elaboration.

From top to bottom, Figure 4 follows the logical sequence of the three steps of the PBC downscaling process: Interpretation of the concept, Localization, and local Operationalization. In the Interpretation step, we distinguish between the Planetary Boundaries concept (PBC) and its purely biophysical interpretation developed within the Planetary Boundaries framework (PBf), which consists of seven components: system, reference state, biophysical processes, control variables, thresholds, boundaries, and state of processes. In the Localization step, we identify an object to be localized and a transformation that adapts this supra-local object into a local one. In doing so, the existence of a prevalent approach to PBC localization emerges (first contribution): the top-down quantification (transformation) of the numerical components of the PBf (objects: indicators and boundary values). This demonstrates that the objects used in the prevalent localization approach stem from an exclusively biophysical interpretation of the PBC. Regarding local operationalization, issues are grouped into three families of constraints (second contribution): integration of the local context; development of social components in the PBC; and appropriation of the localization concept and method by local stakeholders. The comparison of these two theoretical contributions leads to the identification of the operational paradox of the prevalent approach to PBC localization (third contribution).

7.1. Testing the Hypotheses

This graphical summary of this article's contributions (Figure 4) highlights the relevance of the three hypotheses formulated in the introduction and draws some key theoretical implications.

The top-down quantitative approach does indeed hinder local operationalization, thus confirming the second hypothesis; not only does this approach fail to overcome the issues of local operationalization inherent in downscaling, it also creates additional obstacles by marginalizing local stakeholders and ignoring contextual specificities.

The first hypothesis suggested that purely biophysical PBC interpretation favors quantification. However, results show this prevalent tendency is not inevitable. Within the biophysical framework itself, non-quantifiable components like 'system' or 'reference state' offer alternative paths. These qualitative elements require flexible, contextualized transformation modes that better articulate with territorial realities.

These insights also partially validate the third hypothesis. Figure 4 reveals that most operational constraints (OI.1, 2, 3, 6, 7, 8) result less from the biophysical interpretation itself than from its mechanical translation via top-down quantification. However, some fundamental issues—such as ensuring local significance of the concept (OI.4), rethinking territorial governance (OI.5), and strengthening local legitimacy (OI.3)—cannot be resolved within a purely biophysical framework. They require a reinterpretation of the Planetary Boundaries concept to integrate a social dimension capable of anchoring itself in the social dynamics of territories.

These results demonstrate that initial PBC interpretation substantially influences local action possibilities. A purely biophysical understanding of the concept weakens its interpretation. Moreover, it mainly leads to a top-down quantification of PBf components. This approach creates a problematic disconnect from territorial realities. Overcoming this impasse requires enriching the planetary boundaries concept with an explicit social dimension. This dimension must articulate global imperatives with both the diversity of local contexts and territorial stakeholders' action capacities.

7.2. Changing Methods or Perspectives: Three Proposals

In light of this discussion on the relevance of this hypotheses, the reflections developed in this article lead to the formulation of three proposals for improving the local operational-

ization of the Planetary Boundaries concept. These proposals are designed as reflections for future research, both theoretical and practical.

1. Modify the settings of the prevalent approach: The first proposal would be to fill the gaps hindering the operationalization of the Planetary Boundaries framework. As discussed, they are mostly related to the prevalent transformation used to localize the PBf: quantification.

2. Contextualization: The second proposal advocates for a contextualized approach based on rebuilding the entire PBf with local stakeholders. This method would allow for the better integration of specific territorial characteristics and for strengthening the uptake of the PBc at the local scale. It offers methodological flexibility while ensuring scientific rigor. However, this change alone will not resolve the challenges associated with the lack of a social dimension in the traditional interpretation of the PBc.

3. Contextualizing the socio-biophysical concept: The third proposal is to broaden the very content of the concept to be localized, integrating a full social dimension as a complement to the biophysical dimension of the PBf. To this end, the mere addition of social aspects is not sufficient (as conducted, for example, in the doughnut economics framework [43]); it is necessary to rethink the Planetary Boundaries concept as a socio-biophysical whole. This would make it possible, for example, to consider human responsibilities in exceeding boundaries or sustainability objectives for societies. Such an approach would strengthen the relevance of the concept on the local scale.

In conclusion, our analysis highlights that future research should develop, explore, and test the contextualization of a socio-biophysical interpretation of the PBc. This contextualization would therefore not be limited to indicators or boundary values but would apply to all social and biophysical components of the Planetary Boundaries concept.

7.3. Study Limitations

The current study entails some limitations, which nevertheless also provide interesting reflections that could benefit further research.

Methodological limitations: The qualitative analysis of review articles, while providing broad perspectives, may mask nuances present in empirical studies. The categorization process, though systematic, involves interpretative judgments that could be influenced by researcher bias. Nevertheless, qualitative analysis requires a detailed understanding of the paragraphs discussing the PBc and the context of this article to identify relevant extracts and categorize them. It is therefore uncertain whether an automated computer analysis would have generated a list of extracts as comprehensive as the one we produced through our analysis.

The uncertainty of scales: This research focuses on the issues posed by the downscaling of the Planetary Boundaries concept to the local scale. Although the selected review articles address this downscaling, some do not specify the scale considered, while others include supra-local scales; as a consequence, the issues identified could come from feedback at the regional, national, or even continental scale. To obtain greater precision, it would have been interesting to filter the selected extracts also according to the scale to which they refer. However, this would have required diving into the research articles referenced in the selected review articles. In doing so, the analysis would have lost its multidisciplinary and critical vision of the PBc, as it would have been based on experiments rather than on a set of experiences. Moreover, the issues identified are not incompatible with the local scale. We therefore consider the extracts selected to be relevant in providing answers to the question addressed in this article.

Geographical bias: The geographical concentration of research in OECD countries (88%) can limit our understanding of PB localization issues in the global south contexts,

where different governance structures, resource constraints, and frameworks apply. This bias is particularly relevant given that many critical Earth system thresholds are most acutely experienced in the Global South. This limitation may impact the findings in three ways: first, the operational issues identified may be amplified in Global South contexts where additional constraints exist (limited technical capacity, competing development priorities, and different governance structures). Second, findings about the ‘operational paradox’ may actually underestimate the challenges faced in non-OECD contexts, where the disconnect between technical quantification and local realities could be even more pronounced. Third, the dominance of northern perspectives in PB localization may itself contribute to operational failures, as it perpetuates epistemological hierarchies that marginalize alternative ways of conceptualizing human–environment relationships. However, these patterns align with broader inequalities in global environmental knowledge production, where the Global North dominates both research funding and publication venues (Pasgaard et al., 2015) [44]. Ultimately, this limitation reinforces the main argument: the technocratic approach to PB localization marginalizes local perspectives, including those from countries where different governance structures and resource constraints apply.

These limitations, while constraining our findings, also validate our central argument about the need for more inclusive and contextualized approaches to PB localization.

8. Conclusions

This research has explored the fundamental tensions between the global ambition of the Planetary Boundaries concept (PbC), its interpretation, localization, and operationalization at the local scale. Building on the analysis of a multidisciplinary and international corpus of 34 scientific literature reviews, this study makes significant theoretical and methodological contributions to the understanding of downscaling processes in environmental governance.

The deconstruction of this process (interpretation, localization—transformation and objects—, local operationalization) provides a new analytical framework that is more refined and operational, with precise vocabulary. This innovation makes it possible to identify where and how constraints to local operationalization arise.

The qualitative methodology developed provides an interesting contribution to the analysis of the issues involved in downscaling the PbC. Building on a systematic analysis of review articles, it enables these multidisciplinary issues to be extracted and categorized. In doing so, it reveals the predominance of a localization approach to the PbC: the local quantification of the numerical components of the biophysical framework of planetary boundaries. This empirical contribution demonstrates how underlying epistemological assumptions (interpretation) influence the localization approach.

Furthermore, categorizing operational constraints into three types provides a new framework for understanding recurring implementation failures: lack of knowledge of the local context, absence of social components in the concept during localization, and difficulties in uptake of the concept and localization method by local stakeholders. This typology goes beyond a simple technical inventory to reveal the socio-spatial and political dimensions inherent in downscaling processes.

The preceding contributions lead to the conceptualization of the “operational paradox,” the key theoretical contribution of this research. It argues that technically sophisticated localization methods can paradoxically generate constraints on the local operationalization they are supposed to facilitate. This systemic contradiction inherent in technocratic approaches to sustainability challenges the assumption that greater technical sophistication produces better operational results. Therefore, this paradox does not result from poor implementation but stems from fundamental epistemological assumptions that prioritize

measurement over meaning, precision over participation, and standardized solutions over locally adapted responses.

The theoretical scope of these contributions goes well beyond the Pbc. They highlight key challenges in environmental governance. They propose an analytical paradigm shift, transferring attention from “technical failures” to “systemic contradictions.” They reveal that Pbc localization is an inherently political process requiring the recognition of plural knowledge systems, explicit value negotiation, and attention to justice issues. Overall, they thus contribute to debates on the multi-scale governance of sustainability and on the modalities of articulation between expert knowledge and local knowledge, scientific universalism and territorial particularism, and scientific and democratic legitimacy.

These findings necessitate a fundamental reconceptualization of the localization approach. We propose an alternative pathway that integrates two complementary facets: a socio-biophysical interpretation of the Pbc that facilitates territorial anchoring and the contextualization of components deriving from this new interpretation. This alternative approach would prioritize territorial anchoring, stakeholder inclusion, and the co-construction of sustainability trajectories.

In today’s ecological urgency, this research shows that global scientific frameworks’ effectiveness depends more on embracing territorial complexity than on technical sophistication. The challenge extends beyond precise planetary boundary measurement. We must build conceptual and methodological bridges that connect global imperatives with local action capacities. It is in this articulation—between measurement and meaning, between precision and participation, between standardization and adaptation—that lies the transformative potential of the Planetary Boundaries concept to guide a just and territorially anchored ecological transition, paving the way for new paradigms of environmental governance adapted to contemporary systemic issues.

Author Contributions: Conceptualization, D.R.; methodology, D.R.; validation, D.R., G.D.O.-N. and G.M.; formal analysis, D.R.; investigation, D.R.; resources, D.R.; data curation, D.R.; writing—original draft preparation, D.R. and C.B.; writing—review and editing, G.D.O.-N., G.M. and C.B.; visualization, D.R.; supervision, D.R., G.D.O.-N. and G.M.; project administration, D.R. All authors have read and agreed to the published version of the manuscript.

Funding: The first author (D.R.) was funded by “ADEME”, “France Villes et Territoires Durables”, and “France Urbaine”.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of this study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

Pbc	Planetary Boundaries concept
Pbf	Planetary Boundaries framework
OIs	Operationalization issues
LIs	Localization issues

References

1. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.I.; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecol. Soc.* **2009**, *14*, art32. [\[CrossRef\]](#)
2. Rockström, J.; Donges, J.F.; Fetzer, I.; Martin, M.A.; Wang-Erlandsson, L.; Richardson, K. Planetary Boundaries Guide Humanity's Future on Earth. *Nat. Rev. Earth Environ.* **2024**, *5*, 773–788. [\[CrossRef\]](#)
3. Steffen, W.; Richardson, K.; Rockström, J.; Schellnhuber, H.J.; Dube, O.P.; Dutreuil, S.; Lenton, T.M.; Lubchenco, J. The Emergence and Evolution of Earth System Science. *Nat. Rev. Earth. Environ.* **2020**, *1*, 54–63. [\[CrossRef\]](#)
4. Caesar, L.; Sakschewski, B.; Andersen, L.S.; Beringer, T.; Braun, J.; Dennis, D.; Gerten, D.; Heilemann, A.; Kaiser, J.; Kitzmann, N.H.; et al. *Planetary Health Check Report 2024, a Scientific Assessment of the State of the Planet*; Planetary Boundaries Science: Potsdam, Germany, 2024.
5. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 1259855. [\[CrossRef\]](#)
6. Ryberg, M.W.; Andersen, M.M.; Owsianiak, M.; Hauschild, M.Z. Downscaling the Planetary Boundaries in Absolute Environmental Sustainability Assessments—A Review. *J. Clean. Prod.* **2020**, *276*, 123287. [\[CrossRef\]](#)
7. Turner, R.A.; Wills, J. Downscaling Doughnut Economics for Sustainability Governance. *Curr. Opin. Environ. Sustain.* **2022**, *56*, 101180. [\[CrossRef\]](#)
8. Ferretto, A.; Matthews, R.; Brooker, R.; Smith, P. Planetary Boundaries and the Doughnut Frameworks: A Review of Their Local Operability. *Anthropocene* **2022**, *39*, 100347. [\[CrossRef\]](#)
9. Li, M.; Wiedmann, T.; Fang, K.; Hadjikakou, M. The Role of Planetary Boundaries in Assessing Absolute Environmental Sustainability across Scales. *Environ. Int.* **2021**, *152*, 106475. [\[CrossRef\]](#)
10. Wiedmann, T.; Allen, C. City Footprints and SDGs Provide Untapped Potential for Assessing City Sustainability. *Nat. Commun.* **2021**, *12*, 3758. [\[CrossRef\]](#)
11. Biermann, F.; Kim, R.E. The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a “Safe Operating Space” for Humanity. *Annu. Rev. Environ. Resour.* **2020**, *45*, 497–521. [\[CrossRef\]](#)
12. Shao, Q. Paving Ways for a Sustainable Future: A Literature Review. *Environ. Sci. Pollut. Res.* **2020**, *27*, 13032–13043. [\[CrossRef\]](#)
13. Hossain, M.S.; Ifejika Speranza, C. Challenges and Opportunities for Operationalizing the Safe and Just Operating Space Concept at Regional Scale. *Int. J. Sustain. Dev. World Ecol.* **2019**, *27*, 40–54. [\[CrossRef\]](#)
14. Bjørn, A.; Chandrakumar, C.; Boulay, A.-M.; Doka, G.; Fang, K.; Gondran, N.; Hauschild, M.Z.; Kerkhof, A.; King, H.; Margni, M.; et al. Review of Life-Cycle Based Methods for Absolute Environmental Sustainability Assessment and Their Applications. *Environ. Res. Lett.* **2020**, *15*, 083001. [\[CrossRef\]](#)
15. Brown, K. Global Environmental Change II: Planetary Boundaries—A Safe Operating Space for Human Geographers? *Prog. Hum. Geogr.* **2016**, *41*, 118–130. [\[CrossRef\]](#)
16. Chen, X.; Li, C.; Li, M.; Fang, K. Revisiting the Application and Methodological Extensions of the Planetary Boundaries for Sustainability Assessment. *Sci. Total Environ.* **2021**, *788*, 147886. [\[CrossRef\]](#)
17. Cooke, B.; West, S.; Boonstra, W.J. Dwelling in the Biosphere: Exploring an Embodied Human–Environment Connection in Resilience Thinking. *Sustain. Sci.* **2016**, *11*, 831–843. [\[CrossRef\]](#)
18. Čuček, L.; Klemeš, J.J.; Varbanov, P.S.; Kravanja, Z. Significance of Environmental Footprints for Evaluating Sustainability and Security of Development. *Clean Technol. Environ. Policy* **2015**, *17*, 2125–2141. [\[CrossRef\]](#)
19. Dillman, K.J.; Heinonen, J.; Davíðsdóttir, B. A Development of Intergenerational Sustainability Indicators and Thresholds for Mobility System Provisioning: A Socio-Ecological Framework in the Context of Strong Sustainability. *Environ. Sustain. Indic.* **2023**, *18*, 100240. [\[CrossRef\]](#)
20. Downing, A.S.; Bhowmik, A.; Collste, D.; Cornell, S.E.; Donges, J.; Fetzer, I.; Häyhä, T.; Hinton, J.; Lade, S.; Mooij, W.M. Matching Scope, Purpose and Uses of Planetary Boundaries Science. *Environ. Res. Lett.* **2019**, *14*, 073005. [\[CrossRef\]](#)
21. Feitelson, E.; Stern, E. The Double Negative Approach to Sustainability. *Sustain. Dev.* **2023**, *31*, 2109–2121. [\[CrossRef\]](#)
22. Gebler, M.; Juraschek, M.; Thiede, S.; Cerdas, F.; Herrmann, C. Defining the “Positive Impact” of Socio-Technical Systems for Absolute Sustainability: A Literature Review Based on the Identification of System Design Principles and Management Functions. *Sustain. Sci.* **2022**, *17*, 2597–2613. [\[CrossRef\]](#)
23. Goodwin, K.; Wiedmann, T.; Chen, G.; Teh, S.H. Benchmarking Urban Performance against Absolute Measures of Sustainability—A Review. *J. Clean. Prod.* **2021**, *314*, 128020. [\[CrossRef\]](#)
24. Gupta, J.; Liverman, D.; Prodani, K.; Aldunce, P.; Bai, X.; Broadgate, W.; Ciobanu, D.; Gifford, L.; Gordon, C.; Hurlbert, M.; et al. Earth System Justice Needed to Identify and Live within Earth System Boundaries. *Nat. Sustain.* **2023**, *6*, 1–9. [\[CrossRef\]](#)
25. Han, S.; Leng, G.; Yu, L. Review of Quantitative Applications of the Concept of the Water Planetary Boundary at Different Spatial Scales. *Water Resour. Res.* **2023**, *59*, e2022WR033646. [\[CrossRef\]](#)
26. Hurley, I.; Tittensor, D.P. The Uptake of the Biosphere Integrity Planetary Boundary Concept into National and International Environmental Policy. *Glob. Ecol. Conserv.* **2020**, *22*, e01029. [\[CrossRef\]](#)

27. Jabot, R. For an Accounting Translation of the Anthropocene: Fuelling the Debate on Planetary Boundaries. *Sustain. Account. Manag. Policy J.* **2023**, *14*, 21–48. [[CrossRef](#)]
28. Laurent, A.; Owsianiak, M. Potentials and Limitations of Footprints for Gauging Environmental Sustainability. *Curr. Opin. Environ. Sustain.* **2017**, *25*, 20–27. [[CrossRef](#)]
29. Linnenluecke, M.K.; Verreynne, M.-L.; de Villiers Scheepers, M.J.; Venter, C. A Review of Collaborative Planning Approaches for Transformative Change towards a Sustainable Future. *J. Clean. Prod.* **2017**, *142*, 3212–3224. [[CrossRef](#)]
30. Little, J.C.; Hester, E.T.; Carey, C.C. Assessing and Enhancing Environmental Sustainability: A Conceptual Review. *Environ. Sci. Technol.* **2016**, *50*, 6830–6845. [[CrossRef](#)]
31. Matuščík, J.; Kočí, V. What Is a Footprint? A Conceptual Analysis of Environmental Footprint Indicators. *J. Clean. Prod.* **2021**, *285*, 124833. [[CrossRef](#)]
32. Oliver, T.H.; Doherty, B.; Dornelles, A.; Gilbert, N.; Greenwell, M.P.; Harrison, L.J.; Jones, I.M.; Lewis, A.C.; Moller, S.J.; Pilley, V.J.; et al. A Safe and Just Operating Space for Human Identity: A Systems Perspective. *Lancet Planet. Health* **2022**, *6*, e919–e927. [[CrossRef](#)] [[PubMed](#)]
33. Sterk, M.; van de Leemput, I.A.; Peeters, E.T. How to Conceptualize and Operationalize Resilience in Socio-Ecological Systems? *Curr. Opin. Environ. Sustain.* **2017**, *28*, 108–113. [[CrossRef](#)]
34. Sterner, T.; Barbier, E.B.; Bateman, I.; van den Bijgaart, I.; Crépin, A.-S.; Edenhofer, O.; Fischer, C.; Habla, W.; Hassler, J.; Johansson-Stenman, O.; et al. Policy Design for the Anthropocene. *Nat. Sustain.* **2019**, *2*, 14–21. [[CrossRef](#)]
35. van Vuuren, D.P.; Lucas, P.L.; Häyhä, T.; Cornell, S.E.; Stafford-Smith, M. Horses for Courses: Analytical Tools to Explore Planetary Boundaries. *Earth Syst. Dynam.* **2016**, *7*, 267–279. [[CrossRef](#)]
36. Vanham, D.; Leip, A.; Galli, A.; Kastner, T.; Bruckner, M.; Uwizeye, A.; van Dijk, K.; Ercin, E.; Dalin, C.; Brandão, M.; et al. Environmental Footprint Family to Address Local to Planetary Sustainability and Deliver on the SDGs. *Sci. Total Environ.* **2019**, *693*, 133642. [[CrossRef](#)]
37. Vea, E.B.; Ryberg, M.; Richardson, K.; Z Hauschild, M. Framework to Define Environmental Sustainability Boundaries and a Review of Current Approaches. *Environ. Res. Lett.* **2020**, *15*, 103003. [[CrossRef](#)]
38. Wu, L.; Huang, K.; Ridoutt, B.G.; Yu, Y.; Chen, Y. A Planetary Boundary-Based Environmental Footprint Family: From Impacts to Boundaries. *Sci. Total Environ.* **2021**, *785*, 147383. [[CrossRef](#)]
39. Zhang, X.; Fang, X. The Progress and Prospects in the Scenario Simulation Research on the Sustainability of Regional Ecosystem Services Based on a “Safe Operating Space”. *Sustainability* **2023**, *15*, 11249. [[CrossRef](#)]
40. *European Research Council ERC Work Programme 2025*; European Research Council: Brussels, Belgium, 2024.
41. Swyngedouw, E. Apocalypse Forever? *Theory Cult. Soc.* **2010**, *27*, 213–232. [[CrossRef](#)]
42. Häyhä, T.; Lucas, P.L.; van Vuuren, D.P.; Cornell, S.E.; Hoff, H. From Planetary Boundaries to National Fair Shares of the Global Safe Operating Space—How Can the Scales Be Bridged? *Glob. Environ. Change* **2016**, *40*, 60–72. [[CrossRef](#)]
43. Raworth, K. *A Safe and Just Space for Humanity: Can We Live within the Doughnut*; Oxfam GB: Oxford, UK, 2012; Volume 8, ISBN 978-1-78077-059-8.
44. Pasgaard, M.; Dalsgaard, B.; Maruyama, P.K.; Sandel, B.; Strange, N. Geographical Imbalances and Divides in the Scientific Production of Climate Change Knowledge. *Glob. Environ. Change* **2015**, *35*, 279–288. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.