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Review Article

Mapping the intersection of planetary boundaries and environmentally extended input-output analysis: A systematic literature review☆

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ABSTRACT

Since the development of the planetary boundaries (PBs) framework, efforts have been made to operationalise PBs at sub-global scales, from cities to continents. Many of these efforts employ Environmentally Extended Input-Output Analysis (EEIOA), which integrates environmental and material considerations into supply chain analyses. Despite the growing body of research combining PBs and EEIOA, the research is dispersed across various studies and disciplines, necessitating a systematic synthesis to consolidate findings, identify gaps, and guide future research. To address this need, we conducted a systematic literature review focusing on research that integrates the PB framework with EEIOA. Our aim was to answer several key questions, including: What are the most common methodological choices used in studies combining PBs and EEIOA? How has EEIOA informed policy decisions related to living within PBs? Using Scopus and Web of Science, we conducted a comprehensive search covering publications from January 2009 to April 2024. Our review revealed four main methodological frameworks in the literature: "footprint v/s allocated PB", "exceedance footprint", "scenario analysis", and "optimisation modelling". Climate change emerged as the most extensively studied PB, followed by land-system change, freshwater use, nitrogen flows, and phosphorus flows. Policy guidance was central in 50 % of the studies, with 61 % following a responsibility narrative, 15 % human well-being, and 9 % examining socio-economic implications. This review provides critical insights into the intersection of PB and IOA, highlighting methodological trends and gaps. By synthesizing findings, it advances the integration of these frameworks, supporting their application in sustainable consumption policies and broader environmental strategies.

1. Introduction

Unsustainable patterns of production and consumption have led to undeniable environmental degradation, manifesting in phenomena such as climate change and biodiversity loss (Wiedmann et al., 2020). To alter this trajectory, a comprehensive understanding of the Earth's ecological limits and the economic activities that influence them is imperative. In 2009, Rockström et al. introduced the Planetary Boundaries (PBs) framework, identifying nine planetary systems and establishing their critical thresholds that delineate a safe operating space (SOS) for humanity (Rockström et al., 2009). The SOS is defined as the distance between a boundary (regional or global) and a reference value, typically representing pre-industrial conditions (Bjørn et al., 2020b). A few years later, the Doughnut Economics was launched, integrating the PBs framework with a social floor or foundation, in order to include minimum standards of living required for people to thrive (e.g., health, education) (Raworth, 2012).

Since its introduction, the PBs framework has undergone multiple updates (e.g., Gupta et al., 2024; Richardson et al., 2023; Steffen et al., 2015). According to Richardson et al. (2023), six of the nine boundaries have already been transgressed. This transgression jeopardises the stability of Earth's systems, with effects becoming increasingly evident in the form of extreme weather events in recent years. For example, between 2000 and 2019, the United Nations recorded 7348 major disaster events (86 % corresponding to floods, storms, extreme temperature, droughts, and wildfires), resulting in 1.23 million deaths and affecting 4.2 billion people, a sharp increase from the previous two decades (74 % increase in reported disasters) (UNDRR, 2020).

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The concept of PBs is inherently global, yet policies to manage these boundaries are developed and implemented locally within political borders. As a result, numerous attempts have been made to operationalise PBs at sub-global scales. Various allocation methods (e.g., grandfathering, equal per capita) have been employed to downscale PBs to different geographical levels, ranging from cities to continents (e.g., Li et al., 2020a; Shaikh et al., 2024). Studies focused on the operationalisation of PBs typically employ three main methodologies: Life Cycle Assessment (LCA), Integrated Assessment Models (IAMs), and Input-Output Analysis (IOA). LCA is typically applied from a microeconomic perspective, with a focus on the product or company level (Bjørn et al., 2020a), where PBs are used as constraints in the life cycle inventory analysis, as characterisation factors in the life cycle impact assessment, as weighting factors, or as normalisation references in the normalisation step (Li et al., 2021).

For a macroeconomic perspective, IAMs and IOA are usually applied. IAMs are simplified representations of complex physical and social systems, capturing interactions between the economy, society and environment. They integrate insights from multiple disciplines to describe both human and Earth systems, often focusing on energy-land-economy-climate interactions. IAMs employ scenario-based approaches to explore future changes in human-environment interactions and assess management strategies. These scenarios, based on socio-economic trends, policies, technological developments, and societal goals, translate qualitative narratives into quantitative projections (IAMC IIASA, 2025). IOA was introduced by Wassily Leontief in the 1930s, introducing a multi-sectoral perspective to macroeconomics that effectively captures inter-industry linkages (Leontief, 1937). IOA is an analytical method used to understand the relationships between different sectors of an economy and how they interact with one another in the production and consumption of goods and services. Environmentally-Extended Input-Output Analysis (EEIOA) introduces environmental and material aspects of supply chains, facilitating the assessment of various environmental issues such as climate change, water scarcity, and natural resource depletion (Miller and Blair, 2009). More recently, Environmentally-Extended Multi-Regional Input–Output (EEMRIO) models have facilitated detailed analysis of the relations between the location and extent of environmental impacts and the production and consumption of goods and services worldwide, which are facilitated by global supply chains (Wiedmann and Lenzen, 2018). Several studies using EEMRIO have highlighted the unsustainability of current economic practices from both environmental and social viewpoints (e.g., Liao et al., 2023; Vazquez et al., 2023; Wiedmann and Lenzen, 2018), revealing that our current economic activities are placing immense pressure on the Earth's systems and contributing to widespread social inequities.

By encompassing all sectors of the economy, EEIOA can assess indirect and induced effects, providing a more holistic view of environmental impacts compared to LCA, which typically only accounts for the direct and upstream impacts of specific products. Additionally, EEIOA provides a more detailed sectoral and trade-linked analysis of environmental pressures compared to IAMs and has been applied to multiple PBs, whereas IAMs have predominantly been used to study climate change (e.g., de Vos et al., 2021; Soergel et al., 2024). Given the significance of these frameworks, there is a growing body of research integrating PBs with EEIOA to provide comprehensive insights into the sustainability of global patterns of production and consumption. However, this research is dispersed across various studies and disciplines, necessitating a systematic synthesis to consolidate findings, identify gaps, and guide future research.

In the present study, we develop a systematic literature review on research integrating PBs and EEIOA. The objective is to answer several key questions related to the combined application of these frameworks, including: what methodological approaches are most commonly used in studies combining PBs and EEIOA? How has EEIOA informed policy decisions related to living within PBs? By addressing these and other questions, this study aims to provide a comprehensive understanding of the current state of the research and highlight areas for future investigation, offering valuable insights for researchers, policymakers, and practitioners.

2. Literature review

Systematic literature reviews (SLRs) aim to synthesise and compare evidence across studies to answer specific research questions, thereby consolidating or confirming practices, policies, or theoretical relationships. By employing a transparent and repeatable search strategy, a substantial number of relevant studies are captured (Klein and Müller, 2020). SLRs play several critical roles: they can synthesise the current state of knowledge in a field and identify future research priorities; address questions that individual studies cannot; identify issues in primary research that need correction in future studies; and generate or evaluate theories about phenomena. Consequently, SLRs produce various types of knowledge beneficial to different users, such as researchers and policymakers (Page et al., 2021). In this section we describe the state-of-the-art, providing only selected examples of references for brevity. The full text is available in the Supplementary Information (SI) file (see SI-B).

In the last years, a significant number of review articles related to IOA or PBs have been published. Several reviews have addressed IOA from industrial and/or socio-economic perspectives (e.g., Jenniches, 2018; Lambert and Silva, 2012; Pepłowska and Olczak, 2024), as well as from a methodological angle (e.g., Feás, 2023; Ramos-Carvajal et al., 2024). Many reviews have specifically considered EEIOA, addressing different aspects of the methodology. For instance, Wiedmann and Lenzen (2018) focused on global footprint or trade studies from recent years based on the method of global EEMRIO modelling; Haberl et al. (2019) outlined and systematised major socio-metabolic research traditions that study the biophysical basis of economic activity, including EEIOA; and Madsen and Weidema (2023) performed a systematic literature review to clarify how input–output models have been used to analyse household activity patterns, in particular household environmental footprints.

Reviews on PBs have been conducted across various contexts (e.g., the development of the concept over time) (e.g., Biermann and Kim, 2020; Feitelson and Stern, 2023; Kim and Kotzé, 2021), focusing on their relationship to other frameworks (e.g., Allen et al., 2021; Chen et al., 2021; Tao et al., 2024), and from a methodological perspective (e.g., Bai et al., 2024; Bjørn et al., 2020a; Nash et al., 2017). For example, Kim and Kotzé (2021) examined how social scientists frame the PBs framework and what they identify as key regulatory challenges and implications; Tao et al. (2024) discussed the role of ecosystem services within the safe and just operating space framework to promote regional sustainability; and Bai et al. (2024) identified emerging Earth system boundaries sharing approaches, analysing how they are applied across domains and actors, with special focus on businesses and cities. Other reviews have focused on specific PBs, such as land-system change (Haberl et al., 2014), and water (e.g., Bunsen et al., 2021; Gerten et al., 2013; Han et al., 2023); or on PBs in the context of specific economic sectors, such as food production (Wang and Shi, 2024).

Most reviews that address PBs in combination with EEIOA focus on environmental footprints and/or absolute sustainability assessments (e.g., Bunsen et al., 2021; Fang et al., 2014; Laurent and Owsianiak, 2017;). These reviews also explore the implementation of other methodologies, such as LCA, and their combination with other frameworks, such as the Sustainable Development Goals (SDGs). However, to the best of the author's knowledge, no systematic literature review has been developed focusing exclusively on the operationalisation of PBs in combination with EEIOA.

3. Methodology

3.1. Research design

A SLR was conducted in this study to address four specific research questions:

RQ1) *What are the broad modelling approaches that integrate PBs and EEIOA?*
RQ2) *What methodological choices are commonly used in studies combining PBs and EEIOA?*
RQ3) *How does the integration of PBs and EEIOA vary across different geographical scales and coverage?*
RQ4) *How has EEIOA informed policy decisions related to living within PBs?*

The PRISMA 2020 statement was utilised in this SLR (Page et al., 2021). The following sections provide a detailed description of the followed methodology and the items considered.

3.2. Data collection

The first step involved identifying the relevant literature. The search was conducted in April 2024, utilising two databases: Scopus and Web of Science (WoS). These databases are commonly used for literature reviews (e.g., Bjørn et al., 2020a; Li et al., 2021). The publication period considered was from January 2009 to April 2024, given that the PBs framework was introduced in 2009. The selection of suitable articles was refined using the following search string: *TITLE-ABS-KEY* (“*planetary boundar**” *OR* “*planetary limit**” *OR* “*safe operating space*” *OR* “*doughnut economics*” *OR* “*just operating space*”*) AND TITLE-ABS-KEY (*“*EEIO*” *OR* “*consumption based accounting*” *OR* “*EEMRIO*” *OR* “*MRIO*” *OR* “*input output*” *OR* “*social metabolism*” *OR* “*environmentally extended*” *OR* “*input–output*” *OR* “*social accounting matrix*”). The search returned 52 articles in Scopus and 48 articles in WoS. Limiting the scope to English-language journal articles reduced these numbers to 48 and 46, respectively. After combining the articles, removing duplicates, and excluding publications related to “planetary boundary layer”, a total of 56 articles remained, of which 54 were freely available.

In the next step, a manual selection was performed using specific inclusion and exclusion criteria. The inclusion criteria required articles to operationalise PBs and EEIOA in their assessments. Articles were excluded if they only mentioned PBs or used other assessment methods, such as LCA. Only original research articles presenting new findings were considered, excluding review articles and comment pieces. Additionally, articles where policy targets are applied such as nationally determined contributions (NDCs) were excluded, as NDCs only reflect national ambitions, which do not necessarily relate to required emissions reduction (UNEP, 2022). This exclusion was specific to articles assessing the PB of climate change. After applying the inclusion and exclusion criteria, 21 articles were deemed eligible for full analysis.

The third step involved applying the snowballing method (Wohlin, 2014), which involved screening the references of the literature review articles identified in the initial step to uncover additional publications. This approach also introduced grey literature, such as reports, into the search. After an initial screening and applying the same inclusion and exclusion criteria, 12 additional studies were included in the analysis.

3.2.1. Data collection for climate change

During the manual selection of publications, it was observed that the targets of the Paris Agreement were one of the approaches to operationalise the PB of climate change. This realisation prompted a second search, utilising the following search string: *TITLE-ABS-KEY* (“*Paris agreement*” *OR* “*1.5 °C*” *OR* “*2.0 °C*” *OR* “*2 °C*” *OR* “*1.5 degrees C*” *OR* “*2 degrees C*” *OR* “*2.0 degrees C*”) *AND TITLE-ABS-KEY* (“*EEIO*” *OR* “*consumption based accounting*” *OR* “*EEMRIO*” *OR* “*MRIO*” *OR* “*input output*” *OR* “*social metabolism*” *OR* “*environmentally extended*” *OR* “*input–output*” *OR* “*social accounting matrix*”). The search returned 107 and 102 articles in Scopus and WoS, respectively. After combining the articles, removing duplicates, and articles in languages different from English, 122 articles were obtained, of which 121 were freely available. The same inclusion and exclusion criteria were applied, resulting in 21 new articles for the analysis.

After completing the various search steps, 54 studies (hereafter “studies” will be used instead of “articles” to include both peer-reviewed publications and grey literature) were deemed eligible for full analysis. The flow diagram for each search is provided in the SI file (SI-A, Figs. S1 and S2).

3.3. Data analysis

The selected studies were thoroughly reviewed, with a focus on their objectives, methods, results, and conclusions. A content-based analysis was conducted to characterise each study in relation to four characteristics: 1) the operationalisation of the PB framework; 2) how EEIOA was used; 3) the spatial, temporal, and economic scope of the EEIOA analysis, and 4) the overall framing and contributions of the analysis. Each of these four characteristics were described based on a number of variables (see Table 1). For example, PB operationalisation was characterised according to: “PB(s)”, identifying the specific PB(s) assessed; “Control variable(s)”, specifying the control variable(s) used for each PB; “Threshold(s)”, detailing the threshold(s) considered for each control variable; “Allocation method(s)”, describing how each PB is allocated to the assessed population or geographical area; and “Other”, capturing additional relevant information that complements or falls outside the previous variables (e.g., whether the boundary is local or global). Here, it is important to note that there is a relevant issue related to how PBs have been conceptualised and operationalised at “local” (i.e., non-planetary) scales. However, a detailed exploration of these issues is beyond the scope of this analysis.

Further details on the variables of each characteristic used in the analysis can be found in the SI file (SI-B, Table S5). In addition, the file also includes specific information about environmental footprints, as the majority of studies concentrated on footprint assessments.

The collected data were analysed to address the four research questions, highlighting the main findings (see SI-A, Tables S1 and S2). Finally, the novelties and limitations were outlined, and recommendations for future research were proposed.

Table 1
Characteristics and respective variables considered in the content-based analysis.

Characteristics	Variables
PB operationalisation	“PB(s)”, “Control variable(s)”, “Threshold(s)”, “Allocation method(s)”, “Other”
Input-output analysis approach	“Database(s)”, “N° of sectors/products/industries”, “Final demand”, “Origin of satellite account”, “Other”
Study scope	“Geographical coverage”, “Geographical level(s)”, “Temporal coverage”, “Economic sector(s)”
Study main contributions	“Objective”, “Narrative”, “Methodological approach”, “Highlights”, “Novelty”, “Limitations”

4. Results and discussion

This section will first address each research question individually. Following that, we will highlight key findings, including novelties, limitations, and recommendations for future research.

4.1. RQ1: What are the broad modelling approaches that integrate PBs and EEIOA?

From the 54 studies, four primary modelling approaches were identified: "footprint v/s allocated PB", "exceedance footprint", "scenario analysis", and "optimisation modelling". Fig. 1 illustrates how many times each PB is assessed within these approaches. Since some studies evaluate multiple PBs and/or utilise more than one approach, the total number of assessments is 62.

4.1.1. Footprint v/s allocated PB

In this modelling approach, PBs are downscaled and allocated to a specific population or territory, which can be at the global, national, regional, or local level. Using EEIOA, the environmental footprint of the targeted population or territory is calculated. Two accounting methods are applied in this process: consumption-based and/or production-based. Consumption-based accounting attributes all environmental flows, both direct and indirect, along the production chain to the final consumer of the products, regardless of where they are produced. In contrast, production-based (or territorial) accounting calculates the environmental flows generated by the domestic production of goods and services, irrespective of whether those goods are consumed domestically or exported (Bows and Barrett, 2010). The allocated PBs are then compared to the estimated respective footprint to determine whether the population or territory is within the limits of the specific PB.

As shown in Fig. 1, 53 % of the assessments (33 studies) utilise this approach, covering all nine PBs. Among these, climate change is the most frequently studied PB, followed by land-system change, freshwater change, N flows, and P flows. The other PBs are significantly less researched, with ocean acidification being the least explored.

The first ones to compare footprints to downscaled PBs were Hoff and colleagues in 2014, who compared PBs downscaled equally per capita with footprints estimated in previous research. Their main focus was 20 European Union (EU) members, although they also assessed the world, Brazil, China, and India (Hoff et al., 2014). Since then, numerous studies have adopted this approach, utilising various footprint indicators depending on the PB under evaluation, such as freshwater use (e.g., W. Zhang and Fang (2024)), cropland use (e.g., Shaikh et al. (2024)), and biodiversity intactness index (BII) loss (e.g., Vazquez et al. (2023)). Additional indicators, including the ecological footprint—which measures the biologically productive land and sea area required to sustain a population's resource consumption and CO_2 emissions—and the material footprint, which quantifies material extraction, have also been employed (e.g., O'Neill et al. (2018)). While these are not directly linked to specific PBs, their use has been recorded in the SI file (SI-A, Tables S1 and S2). The choice of footprint indicators is closely related to the selection of control variables in each study. Additionally, these assessments have been conducted using both global and local PB thresholds, covering various geographical scales and timeframes. These and other methodological aspects will be explored in the following sections.

4.1.2. Exceedance footprint

As in the "footprint v/s allocated PB" approach, the PBs are downscaled and allocated to a specific population or territory. Based on the allocated PBs, the exceedance is calculated as the difference between the actual use or emission of a PB-related resource or pollutant and the corresponding allocated PB. For example, the exceedance of P use was calculated as: $Exceedance = Domestic\ use\ P\ fertiliser - allocated\ PB$. This exceedance is then distributed across various economic sectors through an exceedance intensity vector, which is integrated into the input-output table. The vector is subsequently used to estimate territorial exceedance footprints.

This approach was developed to assess how and where consumption and production contribute to the transgression of PBs at a local scale,

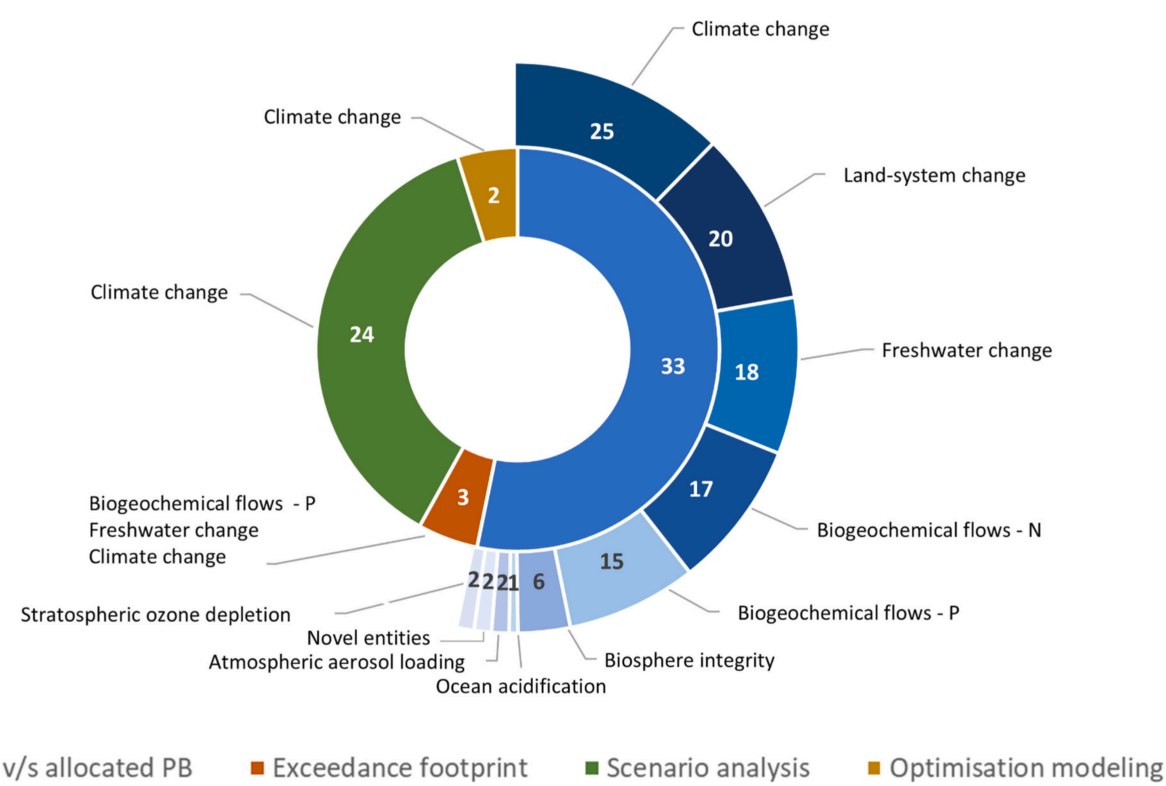

Fig. 1. N° of times each PB is assessed per modelling approach.

highlighting the role of trade in the consumption of embedded or virtual compounds. The "exceedance footprint" approach generates a "map" for each country, where the rows of the resulting matrix indicate the origin of compound exceedances by region and sector, while the columns show the consumed exceedances embodied in final products coming from all regions and sectors. This approach requires the construction of satellite accounts, which is not always the case in the "footprint v/s allocated PB" approach.

This approach was introduced by Li et al. (2019) and was initially applied to assess the P exceedance footprint of 140 countries and regions. Since then, it has been used in two additional studies: Li et al. (2020b) to estimate the water exceedance footprint of 27 Chinese provinces and 10 cities, and Han et al. (2022) to estimate the carbon exceedance footprint of China and 30 Chinese provinces. Li et al. (2020a) also developed a second indicator, the "surplus water footprint", to identify regions where the local water PB has not been exceeded.

4.1.3. *Scenario analysis*

In this approach, scenarios are used to explore and evaluate possible future outcomes by examining different trajectories of environmental, economic, and social factors. As shown in Fig. 1, this approach has primarily been applied to study the PB for climate change, where the PB threshold is typically not downscaled.

Following the definitions of Börjeson et al. (2006) and Vergragt and Quist (2011), three type of scenarios can be identified: i) predictive, answering the question *what will happen* (e.g., trend extrapolations, business as usual scenarios); ii) explorative, answering the question *what could happen* (e.g., forecasting, strategic scenarios); and iii) normative, answering the question *what should happen* to achieve specific targets (i.e., to meet a desired future outcome).

Of the 24 assessments using scenario analysis, nine apply only explorative scenarios (Cap et al., 2024; Fanning and O'Neill, 2016; Huang et al., 2020; Liu et al., 2018; Montt et al., 2018; Scott et al., 2019; Wan et al., 2016; Ward et al., 2019; Zhang et al., 2018), six focus solely on normative scenarios (Ala-Mantila et al., 2023; Bjørn et al., 2023; Bows and Barrett, 2010; Gibon et al., 2015; Jaccard et al., 2021; Wang et al., 2022), five assess and compare explorative and normative scenarios (Bjørn et al., 2018; Huang, 2024; Koide et al., 2021; Li et al., 2020a; Sers, 2022), two combine predictive and explorative scenarios (Parikh et al., 2018; Zhou et al., 2022), and two assess all three types (De Koning et al., 2016; Hasan et al., 2022).

Among the explorative scenarios, two main approaches were identified. One approach examines the effects of climate change on two other areas, namely, the effect on socio-economic aspects (e.g., employment) (Huang et al., 2020; Montt et al., 2018; Ward et al., 2019; Zhang et al., 2018; Zhou et al., 2022); and the effect on water consumption in the energy supply sector (Liu et al., 2018; Wan et al., 2016). The other approach quantifies the effects of socio-economic factors, technological changes, and/or policies on greenhouse gas (GHG) emissions, comparing these results to CO_2 budgets or changes in temperature aligned with specific climate targets (Bjørn et al., 2018; Cap et al., 2024; De Koning et al., 2016; Fanning and O'Neill, 2016; Hasan et al., 2022; Huang, 2024; Koide et al., 2021; Li et al., 2020a; Parikh et al., 2018; Scott et al., 2019; Sers, 2022).

Normative scenarios focus on pathways to achieve the 1.5 °C target (Ala-Mantila et al., 2023; Bjørn et al., 2023; Jaccard et al., 2021; Koide et al., 2021; Li et al., 2020a; Sers, 2022; Wang et al., 2022), 2 °C target (Bows and Barrett, 2010; De Koning et al., 2016; Gibon et al., 2015; Hasan et al., 2022; Huang, 2024), or both targets (Bjørn et al., 2018) set by the Paris Agreement. Aspects such as urbanisation pathways and national emission reduction trajectories are analysed in these scenarios.

Predictive scenarios are applied as business-as-usual (BAU) under current policies, and serve as benchmarks for comparison with explorative and/or normative scenarios (De Koning et al., 2016; Hasan et al., 2022; Parikh et al., 2018; Zhou et al., 2022).

The comparison between these three types of scenarios may help identify where specific trajectories might lead and the actions needed to achieve desired outcomes. In addition, comparing them can reveal challenges that must be addressed to bridge the gap between what is likely and what is necessary for achieving climate goals. For instance, De Koning et al. (2016) developed three scenarios for the year 2050: a BAU scenario, a techno-scenario (TS) that incorporates into the BAU scenario feasible and probable climate mitigation technologies, and a 2 °C scenario (2DS), which includes a shift in demand or a reduction in growth alongside the TS to meet the 2 °C target. Their findings indicate that achieving a 2 °C target is not feasible through technological changes alone. While changes in consumption patterns can help, their impact is limited. The study concludes that reaching the 2 °C goal requires a combination of technological solutions, behavioural changes, and a 50 % reduction in economic growth.

4.1.4. *Optimisation modelling*

The optimisation approach is conducted using an objective function such as minimising environmental impacts or maximising affluence, identifying the optimal decision or course of action that achieves the best outcome, given the limitations and constraints of the system. Koide et al. (2021) and Parikh et al. (2018) combined scenario analysis with optimisation modelling, the former to determine the minimum adoption rate of lifestyle changes to achieve the per-capita decarbonisation target; and the latter, to maximise the present discounted value of private consumption, as part of their socio-economic model.

4.2. *RQ2: What methodological choices are commonly used in studies combining PBs and EEIOA?*

Within the broad modelling approaches outlined above, there are a considerable number of methodological choices that shape the PBs assessments. For example, how PBs are operationalised in terms of control variables, thresholds, and allocation methods (when applicable), as well as which PBs are studied. From the EEIOA perspective, one has to choose the accounting method, the input-output database(s), the assessed demand, the economic sector(s), and the origin of the satellite accounts used in the analyses. Each of these choices are likely to have significant implications on our empirical understanding of PBs and it is not clear to what extent those choices are made in a consistent, or arbitrary manner.

Fig. 2 presents the main control variables, sub-control variables, and global thresholds for the PBs of land-system change, freshwater change, and biogeochemical flows, along with the studies that applied them. A variety of control and sub-control variables are used for each PB, reflecting the diverse approaches in assessing these limits. The most commonly applied sub-control variables include "cropland use" for land-system change, "human consumption of blue water" for freshwater change, "industrial and intentional biological fixation of N" for N flows, and "P flow from fertilisers to erodible land" for P flows. Additionally, some of these variables are associated with different global thresholds, further reflecting the heterogeneity across assessments.

The PBs of Fig. 2 were selected because they are the focus of most assessments, alongside climate change. However, due to the extensive number of studies on climate change, it was not feasible to include it in the figure. For the PB of climate change, three control variables are most commonly used: temperature increase, atmospheric CO_2 concentration, and radiative forcing. Among these, temperature increase has the most sub-control variables, with nine in total, each assessed using multiple thresholds. One widely used sub-control variable is the maximum 1.5 °C increase compared to pre-industrial levels (UNFCCC, 2015), which is translated into a carbon budget. These budgets may be calculated on an annual basis or for a specific time period (e.g., 2012–2100). However, they vary significantly depending on the assessed timeframe and the methodology used for their estimation, such as GWP100 (Global Warming Potential over 100 years) and GTP100 (Global Temperature-change Potential over 100 years). For further details, see IPCC (2013).

PB	Main control variable	Sub-control variable	Global threshold	Publication
Land-system change	Land use	Cropland use	≤15% of global ice-free land surface converted to cropland (Rockström et al., 2009)	Hoff et al. (2014) Zhang et al. (2022) Lucas et al. (2020)
			Low: 10.6 million km^2 (Springmann et al., 2018) Best: 12.6 million km^2 (Springmann et al., 2018) High: 16.4 million km^2 (UNEP, 2014)	Shaikh et al. (2021) Liao et al. (2023) Shaikh et al. (2024)
		Anthropized land area (cropland and urbanization)	19.4 million km2 (Dao et al., 2018)	Regen Melbourne (2023) Vázquez et al. (2023)
	Area available for regeneration of biological resources	-	Around 12 bn global hectares (gha)/y (Fanning and O'Neill (2016) based on Global Footprint Network)	Fanning and O'Neill (2016) The Thriving Cities Initiative (2020) Eboli et al. (2022) Rawsthorne et al. (2022) Dethier et al. (2023)
	Potential net primary production (NPPpot)	Embodied human appropriation of net primary production (eHANPP) Equivalent to 33% of the global NPPpot	18.2 Gt C/y in 2011 (O'Neill et al., 2018)	O'Neill et al. (2018) Zecca (2020) Ecological Transition Counsellor (2022) Hjelmskog et al. (2023)
		Human appropriation of net primary productivity (HANPP)	47% of NPPpot (Running, 2012) Global boundary is estimated per year depending on the total NPPpot (Wang et al., 2024)	Wang et al. (2024)
		NPPpot	50% of the global NPPpot (Wilson, 2016) 32.5 Pg C/y in 2007	Weinzettel et al. (2019)
	Soil erosion	-	1.27E+13 kg soil loss/y (Bjørn and Hauschild, 2015)	Sala et al. (2020)

PB	Main control variable	Sub-control variable	Global threshold	Publication
Freshwater change	Blue water withdrawal	Human consumption of blue water	4000 km^3/y (Rockström et al., 2009)	Hoff et al. (2014) O'Neill et al. (2018) The Thriving Cities Initiative (2020) Zecca (2020) Eboli et al. (2022) Ecological Transition Counsellor (2022) Rawsthorne et al. (2022) Kulionis and Pfister (2022) Hjelmskog et al. (2023) Dethier et al. (2023) Vázquez et al. (2023)
			788 km^3/y (Hu et al., 2020)	Liao et al. (2023)
		Maximum blue water withdrawal as % of mean monthly river flow	25% for low-flow months; 30% for intermediate-flow months; 55% for high-flow months (Steffen et al. (2015) based on Pastor et al. (2014))	Fanning and O'Neill (2016)
		Withdrawals-to-availability (w.t.a)	Maximum 40% (Alcamo and Henrichs, 2002)	Li et al. (2020) Zhang et al. (2022) Zhang and Fang (2024)
		Water availability within a watershed minus a proportion of the water availability retained to ensure ecosystem well-being	Between 30 and 60% (Pastor et al., 2014)	Bunsen et al. (2021)
			Safe: ratio < 0.5 At risk: 0.5 < ratio < 0.75 Unsafe: 0.75 < ratio (Kulionis and Pfister, 2022)	Kulionis and Pfister (2022)
	User deprivation potential (deprivation-weighted water consumption)	-	182000 km^3 world eq/y (Bjørn and Hauschild (2015), recalculated by Bjørn (2017))	Sala et al. (2020)
	Net blue, green and grey water consumption	-	8500 km^3/y (Meyer and Newman, 2018)	Regen Melbourne (2023)

PB	Main control variable	Sub-control variable	Global threshold	Publication
Biogeochemical flows - N	N fixation	Synthetic N fixation	35 Mt N/y (Rockström et al., 2009)	Zhang et al. (2022)
		Industrial and intentional biological fixation of N	62 Mt N/y (Steffen et al., 2015)	Fanning and O'Neill (2016) O'Neill et al. (2018) The Thriving Cities Initiative (2020) Zecca (2020) Lucas et al. (2020) Eboli et al. (2022) Ecological Transition Counsellor (2022) Rawsthorne et al. (2022) Civic Square (2022) Hjelmskog et al. (2023) Dethier et al. (2023)
	Loss of reactive N to the environment	Loss of reactive N to the environment	47.6 Mt N/year (Dao et al., 2015)	Frischknecht et al. (2020)
		Loss of reactive N to the environment	62 Mt N/y (Meyer and Newman (2018) based on Steffen et al. (2015))	Regen Melbourne (2023)
		Fraction of N reaching marine end compartment (marine eutrophication)	2.01E+11 kg N eq/y (Bjørn and Hauschild, 2015)	Sala et al. (2020)
		Accumulated exceedance (terrestrial eutrophication)	6.13E+12 molc N eq/y (Bjørn and Hauschild (2015), recalculated by Bjørn (2017))	Sala et al. (2020)
		Loss of N from agriculture	28.5 Tg N/y (European Environment Agency, 2020)	Vázquez et al. (2023)
	N application from fertilisers	-	69 Tg N/y (Springmann et al., 2018)	Liao et al. (2023)

PB	Main control variable	Sub-control variable	Global threshold	Publication
Biogeochemical flows - P	P flow from fertilisers to erodible land	-	6.2 Mt P/y (Steffen et al., 2015)	Fanning and O'Neill (2016) O'Neill et al. (2018) Zecca (2020) Lucas et al. (2020) Eboli et al. (2022) Ecological Transition Counsellor (2022) Rawsthorne et al. (2022) Civic Square (2022) Hjelmskog et al. (2023) Dethier et al. (2023) Li et al. (2019)
	P released to the environment	P released to the environment	11 Tg P/yr (Meyer and Newman (2018) based on Rockström et al. (2009))	Regen Melbourne (2023)
		Fraction of P reaching freshwater end compartment (freshwater eutrophication)	5.81E+09 kg P eq/y (Bjørn and Hauschild, 2015)	Sala et al. (2020)
		P released from agriculture and urban wastewater	1.87 Tg P/y (Vázquez et al., 2023)	Vázquez et al. (2023)
	P content of the fertiliser used	-	3.5 Mt P/y (wrong reference)	Zhang et al. (2022)
	P application from fertilisers	-	16 Tg P/y (Springmann et al., 2018)	Liao et al. (2023)

Fig. 2. Main control variables, sub-control variables, and global thresholds for the PBs of land-system change, freshwater change, and biogeochemical flows. The reference shown in the column "Global threshold" refers to the publication that originally proposed the threshold. The full references are in Table S3 in the SI-A file.

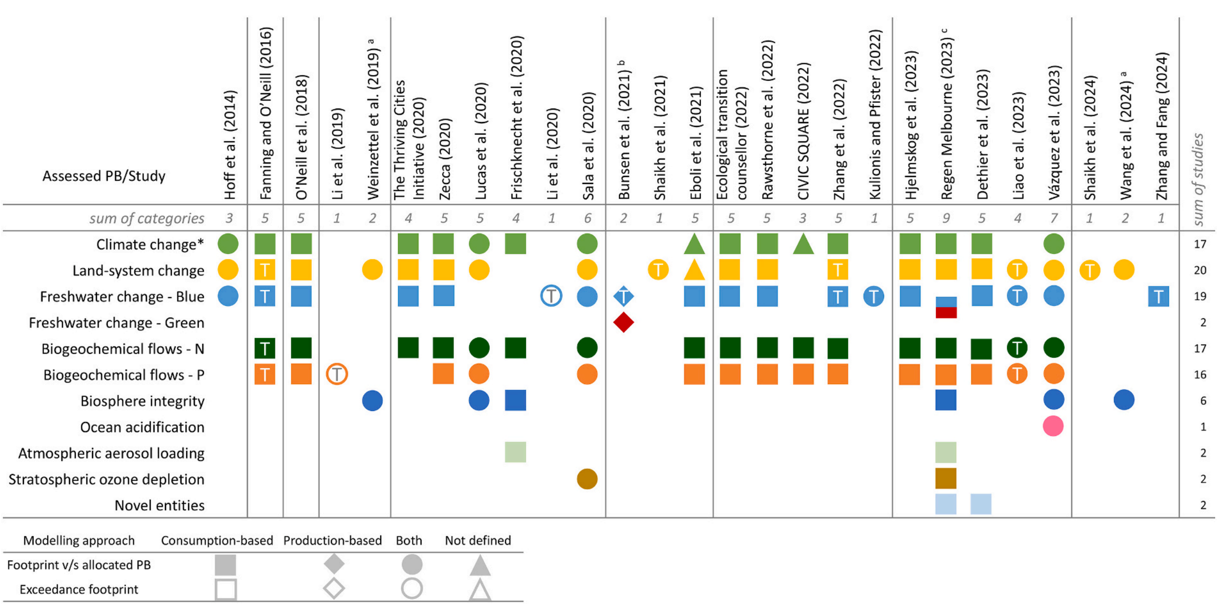

Fig. 3. Coverage of planetary boundaries (PBs) territorial thresholds, in relation to modelling approaches (footprint v/s allocated PB, and exceedance footprint), and accounting methods (consumption based, production based, both, or not defined). [a]Based on the potential net primary production (NPP_{POT}), [b]PB only downscaled for blue water, [c]PB was set as net water (blue, green, and grey water), *only studies where climate change was assessed together with other PBs are included. A "T" is shown when the threshold is estimated considering territorial aspects.

Additional information on climate change and other PBs is provided in the SI file (SI-A, Table S3).

This diversity in control variables and thresholds indicates that different starting points are often chosen, leading to potentially varied outcomes depending on the specific parameters and thresholds applied in each study.

Another source of heterogeneity among studies is the gradual incorporation of territorial thresholds. Typically, thresholds for control variables are defined from a global perspective, often overlooking local considerations. However, some studies have introduced alternative control variables to account for territorial aspects, such as "area available for regeneration of biological resources" for land-system change (Fanning and O'Neill, 2016), or "maximum blue water withdrawal as percentage of mean monthly river flow" for freshwater change (Steffen et al., 2015). While no specific territorial control variables have been defined for N and P flows, there have been efforts to estimate territorial thresholds using the global threshold as a baseline. Fig. 3 shows the coverage of PBs across studies applying territorial thresholds and multiple PBs. For detailed information on climate change-focused studies, please refer to the SI file (SI-A, Tables S1 and S2).

Fig. 3 also highlights the accounting methods used in the studies. From the studies considered in the figure, more than 90 % apply either consumption-based accounting or combined consumption- and production-based approaches. When studies on climate change are included, approximately 80 % still rely on consumption-based or mixed approaches, while 9 % do not use either method, as they focus on broader climate change effects, such as impacts on employment. The consumption-based approach has only gained popularity in recent years as an alternative to production-based accounting, which overlooks the environmental pressures linked to goods and services produced in one country and consumed elsewhere. Each approach has its distinct strengths and limitations, highlighting the importance of using both in combination. Previous research (Karakaya et al., 2019; Tukker et al., 2020) has emphasised the benefits of this combined perspective to capture a fuller picture of environmental impacts.

Among the studies analysed here, Shaikh et al. (2024) illustrate how even countries that fall within safe consumption-based cropland limits can significantly contribute to the exceedance of production-based cropland limits in trading partners due to the trade of commodities like oilseeds, cereals, and fruits and vegetables. Similarly, Vazquez et al. (2023) examine decoupling levels between environmental pressures across six PBs and GDP, using both production- and consumption-based approaches. Their findings reveal substantial disparities between the two methods: for instance, 19 countries show strong decoupling for climate change under a production-based approach, yet three of these countries shift to weak decoupling under a consumption-based approach, indicating that they achieve strong decoupling only by outsourcing part of their emissions to meet their domestic demand. Conversely, other countries such as Poland shift from weak decoupling under a production-based approach to strong decoupling under a consumption-based approach, suggesting that part of their emissions are tied to the demand from other countries.

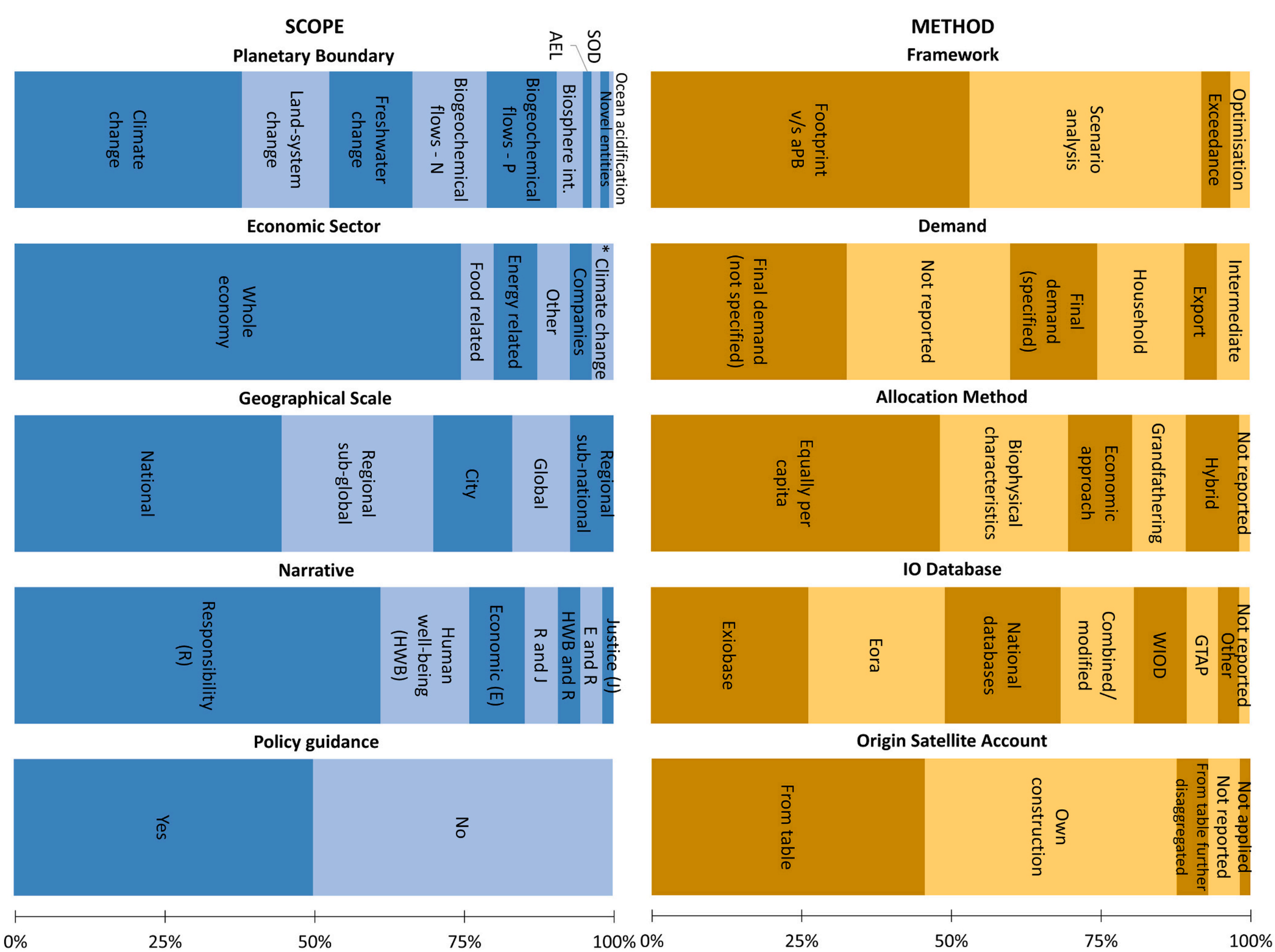

Fig. 4. Overview of the proportions of studies focusing on particular scopes or using particular methods. N: nitrogen, P: phosphorus, AEL: atmospheric aerosol loading, SOD: stratospheric ozone depletion, aPB: allocated Planetary Boundary.

Fig. 4 illustrates additional key aspects related to methodological choices in PBs-EEIOA studies, offering an overview of the proportions of studies focused on specific scopes or using particular methods. For this, we examine the breakdown of studies across “Planetary Boundary”, “Economic Sector,” and all methodological aspects included in the figure. It is important to clarify that the percentages shown in the figure refer to the number of assessments, not the number of studies (i.e., one study can develop several assessments by, for example, focusing on different PBs, using different allocation methods, or different databases). The detail of the data per study is shown in the SI file (SI-A, Tables S1 and S2).

As discussed earlier, the most researched PBs are climate change, land-system change, freshwater change, and biogeochemical flows; with “footprint v/s allocated PB” and “scenario analysis” being the main applied frameworks. Regarding allocation methods, 65 % of the studies apply them. Of the assessments developed in these studies, 48 % apply equally per capita (EPC), followed by biophysical characteristics (21 %), economic approaches like ability to pay (11 %), grandfathering (GF) and hybrid methods (e.g., EPC + GF), each accounting for 9 %. Two percent of the assessments do not report the applied allocation method. The 35 % of the studies that do not apply allocation methods correspond to studies using the “scenario analysis” or “optimisation modelling” frameworks. In the SI file (SI-A, Table S4), the allocation methods are categorised into two main types: those based on socio-economic aspects and those grounded in biophysical aspects. Each method is further detailed to provide a comprehensive understanding.

In terms of the economic sectors studied, around 75 % of the assessments examine impacts of the whole economy, with the remaining 35 % distributed across five other sectors, including assessments on the effects of climate change on other areas like employment. Sectoral assessments are categorised as follows: food-related (including food, agri-food, and dairy products), energy-related (covering power generation, electricity production, and non-electric energy production), other specific sectors (such as real estate), and company-level analyses.

As for the assessed demand, 33 % of the assessments consider final demand but do not specify which specific demands are included. Meanwhile, 27 % of the assessments do not report the demand type considered. In 15 % of the assessments, the demand is clearly specified and includes a combination of household consumption, government spending, non-profit organisations, investment, and exports. Another 15 % of studies focus exclusively on household consumption, while export and intermediate demand each account for 5 % of the studies. The focus on household consumption is particularly important, as it is a primary driver of GHG emissions and resource use compared to other demand categories (Hertwich and Peters, 2009; Ivanova et al., 2016). This focus provides valuable insights by linking environmental pressures to lifestyles and consumption patterns, helping illustrate the environmental impact of consumer behaviour choices (e.g., Bjørn et al. (2018), Koide et al. (2021)). For instance, Koide et al. (2021) examined 65 lifestyle-change options across 52 Japanese cities and found that certain options consistently yielded larger footprint reductions, even across cities with diverse characteristics. Shifts in diet and protein sources, for instance, had a far greater impact than improving food sourcing or reducing food loss, while residing in a zero-energy house had a larger effect than implementing energy-saving behaviours.

EXIOBASE (26 %) and Eora (23 %) are the two most frequently used EEIO databases, followed by national databases (19 %). For specific PBs, Eora is predominantly used in the assessments of P flows (50 %), N flows (44 %), freshwater change (42 %), and land-system change (35 %); EXIOBASE is applied to all PBs (22 % to 100 % of the assessments depending on the PB). In relation to the satellite accounts, in 46 % of the assessments they are used as provided by the original EEIO database, while in 43 % of the cases involved constructing satellite accounts from external sources such as FAOSTAT or national statistics databases. Thirteen percent of the assessments use combined or modified satellite accounts, where different IO databases are integrated, and specific sectors are further disaggregated. For example, Lucas et al. (2020) calculated national carbon footprints using an MRIO model based on IO data from the World Input-Output Database (WIOD), while using EXIOBASE to disaggregate the agricultural sector and a satellite account was constructed to assess biodiversity footprints. In terms of specific PBs, almost 40 % of the assessments for climate change and over 50 % of the assessments for biosphere integrity involve self-constructed accounts.

4.3. RQ3: How does the integration of PBs and EEIOA vary across different geographical scales and coverage?

As depicted in Fig. 4, most of the assessments are conducted at the national level (45 %), followed by the regional sub-global level (e.g., EU) (25 %). Assessments at the city level account for 13 %, while global and regional sub-national assessments are less common, comprising 10 % and 7 %, respectively.

Focusing on national and regional sub-global scales, Fig. 5 presents a comparison of results across studies for identical geographical regions using consumption-based accounting, and equal per capita or territorial allocation methods. Nations and regions were selected based on the availability of multiple studies for comparison. For clarity and given that the EU is included as a region, individual EU member states are displayed only when studies focused specifically on them or a subset of members. Due to methodological variations across studies, we have compared ranges instead of precise values. In some cases, ratios were directly available from the studies; in others, we derived the ratios using the data provided. Additionally, for global or EU assessments, average values were estimated for some studies (e.g., O'Neill et al., 2018; Vazquez et al., 2023).

For climate change, most studies indicate that the PB threshold has already been exceeded. However, significant discrepancies are observed, particularly in the findings of Ala-Mantila et al. (2023) and Hoff et al. (2014). Ala-Mantila et al. report lower exceedance of the thresholds compared to other studies, while Hoff et al. present lower ratios for developing economies. In both cases, most countries in the Global South remain below the climate threshold. The lower exceedance reported by Ala-Mantila et al. may be attributed to their use of a less stringent threshold for the year 2016, set at 7.1 tCO_2e/cap, which is substantially higher than the other applied thresholds (e.g., O'Neill et al. (2018) applied a per capita threshold of 1.61 tCO_2e). The cause of the differences in Hoff et al.'s findings is less transparent, as their study relies on footprints calculated in prior research. It is also noted that studies using different input-output databases tend to yield broadly comparable results. For instance, O'Neill et al. (2018), Vazquez et al. (2023), and Lucas et al. (2020) report findings in the same range despite utilising different databases—Eora, EXIOBASE, and a combination of WIOD and EXIOBASE, respectively.

For land-system change, the results are notably less harmonised between studies. Liao et al. (2023) find that most of the analysed countries already exceed the threshold, except for South Korea. In contrast, Weinzettel et al. (2019) and Wang et al. (2024) indicate that most of the countries are below the threshold. Weinzettel et al. (2019), Wang et al. (2024), and O'Neill et al. (2018) all employ Human Appropriation of Net Primary Production (HANPP) as the proxy for downscaling the PB. There are, however, differences in their results, largely due to the thresholds they apply, which vary from 32.5 Gt C/year in Weinzettel et al. (2019) (the least stringent threshold) to 26.2 Gt C/year in Wang et al. (2024), and 18.2 Gt C/year in O'Neill et al. (2018) (the most stringent threshold), illustrating that less strict thresholds result in fewer countries exceeding the boundary. O'Neill et al. (2018), Vazquez et al. (2023), Shaikh et al. (2021), and Shaikh et al. (2024) share some similarities, particularly in showing that many of the Global North countries exceed the threshold, whereas most Global South countries remain below or around the threshold with a few exceptions (namely Brazil, Mexico, and South Africa, depending on the study). The

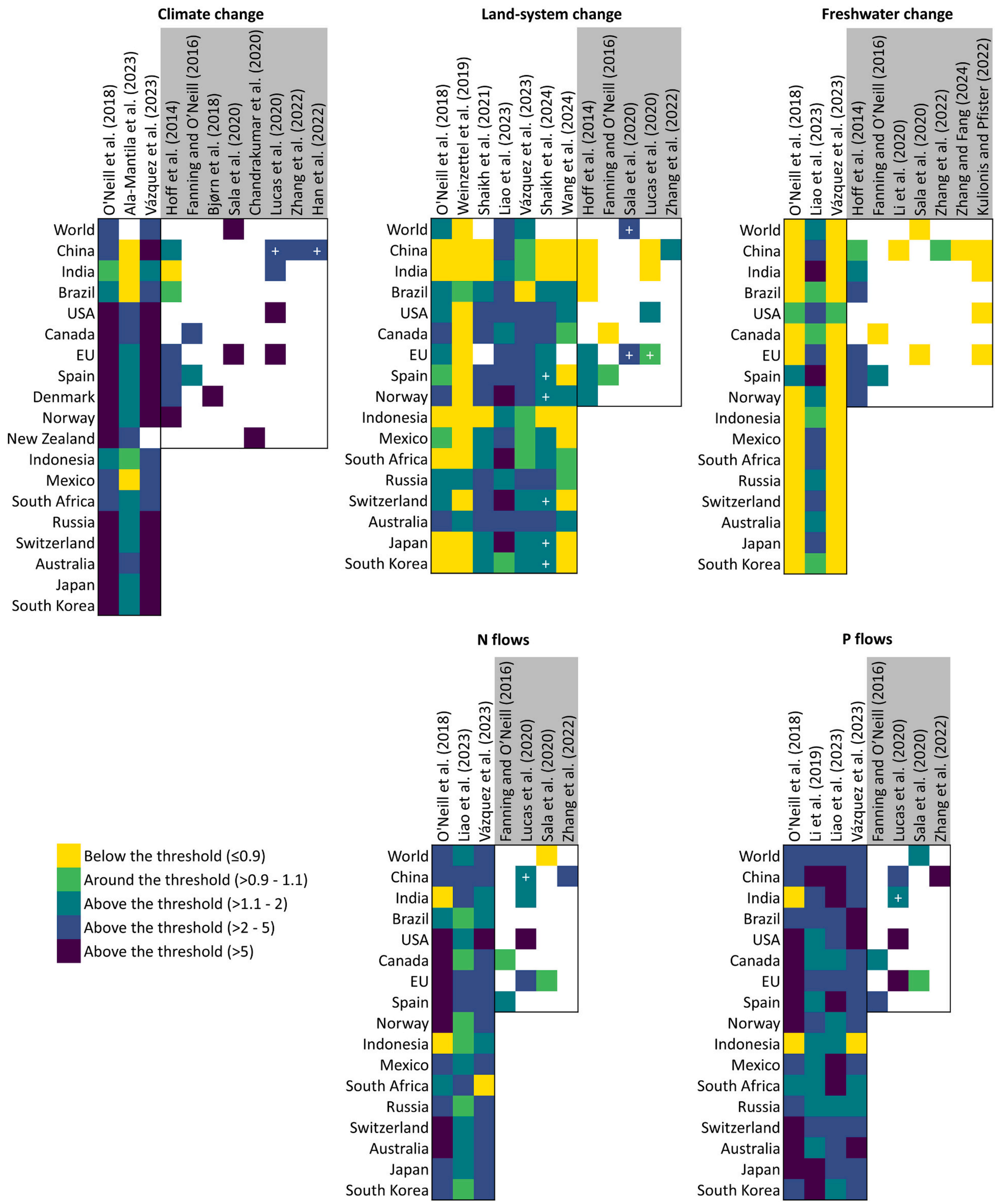

Fig. 5. Comparison of results across studies for the same geographical region, covering five PBs. The symbol "+" indicates that the score meets the range indicated by the associated colour, but that the value could be higher. The white colour indicates that the study did not address that region/nation. Results based on consumption-based accounting.

substantial variation between the results for land-system change could be explained through a number of factors, including the variety in control variables and methodologies used for downscaling the PBs, such as using a HANPP or a territorially-based land-use approach, but also in the differences of databases used including EXIOBASE, Eora, GTAP or modified versions of the aforementioned databases with the inclusion of more localised data using FAOSTAT. However, the role of database selection appears less significant, as differences persist even among studies using the same input-output database. For instance, Shaikh et al. (2021, 2024) and Vazquez et al. (2023) use EXIOBASE but apply different sub-control variables—cropland use and anthropized area, respectively. While the results for Global North countries remain consistent, divergences are observed for Global South countries. Vázquez et al., for example, report lower ratio values for China, India, and Indonesia, yet higher values for Brazil, Mexico, and South Africa.

Regarding freshwater change, the findings across studies show a generally consistent trend of remaining below the threshold, with notable exceptions in the results of Liao et al. (2023) and Hoff et al. (2014), both of which indicate that most of the analysed countries already exceeded the threshold. Similar to the case of climate change, the cause of the differences in Hoff et al.'s findings is less transparent, as their study relies on footprints calculated in prior research. The differences in Liao et al. are likely explained by the difference in the applied PB threshold. Liao et al., focusing on food systems, adopt a more stringent threshold of 788 km^3/year, whereas several other studies assess the entire economy with a more lenient PB of 4000 km^3/year. Particularly for China, all studies show that the country is below or around the threshold, except for Liao et al. (2023). Slight variations in results are also observed in the findings of Hoff et al. (2014) and Zhang et al. (2022), for the latter likely attributable to differences in the downscaling methodology.

For N and P flows, most studies indicate that the PBs have already been exceeded in most countries, with only a few exceptions, such as India, Indonesia and South Africa, depending on the study. These findings can be explained by the high intensity of agricultural and food production systems globally, which are major contributors to nutrient pollution. When focusing solely on N flows, Liao et al. (2023) stands out as the only study where many countries are shown to be around the PB threshold. This discrepancy may stem from the more lenient PB threshold employed by Liao et al. compared to other studies, as well as their use of a modified database that integrates EXIOBASE with data from Eora and FAOSTAT. In terms of P flows, comparisons of the exceedance footprint estimated by Li et al. (2019) reveal that in general, their results align relatively close with those of other studies. However, some significant differences are observed, particularly for countries such as the USA, Spain, Mexico, and Australia. Li et al.'s study indicates lower exceedance ratios for these countries, attributable to the "exceedance footprint" methodology, which allocates embedded or virtual compounds to final consumers through trade. This approach suggests that a portion of the environmental footprint associated with these countries is effectively exported, resulting in a reduced consumption-based footprint for domestic consumers.

Based on the results illustrated in Fig. 5, it is evident that several factors influence the evaluation of national footprint ratios relative to PBs within the same geographical regions. Among these, the choices of the control variable and threshold stand out as some of the most significant determinants, likely followed by the allocation method employed. In contrast, the selection of the input-output database appears to have a comparatively lower impact on the outcomes.

4.4. RQ4: How has EEIOA informed policy decisions related to living within PBs?

While the previous three research questions dealt with the methodological approaches and quantitative outcomes of the studies, the final research question extends beyond these issues to examine how studies communicate their results and the extent to which they are intended to inform policymakers. This focus is essential because research that actively engages with policy applications helps bridge the gap between science and policy, transforming complex data into actionable insights that clarify potential social, economic, and environmental impacts of policy decisions. By fostering evidence-based solutions, such research supports the formulation of strategies that address both immediate needs and longer-term challenges (e.g., climate adaptation).

As presented in Fig. 4, half of the studies explicitly provide guidance for policymakers, while the remaining 50 % make limited or no mention of policymaking or decision-making processes. One example is Shaikh et al. (2024), who provide policy recommendations aimed at promoting responsible consumption and production in alignment with the SDG 12, specifically focusing on agri-food systems. Their recommendations include targeted measures for both producer and consumer countries, as well as strategies related to trade agreements and supply chain management.

We also assessed the narrative perspective that each study adopts to frame and present its findings, revealing four primary narrative approaches:

- Responsibility: Based on causal responsibility (Moos and Arndt, 2023). The focus is on identifying and quantifying the contributions of various actors to the problem. The actors can be categorised at different levels (e.g., geographical, user, or economic level).
- Justice: Based on distributive justice (Miller, 1999). It supports the fair distribution of the burdens associated with the crisis and its mitigation efforts, considering socio-economic inequalities, national economic capabilities, and national historical contribution to the crisis.
- Human well-being: The focus is on promoting human well-being while respecting the Earth's thresholds. Human well-being is assessed through indicators beyond GDP (e.g., education).
- Economic: This approach considers how PB-related flows (e.g., CO_2 emissions) and the measures taken to mitigate them affect economic indicators such as employment, productivity, and resource allocation.

The responsibility narrative dominates, with 61 % of the studies applying it, while 15 % focus mainly on human well-being, 9 % on economic aspects, and only 2 % on justice. Additionally, some studies integrate multiple perspectives, with 6 % combining responsibility and justice, 4 % merging human well-being with responsibility, and another 4 % blending economic factors with responsibility.

Fig. 6 organises the studies chronologically by narrative and indicates whether they provide policy guidance. The figure shows distinct trends by narrative: studies framed around the concept of responsibility show less explicit policy guidance, while those emphasising human well-being often include policy recommendations. Most of the studies under the human well-being narrative apply the "City Portraits" methodology, developed through "The Thriving Cities Initiative" (The Thriving Cities Initiative, 2020). This approach downscales the Doughnut Economics framework to the city level, allowing for localised assessments of social and ecological sustainability (Doughnut Economics Action Lab, 2024). The City Portraits methodology examines cities through social and ecological lenses, both locally and globally, using indicators like water provisioning, housing, and health. Particularly relevant to this SLR is the global-ecological lens, which estimates the city's footprint and compares it against its allocated share of the PBs. This comprehensive framework has been applied to cities such as Amsterdam, Edinburgh, Barcelona, London, and Brussels.

The contrast in policy guidance across narratives suggests that research focused on well-being and its local application often has more actionable insights for policymakers, whereas studies centred on responsibility may be more academic, primarily highlighting accountability without specific policy interventions.

4.5. Novelties, limitations, and recommendations

The methodological approaches to integrating the PBs framework with EEIOA have significantly evolved since the establishment of the PBs framework. Fig. 6 reveals a surge in research efforts combining these methodologies since 2018, signalling a growing interest in combining these methodologies. Early work in this area includes Bows and Barrett (2010), who pioneered the integration of EEIOA with the 2 °C climate target through scenario analysis, and Hoff et al. (2014), who were the first to compare national footprints with downscaled PBs. Since these foundational studies, numerous innovations have been introduced. For example, Fanning and O'Neill (2016) integrated the PB framework with the concept of a steady-state economy, providing insights into how

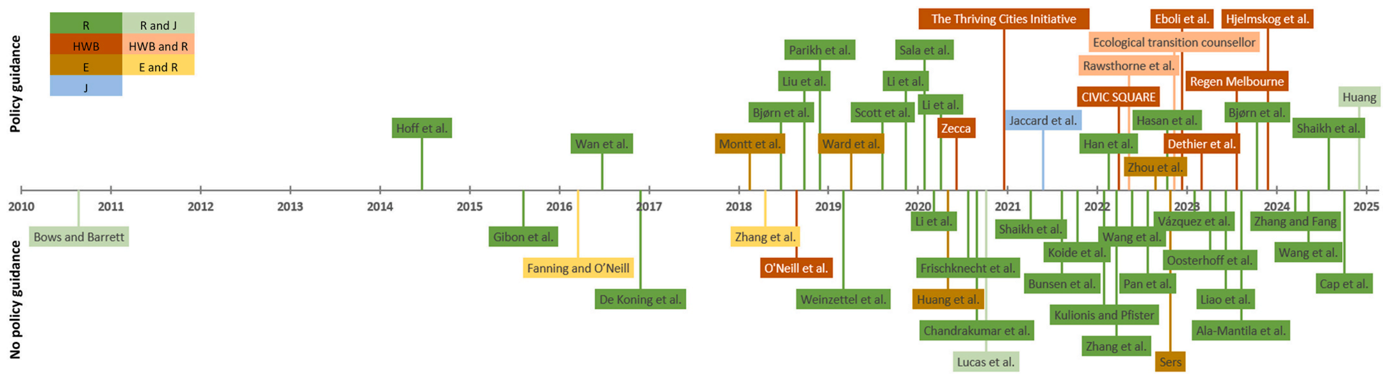

Fig. 6. Studies organised chronologically by narrative, indicating whether they provide policy guidance. R: responsibility, J: justice, HWB: human well-being, E: economic.

economies could operate within ecological limits. Li et al. (2019) introduced the "exceedance footprint", which incorporates the role of trade in the consumption of embedded or virtual compounds. Table 2 summarises these and other key developments, highlighting the methodological advancements that have shaped this field over time.

Nevertheless, despite significant advances in this field, key limitations remain to be addressed. Here, we discuss the major limitations observed across studies, aside from those associated with specific methodological choices.

In terms of PBs, three main challenges emerge. First, spatial heterogeneity is rarely considered in the operationalisation of PBs. While some progress has been made for PBs like land-system change and freshwater use, these are still constrained by limitations, such as the assumption of time-invariant national biophysical limits (e.g., Shaikh et al. (2021)). Second, another important issue lies in the common reliance on an equal per capita allocation, which, while straightforward, oversimplifies the complexity of distributing planetary resources and responsibilities. There is no technically "correct" way to distribute shares of source and sink capacities across societies, as this distribution involves normative decisions and is deeply influenced by factors of geopolitical economy, such as power dynamics, ideological orientations, and the legitimacy of decision-making entities (Fanning and O'Neill, 2016). Finally, while nearly 40 % of the studies assess two or more PBs simultaneously, current assessments still fail to account for the interdependencies among PBs. This represents a critical gap, as ecological processes are deeply interconnected and can amplify each other's impacts. For example, global warming could trigger tipping points such as the transformation of large areas of the Amazon rainforest into savanna, which would directly impact PBs like biodiversity, freshwater availability, and land use. A reduction in forest cover would also decrease CO_2 sequestration, exacerbating warming in a positive feedback loop (Steffen et al., 2018). Ignoring these interactions could lead to an underestimation of humanity's SOS and an inaccurate assessment of our actual standing regarding environmental footprints and resource consumption. One attempt to integrate multiple ecological processes has involved the use of Net Primary Production (NPP) as it encompasses land cover, water resources, major biogeochemical cycles, climate change, and biodiversity impacts. However, precise thresholds on HANPP remain inconclusive, risking underestimating the severity of its growth (Häyhä et al., 2018; Wang et al., 2024).

Regarding EEIOA, three key limitations consistently arise in the studies. First, EEIOA is based on aggregated sectoral data, which can hide variations in environmental impacts within sectors. This aggregation may conceal differences between industries or products and reduce the model's accuracy in identifying specific drivers of environmental impacts. For example, the sector detail for each country in Eora ranges between 25 (for many developing economies) to more than 500 sectors (in some industrialised countries) (Giljum et al., 2019). Second, EEIOA typically lacks spatial granularity, providing national or regional averages, which limits its ability to address geographically specific environmental impacts (e.g., local water scarcity). This spatial limitation is particularly problematic for addressing PBs where the local context is crucial, such as land-system or freshwater change. Additionally, some input-output tables are characterised by relatively low spatial resolution, further limiting spatial specificity. For example, EXIOBASE differentiates data for 44 countries, with the rest of the world aggregated into five broader regional groups. Third, EEIOA is generally limited to specific environmental categories, like GHG emissions or water use, and there might be environmental stressors that are not accounted for. For instance, while EXIOBASE provides extensive data, it omits certain greenhouse gases that contribute to global warming, such as ethane or propane, as noted by Vazquez et al. (2023). Additionally, the typical compartmentalisation of environmental categories in EEIOA prevents capturing the interactions and feedback loops between these categories. For example, EEIOA may separately analyse carbon emissions and water use but lack insights into how water scarcity might influence energy production and, consequently, emissions.

Limitations are also evident in the broader methodological frameworks that integrate the PB framework and EEIOA. Even though the footprint-related frameworks have been used to assess all PBs, for some of them such as novel entities, clear boundaries remain undefined, and the lack of satellite accounts further difficult the estimation of their footprints. For scenario analysis, the focus remains heavily on technological advancements or traditional economic metrics like GDP, while the well-being associated with different consumption patterns is often overlooked. This emphasis on technology and economic metrics means that scenarios may miss insights into how various lifestyle choices or consumption behaviours impact human well-being and environmental sustainability. Moreover, scenario assessments have primarily been developed for climate change, leaving a gap in modelling for other PBs, which could provide valuable pathways to mitigate related environmental pressures.

Across all frameworks, there is significant heterogeneity in methodological choices, with no clear trends emerging, and often little justification for those choices. This makes it challenging to determine which control variable, threshold, or input-output database is most appropriate for assessing each PB. Furthermore, most studies fail to account for rebound effects, with only a few exceptions for climate change, such as Parikh et al. (2018) and Koide et al. (2021). Ignoring rebound effects can result in overly optimistic projections of environmental benefits, leading to ineffective or counterproductive policy measures.

Emerging trends highlight efforts to address some of the existing gaps. These trends include the definition of local boundaries and the evaluation of environmental pressures at sub-national scales; the adoption of consumption-based accounting to better evaluate

Table 2
Summary of main novelties. CC: climate change, LSC: land-system change, FC: freshwater change, NF: nitrogen flows, PF: phosphorus flows, BI: biosphere integrity, OA: ocean acidification.

Publication	Planetary boundary	Main novelties
Bows and Barrett (2010)	CC	Consumption-based accounting coupled with cumulative carbon budget for determining compliance with 2 °C target.
Hoff et al. (2014)	CC, LSC, FC	Comparison of footprints with downscaled PBs.
Gibon et al. (2015)	CC	LCA and MRIO integration for scenario analysis.
De Koning et al. (2016)	CC	Scenario on demand-side measures based on behavioural changes of consumers.
Fanning and O'Neill (2016)	CC, LSC, FC, NF, PF	Estimation of territorial thresholds for FC, LSC, NF, and PF. PB framework and the concept of a steady-state economy are integrated to track indicators of sustainable scale.
Wan et al. (2016)	CC	Impacts of policy-induced fuel mix adjustments under low-carbon pathways at global scale on direct and indirect water consumption.
Montt et al. (2018)	CC	Seeking to identify the characteristics that best predict employment gains or losses and measure the ability of economies to adapt to the projected employment changes on a 2 °C scenario.
O'Neill et al. (2018)	CC, LSC, FC, NF, PF	Biophysical resource use to meeting people's basic needs, and whether this level of resource use can be extended to all people without exceeding critical planetary boundaries.
Parikh et al. (2018)	CC	Temporal dynamic optimising model with endogenous demand and endogenous income distribution. Impact of rebound effect.
Zhang et al. (2018)	CC	Development of the international ripple effect input-output model, to evaluate the economic ripple effect due to climate change impacts of the United States on the other regions.
Li et al. (2019)	PF, FC, CC	Development of the exceedance footprint concept
Lucas et al. (2020)	CC, LSC, NF, PF, BI	Distributional consequences of alternative allocation approaches based on different perspectives on distributive fairness
Chandrakumar et al. (2020)	CC	Influence of choice of GHG accounting approach, GHG metric, time horizon, climate threshold, global emissions budget calculation method, and effort-sharing approach.
Bunsen et al. (2021)	FC	Unprecedented spatial detail at the global level, for the estimation of territorial thresholds.
Jaccard et al. (2021)	CC	Conditions for the European energy use inequality (within and between European countries) to be compatible with the achievement of global climate goals and a decent standard of living.
Oosterhoff et al. (2023)	CC	Framework for assigning a share of the safe operating space to both business-to-consumer and business-to-business industries and companies.
Vazquez et al. (2023)	CC, LSC, FC, NF, PF, BI, OA	Degree of decoupling between GDP and absolute environmental sustainability assessment metrics at a global and country level.
Bjørn et al. (2023)	CC	Multi-basket approach for setting science-based targets that differentiates between short-lived and long-lived GHG emissions, leading to an improved alignment of corporate emission reduction targets with the 1.5 °C goal.
Zhang and Fang (2024)	FC	Impact of virtual and physical transfer of water within a country.
Cap et al. (2024)	CC	'Decarbonisation Divergence' scenario in order to assess only industrial decarbonisation, without household decarbonisation.

responsibilities, particularly by attributing environmental impacts to end-users across global supply chains; the incorporation of well-being metrics alongside analyses of lifestyle changes and consumer behaviour to identify pathways for living within the boundaries; and the exploration of the societal and economic impacts of climate change, underlining the necessity of linking ecological and socio-economic dimensions.

Future research directions include but are not limited to integrating potential PB interactions into the model, expanding the study of under-researched PBs such as biodiversity integrity, and evaluating the socio-economic implications of other PB transgressions. Additionally, including rebound effects on the assessments is crucial in order to anticipate and mitigate unintended consequences that can arise from lifestyle changes, technological innovations, and/or economic developments, ensuring that interventions genuinely contribute to achieving sustainability goals and respecting PBs. Thus, this consideration should extend beyond assessments of climate change to encompass other PBs (e.g., Ge and Wang (2024)).

Crucially, the purpose for integrating PBs and EEIOA is to provide additional information on where, how, why and by whom those crucial global systems functions are being transgressed. This information is necessary in order to help guide efforts in creating a 'just and safe operating space for humanity'. However, to date the choices regarding how the notion of 'just' is understood and operationalised in this context have been somewhat arbitrary. It is therefore vital that future PBs-EEIOA research better addresses and incorporates notions of justice. This can be achieved through the use of diverse allocation methods and the inclusion of thresholds that address both intergenerational equity, as the PB framework traditionally does, and intragenerational justice, for example, considering distributional equity within and between societies (e.g., Gupta et al. (2024)). Justice considerations can also be strengthened by integrating inequality metrics such as the Gini coefficient, which enables the measurement of disparities in expenditures and environmental footprints. These metrics can be applied to assess inequality both between and within countries, providing deeper insights into the distributional aspects of sustainability (e.g., Tian et al. (2024)).

The proposed future research directions have significant potential to assist policymakers by providing insights into sustainability challenges and their solutions. Understanding potential interactions between PBs can guide policymakers in creating integrated strategies that address multiple environmental challenges simultaneously. Exploring how exceeding PB thresholds affects economies and societies enables policymakers to better anticipate and mitigate risks; by factoring in rebound effects, policymakers can better measure the true impact of their interventions; and including both inter- and intragenerational equity in PB assessments can help policymakers design fairer policies. Integrating tools like the Gini coefficient provides policymakers with quantifiable insights into disparities in environmental impacts and resource consumption. These insights are critical for developing targeted interventions to reduce inequalities, ensuring that sustainability efforts do not exacerbate social inequities.

5. Conclusions

In this study, we conducted a systematic literature review of 54 studies that integrate Planetary Boundaries (PBs) and Environmentally

Extended Input-Output Analysis (EEIOA). We identified four primary modelling approaches: "footprint v/s allocated PB," "exceedance footprint," "scenario analysis," and "optimisation modelling." Climate change, land-system change, freshwater use, and biogeochemical flows were the most studied PBs, with "footprint v/s allocated PB" and "scenario analysis" being the most frequently applied modelling approaches.

The review revealed significant methodological heterogeneity, particularly in the choice of control variables, thresholds, allocation methods, and input-output databases. The choice of control variables and thresholds had the greatest influence on the results, followed by the allocation methods, while input-output databases had a comparatively lower impact. From a policy perspective, half of the studies provided explicit guidance, with responsibility emerging as the dominant narrative among justice, human well-being, and economic.

Despite the growing application of PB-EEIOA, several challenges persist. The operationalisation of PBs often lacks spatial differentiation, relies on oversimplified per capita allocations, and fails to account for interdependencies, leading to underestimated risks and uncertainties. EEIOA-based studies face limitations due to sectoral aggregation, low spatial resolution, and compartmentalised approaches to environmental stressors, restricting their ability to capture feedback loops. Methodological inconsistencies, a lack of clear justifications for parameter choices, and the omission of rebound effects further undermine robustness.

Nevertheless, emerging research trends indicate promising advancements. Local PB boundary assessments, consumption-based accounting, and the integration of well-being metrics are gaining traction as means of improving sustainability assessments. Expanding scenario modelling beyond climate change to other PBs and incorporating socio-economic factors could enhance the policy relevance of these approaches. Future research should prioritise integrating PB interdependencies to develop more holistic studies, expanding the study of under-researched PBs such as biodiversity integrity, and assessing the socio-economic implications of PB transgressions. Additionally, incorporating rebound effects beyond climate change assessments and strengthening justice considerations through diverse allocation methods and inequality metrics, would provide deeper insights into intra- and intergenerational equity.

For policymakers, these findings underscore the need for integrated sustainability strategies that address multiple environmental challenges simultaneously. Understanding PB interactions is essential for developing more effective interventions, while incorporating equity considerations can ensure that sustainability efforts do not exacerbate social inequalities. By leveraging these insights, policymakers can design fairer and more impactful policies that contribute to maintaining a just and safe operating space for humanity.

CRediT authorship contribution statement

María Fernanda Godoy León: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alison Bankert:** Writing – review & editing, Investigation. **Diego Torralva Becerra:** Writing – review & editing, Visualization. **David J. Abson:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.04.015.

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