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Join the dots on planetary boundary interactions

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Abstract. Planetary boundaries (PBs) are complexly interlinked, as the transgression of either one can worsen the status of others. Such cascading processes can accelerate Earth system destabilization and shrink humanity's safe manoeuvring space. To demonstrate the crucial need to maintain multiple PBs, we unravel interactions between the three PBs for freshwater change, climate change and land-system change (representative of key biosphere–atmosphere feedbacks), and how they are linked via PB control and response variables. Thereby we exemplify how transgressions of these PBs are driven both directly by human activities and indirectly by biophysically or anthropogenically mediated effects of other PBs' transgressions. As we also highlight, measures to maintain a single PB – such as large-scale terrestrial carbon dioxide removal aimed at lowering pressure on the climate change PB – can unintentionally become a force of transgression of other PBs, creating new impacts. To identify fallacies and uncontrolled feedbacks that may put Earth system stability at further risk, we propose a systematic model-based assessment of interacting impacts of PB transgressions and of measures to maintain multiple PBs simultaneously.

1 Introduction

In the present Anthropocene, Earth is showing signs of loss of resilience toward increasing anthropogenic pressures (Rocha, 2022; Ke et al., 2024). Hence, attention shifts to global environmental problems on top of climate change (Hansen Wood & van den Bergh, 2024) and enhanced approaches of 'systemic sustainability', including identification of integral strategies to steer the Earth system into a sustainable and just future (Rockström et al., 2021; Fletcher et al., 2024).

Against this backdrop, the scientific framework of planetary boundaries (PBs) defines precautionary limits to (anthropogenic) change in nine processes that together regulate Earth system functioning (for seminal papers see Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023). A change in a PB's control variable, especially a transgression of the PB value, can lead to gradual or abrupt changes in response variables representing (undesirable) changes in other features of the Earth system and of societies (Rockström et al., 2009) – including control variables of other PBs. PB interactions can be biophysically mediated, reactive human-mediated, or due to parallel human drivers (Lade et al., 2020). The two latter types are driven by human behaviour, either as a reaction to a changing in a PB status (e.g. climate change leading to more irrigation and thus freshwater change), or through the same behaviour driving multiple PB transgressions (e.g. land clearing directly affecting not only land-system change but also freshwater change, climate change, biodiversity and other Earth system features considered in the PB framework). Biophysically mediated interactions refer to changes in a PB influencing another PB through a biophysical mechanism. For instance, model studies showed that maintaining the land-system change PB would be critical to prevent climate change amplification (Richardson et al., 2023); and conversely, that further transgression of the climate change PB will affect the land-system change PB through substantial shifts in boreal and temperate forest distribution, also inducing knock-on effects on yet other PBs (Tobian et al., 2024). Besides these two applications there are, to our knowledge, only a few other model studies that explicitly quantify certain PB interactions and their impacts, including Anderies et al. (2013) and Lade et al. (2021). In addition, expert knowledge-based, semi-quantitative synopses of presumed directions and strengths provide insights into the many and complex interactions involved (Rockström et al., 2009; Lade et al., 2020; Chrysafi et al., 2022). For instance, Lade et al. (2020) found documented evidence for about half of all theoretically possible PB interactions, with biophysically mediated interactions contributing 31% of the current changes in the Earth system compared to PBs, direct human impacts 40%, parallel human drivers 28%, and reactive human-mediated interactions 1%, respectively. But, the collective drivers and impacts of PB transgression, and the resulting cascading or parallel effects on other PBs, remain to be assessed comprehensively and systematically. Analogously, knowledge about integrative solutions toward achieving a safe corridor for societies (Rockström et al., 2021; 2023) is to be advanced and integrated, ideally under a systemic sustainability lens (Moallemi et al., 2025).

This Perspective paper portrays a segment of the complex larger network of PB interactions: how the PB for "blue" (streamflow) and "green" (soil moisture) freshwater change (PB_{FC}) is intertwined with land-system change (PB_{LC}) and climate change (PB_{CC}). In essence, we show that the present transgression of PB_{FC} is largely driven by, and feeds back to, concurrent transgressions of PB_{LC} and PB_{CC}, and that these feedback loops appear to increasingly self-amplify. As also shown, one-sided countermeasures aimed at maintaining only one PB – like biomass plantations for carbon sequestration to curb further PB_{CC} transgression (e.g. Boysen et al., 2017; Zhao et al., 2024) – can become drivers of transgression of other PBs, potentially creating more problems than solutions for Earth system resilience. We conclude with a proposal for systematic assessment of PB interactions, impacts and synergistic opportunities aimed at maintaining multiple PBs simultaneously.

2 Process interactions between three PBs

Here, we detail main processes via which anthropogenic drivers change the status of their control variables, potentially leading to ± strong PB transgression outside the safe operating space into the zones of increasing risk or high risk. Response and impact variables with which impacts of these transgressions could be evaluated are presented further below. While beyond the scope of this article, many interactions across the full set of PBs may interplay with the three-way interactions considered here (see

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more details and reviews of Earth system processes related to PBs in Gleeson et al., 2020; Lade et al., 2020; Chrysafi et al., 2022; Wang-Erlandsson et al., 2022; Tomalka et al., 2024). We focus on the following drivers and interactions (also depicted in Fig. 1):

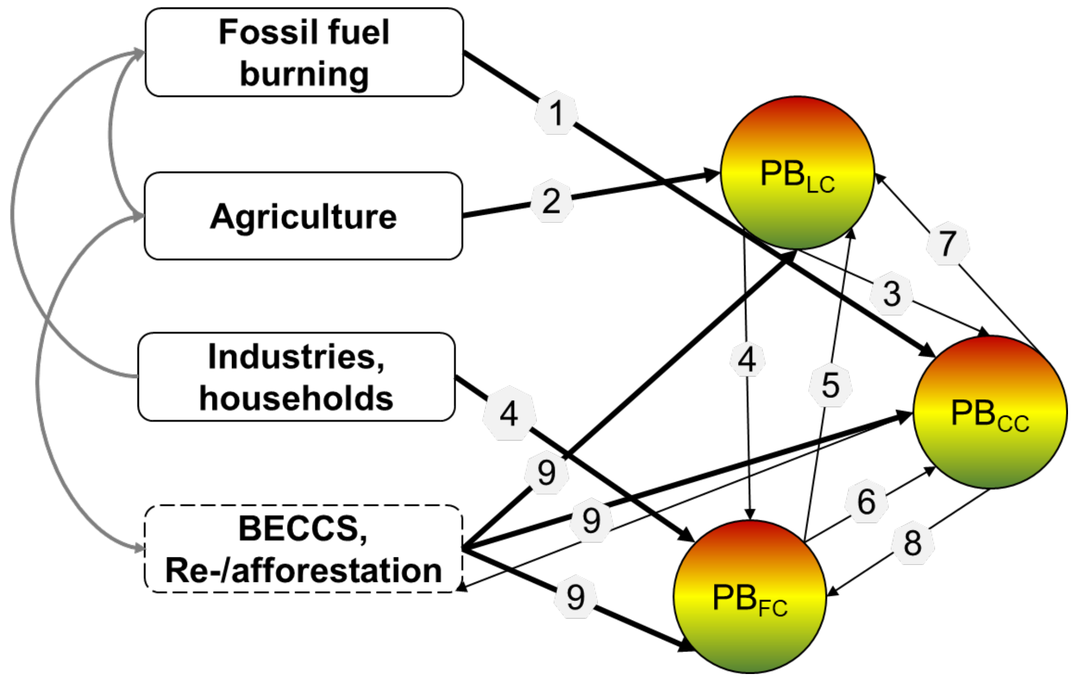

Figure 1: Schematic illustration of interactions between the three PBs considered (PB$_{LC}$, land-system change; PB$_{CC}$, climate change; PB$_{FC}$, freshwater change). Main human drivers of PB status changes are shown on the left, with their direct influences indicated by thick arrows. The grey arrows illustrate connections between the drivers, BECCS and re-/afforestation being a reactive human-mediated interaction (hence marked with dotted outline). Associated biophysically mediated interactions between the PBs are indicated with thin arrows. The numbers assigned to the arrows refer to the numbering in the text that briefly describes each interaction. As interactions are typically amplifying rather than attenuating, no sign of change is given.

1. Fossil fuel burning by industries, households and in agricultural activities leads to greenhouse gas emissions that are quantitatively the most important driver of PB$_{CC}$ transgression (Campbell et al., 2017).

2. Agricultural practices as a direct human driver strongly affect all terrestrial PBs (Campbell et al., 2017; Springmann et al., 2018; Gerten et al., 2020). Specifically, they have led to widespread replacement of forests and natural grasslands by cropland and pasture, primarily worsening the PB$_{LC}$ status.

3. Mediated by the changes in the PB$_{LC}$ status and associated management practices, agriculture and the wider food system also contribute to PBCC transgression due to release of carbon dioxide, nitrous oxide, and methane (contributing about a third

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to total greenhouse gas emissions; Campbell et al., 2017; Tubiello et al., 2021). Further indirect effects on PB_{CC} happen in multifarious ways, mainly by altered albedo, carbon fluxes, and atmospheric moisture flows (Tobian et al., 2024; Windisch et al., 2025).

4. Changes in the PB_{LC} status affect the PB_{FC} status also: Deforestation (via changes e.g. in phenology, rooting depths, transpiration) usually decreases evapotranspiration and increases streamflow with varied effects on soil moisture; and in case of crop irrigation, water withdrawal decreases streamflow and its on-farm application increases soil moisture (Porkka et al., 2024). Besides, industries and households directly drive blue PB_{FC} transgression.

5. Changes in PB_{FC} can in turn feed back to PB_{LC}, e.g. either enabling or limiting expansion of cropland and its irrigation, or preventing establishment and growth of certain natural vegetation types.

6. Concurrently, changes in PB_{FC} can also feed back to PB_{CC}, especially since drier soils and droughts can cause plant water stress leading to reduced land carbon storage and uptake from the atmosphere (e.g. Yang et al., 2024; Wang-Erlandsson et al., 2025).

7. The interactions are further complicated by the increasing impacts of intensifying PB_{CC} transgression. This concerns PB_{LC} in that climate change affects large-scale vegetation distribution and thus forest area, as demonstrated explicitly by Tobian et al. (2024) for a suite of future scenarios.

8. PB_{CC} transgression also affects PB_{FC} through climate-driven decreases or increases of soil moisture and streamflow in many regions (Caretta et al., 2022). Self-reinforcing feedbacks can occur in general, in that e.g. nonlinear, tipping point-like developments such as changes in wetland extent and permafrost thawing (affecting PB_{FC}) or forest dieback (affecting PB_{LC}) accelerate PB_{CC} transgression (Lenton et al., 2023).

9. Reactive human-mediated interactions happen if humans react to changes in a PB status – which is potentially counterproductive as it can lead to unintended pressure on other PBs. For instance, increased blue water withdrawals to ease effects of PB_{CC} transgression can aggravate PB_{FC} transgression. Another example with potentially significant impacts is BECCS (Bioenergy with Carbon Capture and Storage), aimed at relieving pressure on PB_{CC} while increasing pressure on PB_{LC} and PB_{FC} as it relies on substantial appropriation of land and water (Stenzel et al., 2021; Braun et al., 2025). These and subsequent process interactions and feedbacks would add to the commensurable effects of agriculture described above, including e.g. water feedbacks through re-/afforestation (Ricciardi et al., 2022).

3 PB interactions through interconnected control and response variables

To improve the PB framework through better understanding and eventual quantification of PB interactions, we need to relate

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their control variables (that can be affected by people and control the state and functioning of the Earth system) to each other and to other affected response variables (that are used to assess safe levels of the control variables). The term "response variables" has not been used consistently throughout previous work and, to our knowledge, such variables are neither formally defined nor quantified relative to a change in the control variables. However, some candidates have been suggested and used to define the PBs. PB_{CC} accounts for global mean temperature change, together with "long-term reinforcing feedback processes" and "Earth's subsystems (…) moving outside their stable Holocene state", including destabilisation of large polar ice sheets (Rockström et al., 2009). PB_{LC} represents forests' influence on the climate system and land cover change tipping points, whereas PB_{FC} accounts for "river regulation and aquatic ecosystem integrity" (blue water) and "hydrological regulation of terrestrial ecosystems, climate, and biogeochemical processes" (green water), respectively (Richardson et al., 2023).

Table 1 lists these overarching response variables tied to the control variables. We also suggest more concrete "impact variables", which represent impacts of changes in control and response variables on specific components of the Earth system that can be observed or modelled. They can be used to assess linkages across PBs as well as cascading biospheric and socioeconomic impacts (including on human well-being, livelihoods, or ecosystem services) in relation to other assessment frameworks.

Table 1: The three PBs' control, response and impact variables. Response variables are taken from suggestions in the seminal PB papers, suggested more specific impact variables are selected from the Planetary Health Check Report (PBScience, 2025) and other frameworks and assessments: the Intergovernmental Panel on Climate Change (IPCC, 2022); the Sustainable Development Goals (SDGs) and their indicators (e.g. van Vuuren et al., 2022); the System of Environmental-Economic Accounting – Ecosystem Accounting (Edens et al., 2022); and the IPBES–IPCC co-sponsored workshop report on biodiversity and climate change (Pörtner et al., 2021).

Planetary Boundary (control variable with its PB value *cf.* Richardson et al., 2023)	**Response variables** (*cf.* Rockström et al., 2009; Steffen et al., 2015; Richardson et al., 2023)	**Examples for impact variables, grouped by interactive effects on the respective two other PBs** (specific references extracted primarily from the reviewed reports)
Climate change, PB_{CC} Atmospheric CO_2 concentration <350 ppm; total anthropogenic radiative forcing at the top of the atmosphere <1 W m^{-2}	Global mean surface temperature and associated changes in climate system	PB_{LC}: Wildfire frequency and extent (Bowman et al., 2009); heat-related mortality in ecosystems (Mora et al., 2017); biome production decline (Ciais et al., 2005; Wei et al., 2022) PB_{FC}: Glacier/snowpack retreat and polar ice sheet loss (Stueve et al., 2011); drought frequency and duration (Sheffield & Wood, 2008)
Land-system change, PB_{LC} Remaining global forest area <75%; <50% for temperate forest biomes; <85% for boreal and tropical forest biomes)	Influence on the climate system and land cover change tipping points (Richardson et al., 2023)	PB_{CC}: Forest degradation (Foley et al., 2005; Sims et al., 2019), impact on air temperature and its extremes (Alkama and Cescatti, 2016) PB_{FC}: Soil erosion rate (Borrelli et al., 2017); desertification index (Cherlet et al., 2018); agricultural land intensity (Felipe-Lucia et al., 2020)

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Freshwater change, PB_{FC} Percentage land area with significant dry or wet departure of streamflow or soil moisture >10.2% (blue water) and >11.1% (green water), respectively	Integrity of freshwater ecosystems, hydrological regulation of terrestrial ecosystems, climate, and biogeochemical processes	PB_{CC}: Vegetation water stress (Gerten et al., 2007; Pace et al., 2021); moisture feedback, carbon uptake by terrestrial systems (Bunsen et al., 2021); permafrost thawing (Runge et al., 2022) PB_{LC}: Biomass production, biodiversity (Bunsen et al., 2021)

We acknowledge that our suggested list of response variables is provisional, as we focus on only three PBs on purpose. Further analysis is recommended to identify better or complementary variables – using e.g. further indicator collations such as the 'Essential Variables' (Schrodt et al., 2024), machine-learning techniques able to detect synchronies in multidimensional datasets (Willcock et al., 2018; Manley et al., 2022), or algorithms able to assess the agreement between PB control and response variables and other, independent metrics (as in Stenzel et al., 2025). Nonetheless, the current selection is a starting point for systematic quantitative analysis of PB interactions (sketched below), and the impact variables may serve as early-warning signals important for cross-scale monitoring and guiding integrated sustainability policies. Crucial knowledge gaps remain regarding the role of biodiversity/biosphere integrity as a "core boundary" (Steffen et al., 2015; Richardson et al., 2023) and/or an ultimate response variable that feeds back to the other PBs through loss of ecosystem functions and resilience (Mace et al., 2014). Also, as the regulating medium for at least five PBs, soils were suggested to be a 'master variable' (Kopittke et al., 2021), and soil degradation as an additional PB (Kraamwinkel et al., 2021). Arguably, soils are inseparable from biosphere integrity as more than half of all terrestrial biodiversity exists belowground (Antony et al., 2023), and feedbacks between below- and aboveground processes are important for ecosystem functioning (Thakur et al., 2021, Bardgett & van der Putten, 2014).

4 Suggested modelling agenda

In order to gain improved process understanding of PB interactions and their impacts, analyses should go beyond approaches such as expert elicitation (Chrysafi et al., 2022) or literature review (Lade et al., 2020). We recommend development of a systematic, internally consistent, model-based analysis of drivers of change in PB statuses, impacts of these changes and eventual PB transgressions, and involved interactive effects between PBs (Earth system feedbacks). At its core, this shall include the modelling of control–response interactions, with variables suggested in Table 1 translated into a formal simulation protocol with specified units, and their simulated interaction strengths analysed e.g. by normalisation approaches as applied in Lade et al. (2020, 2021) and Zoller et al. (2025). Process-based models like the Dynamic Global Vegetation Model LPJmL have demonstrated capability to simulate biophysical processes underlying PBs and their interactions (Schaphoff et al., 2018), and dedicated analysis and visualization tools are now available that facilitate the post-processing of simulation outputs so as to calculate and plot spatial-temporal PB statuses (Gerten, Braun & Breier et al., 2025). Such terrestrial biosphere models can be employed to systematically quantify impacts of PB transgression on other PBs and related Earth system processes, as shown

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in some recent applications: Using LPJmL model outputs, Lade et al. (2021) have developed and quantified an Earth system change metric for use by actors such as companies and investors that addresses multiple PBs, while Tobian et al. (2024) used that same model– forced by a CMIP6 multi-model climate change ensemble – for a stratified analysis of how different magnitudes of PB_{CC} transgressions affect PB_{LC} (through forest biome shifts). Furthermore, studies have emerged that not only use climate models but also impact models or land surface models intercomparatively to address model structural uncertainties in PB calculations, namely as reflected in the ISIMIP ensemble (Virkki et al., 2022; Lai et al., 2023; Porkka et al., 2024; Stenzel et al., 2025; see https://www.isimip.org). Simulation protocols of these model intercomparison initiatives, together with analytical software as developed by Gerten, Braun & Breier et al. (2025), could be enhanced to fully account for processes governing PB dynamics, in an effort to create a 'Planetary Boundaries Model Intercomparison' for past and potential future conditions. In such analyses, increasing impacts in proportion to changing PB statuses could be illustrated as "burning ember" bar plots or maps, as frequently done for impacts of rising global mean temperature (a proxy for different degrees of PB_{CC} transgression) (Smith et al., 2009; Gerten et al., 2013; Schellnhuber et al., 2016; Tobian et al., 2024), visually similar to the green–yellow–red colour spectrum used in PB science (Rockström et al., 2024). One shortcoming is that impact models are typically being used in a stand-alone mode, treating the climate (and thus PB_{CC}) as a forcing input only. Capturing three-way feedbacks between PB_{CC}, PB_{FC} and PB_{LC} requires more enhanced Earth system models that endogenize the representation of atmosphere dynamics (see application in Richardson et al. 2023 of the Potsdam Earth Model POEM, detailed by Drüke et al., 2024). Future scenarios could also be designed so as to assess how the risk of tipping points in the Earth system may increase along with (synchronous) PB transgressions, ideally as part of the TIPMIP initiative and its simulation setup (https://tipmip.org).

Comprehensive studies of impacts of PB transgression will ultimately help to corroborate, or adjust, the current definition of PB control variables and their threshold values positioning the PB value and the zones of increasing and high risk. Moreover, factorial model simulations in which control variables are held constant over time can be designed to attribute changes in PB statuses to certain drivers, and to disentangle at least some of the intricately linked processes. Using such a setup, Virkki et al. (2025) show that PB_{FC} is transgressed not only due to direct human drivers (water use and management) but also due to indirect, biophysically mediated effects from the concurrent transgression of PB_{CC}. Valuable other data from remote sensing and other observations can be integrated with the modelling to trace the status of PBs (Haberl et al., 2014; Zhang et al., 2021).

Since their systemic interactions and resulting impacts may intensify in the future, potentially increasing the "dynamic risk space" (the product of pressure levels on the individual PBs; Tobian, 2024), further PB transgressions should be avoided. Thus, prospectively, the analysis of drivers, interactions and impacts associated with PB transgressions shall integrate options to alleviate pressure on PBs and minimize impacts of their transgression. Regarding the interaction of PB_{FC}, PB_{LC} and PB_{CC} (and further PBs), the role of the agri-food system comes into focus (Campbell et al., 2017; Gerten & Kummu, 2021). Some assessments have already quantified the potential of various leverage points – including improved water and crop management, redistribution of cropland, international trade, and diet changes – which elucidates how a more sustainable agri-food system

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can create opportunities to reduce overall pressure on the PBs (Gerten et al., 2020; Liao et al., 2023). Recent studies based on Integrated Assessment Models portray potential future socioeconomic pathways and how they affect PBs (Beier et al., 2025; van Vuuren et al., 2025), yet they do not consider subglobal PB patterns and lack explicit simulation of consequences of PB interactions and Earth system feedbacks. Newer modelling approaches that endogenize the simulation of human responses to changing environmental conditions and *vice versa* can potentially be used to model how and under what conditions adaptive farmer responses can help to maintain PBs (Breier et al., 2024; Yoon et al., 2024). In an analogous manner, the effects of reactive human-mediated interactions such as BECCS (if implemented at large scale as a contribution to avoid further transgression of PB_{CC}) on other PBs' statuses could be modelled. This would ideally include a systematic and consistent combinatorics of options to produce both enough food for a growing world population and enough negative emissions – while maintaining multiple PBs (e.g. fusing simulation approaches as in Gerten et al., 2020; Braun et al., 2025).

5 Conclusion: policy-injective applications of a 'PB interactions and impacts simulator'

The present Perspective article reinforces the PB framework's underlying assumption that PBs are tightly interlinked, in that a worsening status or transgression of a PB can affect the status of others. It proposes an agenda for using Earth system modelling to assess these interlinkages, their impacts, their drivers, and potential leverage points to avoid further transgressions. While our present suggestion focuses on three PBs, a more comprehensive model framework is ultimately needed that will enable exploration of the larger network of interactions between all nine PBs. Exemplary high-level and policy-relevant research questions to be answered with such an assessment setup are: (i) Does the transgression of a PB amplify other PBs' transgressions globally or regionally? (ii) Can PB_{CC} be maintained (including achievement of the Paris Agreement) without maintaining PB_{FC} and PB_{LC} in parallel, since their transgressions appear to amplify each other in three-way interactions? (iii) Likewise, can PB_{CC} still be maintained without transgressing PB_{FC} and PB_{LC} (due e.g. to appropriation of water and land through BECCS) – while at the same time producing sufficient food for a growing world population? (iv) Do intensifying and feedback-looped transgressions of PB_{CC}, PB_{FC} and PB_{LC} indeed increase the dynamic risk space, or can certain 'overshoots' of PBs be tolerated?

Regarding such policy implications, we emphasise the need to avoid that measures intended to preserve a single PB increase pressure on other PBs that can happen by way of indirect interactions, as shown for the relatively well-examined example of BECCS. Other such potential 'traps', involving other PBs than those considered here, are: too fast removal of aerosols (to relieve pressure on the PB for aerosol loading) that may speed up global warming (Wang et al., 2024; Francke & Heistermann, 2025; Hansen et al., 2025), also interacting with both the water cycle, i.e. PB_{FC} (Junkermann & Hacker, 2022) and the nitrogen cycle, i.e. the biogeochemical flows PB (Gong et al., 2024); nutrient reduction management to maintain the biogeochemical flows PB can produce significant influence on aquatic/marine ecosystems like the Baltic Sea, i.e. the biosphere integrity PB (Blenckner et al. 2021), and even lead to economic spillover effects on other PBs in other regions (Engström et al., 2020). In sum, avoidance of countereffective, potentially dangerous reinforcing feedbacks necessitates a systemic perspective across all

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PBs and synergistic, not contradictive policies (Kroll et al., 2019; Pörtner et al., 2023; Liu et al., 2025). It is also important to recognise the bottom-up nature of many PB interactions (Chrysafi et al., 2022), linking the planetary-scale processes to local policy and governance as well as business contexts (Meyer & Newman, 2020; Zipper et al., 2020; Crona et al., 2023; Bai et al., 2024; Gopal & Pitts, 2024). This will enable that short-term decisions support long-term goals compatible with human rights (e.g. Järvensivu et al., 2021; Mevono Mvogo, 2024; Kallis et al., 2025), and help to set science-based targets, local or sectoral 'budgets' in line with PBs (Gifford et al., 2023). Ultimately, as PB transgressions and both their direct and indirect PB interactions eventually originate from human actions (Lade et al., 2020), understanding our socio-metabolic relationships and what types of material relationships emerge as a function of human activities is pivotal (Brand et al., 2021; Schandl et al., 2025).

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