Entering the dynamic risk space

Assessing planetary boundary interactions through process-based quantifications

Arne Tobian

Doctoral Thesis in Sustainability Science at Stockholm University, Sweden 2024

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Academic dissertation for the Degree of Doctor of Philosophy in Sustainability Science at Stockholm University to be publicly defended on Thursday 28 March 2024 at 13.00 in hörsal 4, hus 2, Campus Albano, Greta Arwidssons Väg 30.

Abstract

The planetary boundaries framework is an effort to define a safe operating space for humanity. Its rationale is that sustainable development needs to be achieved in ways that safeguard the stability of the Earth system on which human prosperity relies. However, very few studies explicitly examine the interactions of the Earth system processes that underlie individual boundaries.

My overarching research question is: how can continued anthropogenic climate change affect the geospatially resolvable land and water planetary boundaries, and what are the implications for human livelihood? For most of my analysis, I use the LPJmL dynamic global vegetation model because it contains suitable process representations that provide a dynamic and adaptive Earth system perspective for my investigation of key planetary boundary interactions of the climate, land, water and ecosystem nexus.

Paper I emphasizes the importance of green water dynamics (that is terrestrial precipitation, evapotranspiration and plant-available soil moisture) for ecosystem resilience and human well-being. The underlying analysis suggests that the current status of the proposed planetary boundary for green water is already transgressed. Paper II reveals long-term spatiotemporal dynamics of planetary boundary interactions as breaching the climate change boundary critically affects the world's major forest biomes. Notably, the most extreme climate change scenarios led to the emergence of a southern boreal dieback in the simulations. Tropical forests further show a shift from evergreen to deciduous rainforest, an important process which is not captured by the definition of the land-system change boundary. Maintaining climate change at the planetary boundary co-stabilizes the land-system change boundary. Paper III extends the biophysical understanding of planetary boundary interactions by discussing their impact on human livelihood and the attainment of the Sustainable Development Goals. Future climate change causes increases in dry anomalies of green water in ~30% of the global land area by the end of the century. As of today (here referring to 2015), nearly a quarter of the world population and ~28% of global harvest would be affected. The dynamic risk space terminology is established to fill the conceptual gap in the analysis of planetary boundary interactions. Paper IV highlights how planetary stability constitutes the non-negotiable fundament for human development and argues why the Sustainable Development Goals have to be aligned with the planetary boundaries framework and which perils might arise from their interactions. Paper V presents the land-system change reallocation tool algorithm which allows for a scenario-driven rearrangement of human land-use to meet varying transgression levels of the land-system change boundary.

My results of Paper I-V advance the understanding of interactions in the planetary boundaries framework. Moreover, my analysis in a process-based and validated modeling environment gives spatiotemporal detail of the processes at play that exceeds the potential of previously used conceptual models. My work fills a crucial gap in the operationalization of the planetary boundary framework by providing insights into how and where different policy options produce positive or negative outcomes across boundaries. The holistic understanding I present is a prerequisite for any application of the planetary boundaries framework that focuses on future conditions.

Keywords: *Planetary boundaries, climate change, land-use change, Earth system interactions, ecosystem modeling, green water.*

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In loving memory of my
dear friend Hans,
whose vibrant spirit and
love for life inspire me
daily, reminding me of
the fragility and
importance of every
moment.

“Ich hielt es für besser, etwas zu leisten, als nichts zu versuchen, weil man nicht alles leisten kann”

“I considered it better to achieve something than to try nothing, because you can't accomplish everything”

-- Alexander von Humboldt

Abstract

The planetary boundaries framework is an effort to define a safe operating space for humanity. Its rationale is that sustainable development needs to be achieved in ways that safeguard the stability of the Earth system on which human prosperity relies. However, very few studies explicitly examine the interactions of the Earth system processes that underlie individual boundaries.

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My results of Paper I-V advance the understanding of interactions in the planetary boundaries framework. Moreover, my analysis in a process-based and validated modeling environment gives spatiotemporal detail of the processes at play that exceeds the potential of previously used conceptual models. My work fills a crucial gap in the operationalization of the planetary boundary framework by providing insights into how and where different policy options produce positive or negative outcomes across boundaries. The holistic understanding I present is a prerequisite for any application of the planetary boundaries framework that focuses on future conditions.

Keywords: Planetary boundaries, climate change, land-use change, Earth system interactions, ecosystem modeling, green water

Sammanfattning

Ramverket för de planetära gränserna är ett försök att definiera ett säkert handlingsutrymme för mänskligheten. Tanken är att hållbar utveckling behöver uppnås på ett sätt som bevarar stabiliteten i det jordsystem som mänsklighetens välstånd är beroende av. Emellertid finns få studier som undersöker samspelet mellan de processer i jordsystemet som ligger till grund för individuella gränser. Min övergripande forskningsfråga är: **hur kan fortsatta antropogena klimatförändringar påverka de geospatialt lösbara planetära gränserna för land och vatten, och vilka är konsekvenserna för människors försörjning?** För de flesta av mina analyser använder jag den dynamiska globala vegetationsmodellen LPJmL vilken ger mig ett dynamiskt och anpassningsbart jordsystemsperspektiv för att undersöka planetära gränsinteraktioner mellan klimat, mark, vatten och ekosystem.

Paper I betonar vikten av dynamiken hos grönt vatten (det vill säga markbunden nederbörd, avdunstningstranspiration och markfuktighet tillgänglig för växter) för ekosystemens motståndskraft och människors välbefinnande. Den grundläggande analysen tyder på att den föreslagna planetära gränsen för grönt vatten redan har överskridits. **Paper II** visar långsiktiga spatiala och tidsmässiga dynamiker av interaktioner mellan planetära gränser eftersom överskridandet av klimatförändringsgränsen har en betydande inverkan på världens största skogsbiomer. De mest extrema klimatförändringsscenarierna ledde till en sydboreal skogsdöd i simuleringarna. Tropiska skogar visar även på en övergång från vintergrön till lövfällande regnskogen, en viktig process som inte fångas upp av definitionen av gränsen för förändringar i markanvändning. Att ha kvar klimatförändringarna vid den planetära gränsen stabiliserar samtidigt gränsen för förändring av landsystemet. **Paper III** fördjupar den biofysiska förståelsen av interaktioner mellan planetära gränser genom att diskutera deras inverkan på människors försörjning och förverkligandet av de globala målen för hållbar utveckling. Framtida klimatförändringar orsakar ökningar av torra anomalier av grönt vatten på cirka 30% av den globala landytan fram till slutet av seklet. I dagsläget (här avses 2015) skulle nästan en fjärdedel av världens befolkning och cirka 28% av den globala skörden påverkas. Ett nytt begrepp "dynamisk riskrymdsterminologi" presenteras för att fylla den konceptuella luckan i analysen av interaktioner mellan planetära gränser. **Paper IV** belyser hur planetär stabilitet utgör den icke-förhandlingsbara grunden för mänsklig utveckling och argumenterar för varför de globala målen för hållbar utveckling bör anpassas till ramverket för planetära gränser. Dessutom adresseras risker som kan uppstå ifrån interaktionerna i ramverket för planetära gränser. **Paper V** presenterar algoritmen för verktyget för omallokering av förändringar i markanvändning. Denna algoritm gör det möjliggör en scenariostyrd omfördelning av mänsklig markanvändning för att hantera varierande överträdelsegrader av gränsen för förändringar i markanvändning.

Mina resultat av Paper I-V bidrar till en ökad förståelse av interaktioner inom ramverket för planetära gränser. Analysen i en processbaserad och validerad modelleringsmiljö ger detaljerad information om rumsliga och tidsmässiga processerna, vilket överstiger potentialen hos tidigare använda konceptuella modeller. Mitt arbete bidrar till i operationalisering av ramverket för planetära gränser med insikter gränser genom att visa hur olika handlingsalternativ ger positiva eller negativa resultat över gränserna. Den holistiska förståelse jag presenterar är en förutsättning för alla tillämpningar av ramverket planetära gränser som är inriktade på framtida förhållanden.

Nyckelord: Planetära gränser, klimatförändringar, förändringar i markanvändning, jordsystemsinteraktioner, ekosystemmodellering, grönt vatten

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Writing this thesis has been a profound journey, one filled with challenges and growth. I owe my deepest gratitude to the individuals and groups whose unwavering support and guidance have been instrumental in bringing this work to fruition.

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List of Papers

I. Wang-Erlandsson, L., **Tobian, A.***, van der Ent, R. J.*, Fetzer, I.*, te Wierik, S.*, Porkka, M.*, Staal, A.*, Jaramillo, F.*, Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X., & Rockström, J. (2022). A planetary boundary for green water. *Nature Reviews Earth & Environment,* 3, 380–392.
Highlights the various roles of green water for maintaining critical Earth system functions and establishes green water as an integral part of the planetary boundary for freshwater change.
Contributions: A, B, C, E, G, H, I; my particular contributions are further described in the paper.

II. **Tobian, A.,** Gerten, D., Fetzer, I., Schaphoff, S., Seaby Andersen, L., Cornell, S., & Rockström, J. (Submitted manuscript). Climate change critically affects the status of the land-system change planetary boundary. Under review at *Environmental Research Letters*.
Systematic analysis of interactions between planetary boundaries. It is revealing that breaching the climate change boundary leads to a critical transgression of the land-system change boundary, causing shifts in forest biomes, but also impacts other planetary boundaries such as freshwater change and biosphere integrity, emphasizing the need for a systemic understanding of these interactions.
Contributions: A, B, C, D, E, F, G, H, I

III. **Tobian, A.***, Nyasulu, M.K.*, et al. (Manuscript). Planetary boundaries interactions and food production: Exploring the dynamic risk space. In preparation for *One Earth*.
Examines the impact of the interactions between the planetary boundary for climate change and green water on rising food insecurities. It discussed planetary boundary interactions in the context of a dynamic risk space and emphasizes the need to explicitly include green water in Sustainable Development Goals (SDG).
Contributions: A, B, D, E, F, G, I

IV. **Tobian, A.**, Collste, D. and Rockström, J. The planetary boundaries buttress the Sustainable Development Goals. (Submitted manuscript). Invited book chapter for *The Elgar Companion to Transforming our World: the UN 2030 Agenda for Sustainable Development*. (Editors: Jeffrey Sachs, Patrick Paul Walsh, Ciara Whelan, Mark Orrs)

Advocates aligning the United Nations' Sustainable Development Goals (SDGs) with planetary boundaries to safeguard Earth's regulatory capacity. It warns of bidirectional misalignments, where actions for SDGs may intensify planetary pressures, hindering progress and vice-versa. Urging global collaboration, it emphasizes finding synergies to simultaneously achieve SDGs and limit pressures on planetary boundaries for a stable Anthropocene.
Contributions: A, D, G, I

V. **Tobian, A.**, Cornell, S., Fetzer, I., Gerten, D., Rockström, J. (Manuscript). The Land-Use Change Allocation Tool (lucatoo) and its application to the planetary boundary of land system change. In preparation for *Geoscientific Model Development.*
Anthropogenic land-use changes are a key driver of global environmental change in the Anthropocene. Current land-use projections lack alignment with the planetary boundary for land-system change. Introduces a tool for assessing diverse afforestation and deforestation scenarios as a basis to study their impact on related boundaries at grid cell scale.
Contributions: A, B, C, D, E, F, G, I

Contributions (CRediT guidelines)

A Conceptualisation
B Methodology
C Software
D Formal Analysis
E Investigation
F Data Curation
G Writing - Original Draft
H Writing - Review & Editing
I Visualization

**Author contributions can be considered equal*

Papers outside the thesis

I. Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S., Donges, J., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., **Tobian, A.**, Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, 9(37), p. eadh2458.
The updated planetary boundaries framework assessment indicates that six boundaries, including novel entities and aerosol loading, are transgressed, placing Earth beyond a safe operating space. Systemic consideration is essential for addressing anthropogenic impacts as Earth system modeling of different transgression levels of the climate and land system change boundaries show.
Contributions: B, C, G, E

II. Chrysafi, A., Virkki, V., Jalava, M., Sandström, V., Piipponen, J., Porkka, M., Lade, S. J., La Mere, K., Wang-Erlandsson, L., Scherer, L., Andersen, L., Bennett, E., Brauman, K., Cooper, G., De Palma, A., Döll, P., Downing, A., DuBois, T., Fetzer, I., Fulton, E., Gerten, D., Jaafar, H., Jägermeyr, J., Jaramillo, F., Jung, M., Kahiluoto, H., Lassaletta, L., Mackay, A., Mason-D'Croz, D., Mekonnen, M., Nash, K., Pastor, A., Ramankutty, N., Ridoutt, B., Siebert, S., Simmons, B., Staal, A., Sun, Z., **Tobian, A.**, Usubiaga-Liaño, A., van der Ent, R., van Soesbergen, A., Verburg, P., Wada, Y., Zipper, S., Kummu, M. (2022). Quantifying Earth system interactions for sustainable food production via expert elicitation. *Nature Sustainability,* 5, 830–842.
Expert insights reveal strong interactions between planetary boundaries, notably with green water and land system changes affecting other processes. Provides a complex network of mechanisms, guiding future research prioritization for improved Earth system modeling and sustainable food production.
Contributions: B

III. Porkka, M.*, Virkki, V.*, Wang-Erlandsson, L., Gerten, D., Gleeson, T., Mohan, C., Fetzer, I., Jaramillo, F., Staal, A., te Wierik, S., **Tobian, A.**, van der Ent, R., Döll, P., Flörke, M., Gosling, S., Hanasaki, N., Satoh, Y., Müller Schmied, H., Wanders, N., Rockström, J., Kummu, M. (Manuscript). Streamflow and soil moisture shift far beyond pre-industrial conditions globally – planetary boundary for freshwater change transgressed. Accepted by *Nature Water*.
Evaluates anthropogenic impacts on the freshwater cycle over a 145-year industrial period using a global hydrological model ensemble. Findings reveal

increased local deviations in streamflow and soil moisture on 45% of the land area, signaling a substantial shift and transgression of the new planetary boundary for freshwater change.
Contributions: G, H

IV. Drüke, M., Lucht, W., von Bloh, W., Petri, S., Sakschewski, B., **Tobian, A.**, Loriani, S., Schaphoff, S., Feulner, G., Thonicke, K. (Manuscript). The long-term impact of transgressing planetary boundaries on biophysical atmosphere-land interactions. Under review at *Earth System Dynamics*. Preprint available at: https://doi.org/10.5194/egusphere-2023-2133.
Assesses long-term transgressions of climate and land system change boundaries using an Earth system model. Findings indicate increased global temperature, aridity, substantial vegetation carbon loss, and notable carbon emissions. A restoration scenario proves beneficial, emphasizing the need to respect planetary boundaries for a resilient Earth system.
Contributions: B, C, H

Glossary

This glossary introduces the key terminology for my research. There is no standard scientific definition for many key terms that support my research and their meaning is often flexible, if not contested. This glossary provides the reader with my understanding of these terms for the purpose of clarification as they are used throughout this thesis.

Earth system stability: The well-functioning of the Earth system, encompassing the biophysical components of the atmosphere, oceans, forests, waterways, biodiversity, and biogeochemical cycles.

Earth system resilience: Earth's capacity to sustain the key functionalities of the subsystems and processes it is composed of under mounting anthropogenic pressures.

Planetary boundaries framework: Constitutes of nine planetary boundaries that are defined as safe bounds for human interference with vital subsystems and processes. Together, these processes regulate the state and functioning of the Earth system.

Control variable: Planetary boundary specific indicator that captures and monitors human interference with the respective Earth system process.

Pressure level: The value of the boundary-specific control variable, reflecting how much pressure is exerted on the Earth system process for which a boundary has been identified.

Safe operating space: Delineated by the nine planetary boundaries. LImiting human pressures to stay within this space is understood to safeguard Earth system stability in the long-term.

Boundary transgression: A boundary is considered breached once the control variable is beyond the boundary value.

Zone of increasing risk: Boundary-specific, ongoing and significant transgression of a planetary boundary increases the chance of non-linear change and the emergence of regime shifts and tipping points.

Planetary boundary interaction: Planetary boundaries are stability indicators for deeply interconnected Earth system processes. Transgressions of boundaries could destabilize linked components of the Earth system, thereby amplifying existing human impacts.

Green water: The component of the world's freshwater found in precipitation over land, evapotranspiration and plant-available soil moisture. In the planetary boundaries framework, the green water indicator (control variable) is the root-zone soil moisture.

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1 Introduction

1.1. Earth system dynamics and global sustainability risks

Earth can be described as a complex adaptive system, marked by nonlinear feedbacks, spatiotemporal heterogeneity, regime shifts, tipping points and the emergence of alternative stable states (Levin, 2002). Moreover, the habitability of the natural environment is the result of the interdependent co-evolution of the geosphere and biosphere, fostering conditions conducive to the emergence and sustenance of complex life forms (Chopra and Lineweaver, 2016). This implies that life (including humans) is adapting to changes in the environment in a complex and often nonlinear fashion while exerting a strong influence on the biophysical environment itself.

The 1986 Bretherton Report's iconic diagram is an influential representation of the Earth system and the interacting processes that connect its several components, including the physical climate system and the biosphere (NASA Advisory Council. Earth System Sciences Committee, 1986). It has informed the international development of Earth system models and observations over several decades. Steffen et al. (2020) updated this figure and placed humanity not outside the Earth system as an external driver - as was done in the original diagram - but as an integrative sphere that is interacting with the various internal dynamics of the Earth system. Accounting for this *Anthroposphere* means fully integrating human dynamics as a primary force of environmental change with the biophysical dynamics of the complex adaptive Earth system.

The intertwinedness of complex social and ecological issues is increasingly recognised: environmental changes are predominantly caused by human activity, and changes in the environment have, in turn, a substantial impact on human development and well-being. The challenge of global sustainability is to ensure an accommodating and relatively predictable Earth system while providing a sufficient quality of life for all (Meadows *et al.*, 1972; Griggs *et al.*, 2013; Rockström *et al.*, 2016). Or, as Folke *et al.* (2011) put it *"Human development and progress must be reconnected to the capacity of the biosphere and essential ecosystem services to be sustained."* Planetary stability has to be assessed in the face of multiple environmental crises.

1.2. The planetary boundaries framework

Taking a whole Earth system approach, implying the need for humanity to be stewards of the entire planet, the planetary boundary framework quantifies the extent of human perturbations of fundamental Earth system processes. First published in 2009 (Rockström *et al.*, 2009a, 2009b) with subsequent updates (Steffen *et al.*, 2015; Richardson *et al.*, 2023), the planetary boundaries framework defines a safe operating space of planetary stability for humanity. Nine crucial Earth system functions and processes have been identified that together regulate the state of the Earth system. Each process is quantified in terms of particular control variables (e.g., CO_2 emissions are a control variable for the Climate change planetary boundary). In concert, these planetary boundaries are an effort to delineate a safe operating space for humanity to preserve long-term planetary stability and habitability.

Fig 1 is a schematic illustration of a single planetary boundary. The boundary position (solid black line) delineates the Holocene-like well described and relatively stable safe space (green) from a zone of increasing risk (yellow to purple). The Holocene epoch is chosen as the reference point since it is only when experiencing the stable and accommodating conditions of the Holocene that humanity carried out the Neolithic revolution, the starting point for modern civilisations (for a recent reanalysis study refer to Osman *et al.* (2021)). This relative stability is, however, at risk if human pressures breach boundaries and extensively and continuously move away from the safe operating space. The size of the wedge (and distance to the boundary position) depicts the anthropogenic pressure level, i.e. how far humanity is currently outside the estimated safe space for the represented Earth system process.

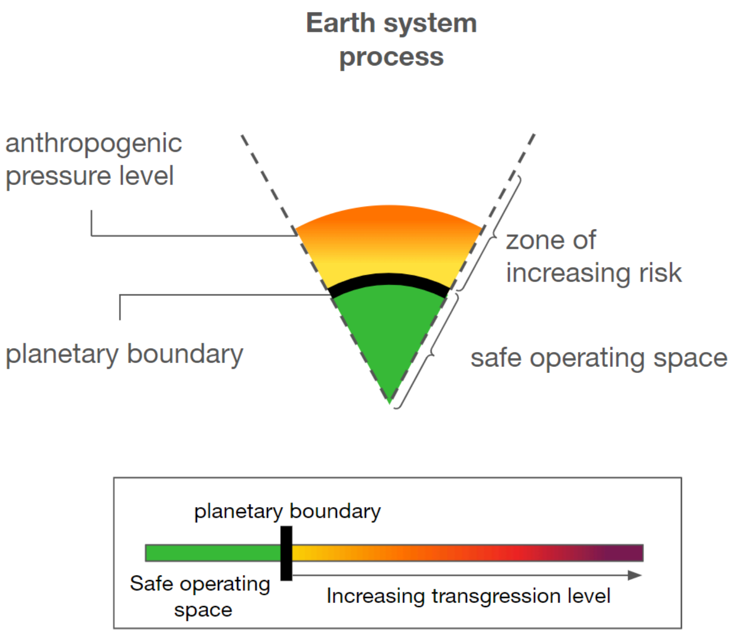

Figure 1. Schematic illustration of the planetary boundary and transgression level for one of the nine Earth system processes included in the planetary boundaries framework. The identified planetary boundary (bold black line) for the process demarcates the relatively safe Holocene-like safe operating space (green) from the zone of increasing risk (yellow to dark red). The high risk space (situated beyond the increasing risk space) introduced by Richardson *et al.* (2023) has been deliberately left out as the perception of high-risk areas might be overrepresented (Mahecha and Kraemer, 2023). The length of the wedge is measured via the boundary-specific control variable, which indicates if the anthropogenic pressure level is currently exceeding the planetary boundary. Own graphic, based on Richardson *et al.* (2023).

The stability of the Earth system process represented by each boundary can be threatened by anthropogenic pressures that exceed the boundary level as well as state shifts in the Earth system, highlighting the co-dependency of individual planetary boundary stability indicators. The framework's rationale is that keeping human-caused pressure levels at or under the boundary values and staying within this Holocene-like safe space would increase the chance of safeguarding a resilient and stable Earth system for generations to come (Fig 1). Losses of resilience in these interlinked processes increases the risk of the emergence of non-linear regime shifts and tipping points as ecosystems adapt to the changed environmental circumstances (see 3.1. Roots in sustainability sciences). As a result, the trajectory of the Earth system is drifting away from the well-described and relatively stable state of the Holocene towards a new Earth system state characterized by non-linear change, uncertainty and risks for human well-being.

Safe boundary positions have been scientifically quantified using boundary-specific control variables that allow for monitoring the status of the Earth system with regard to the nine proposed biophysical processes that underpin global sustainability in the Anthropocene. Two of the nine boundaries, namely those for climate change and biosphere integrity, are at the core of the framework due to their fundamental role in maintaining Earth system stability. Together with the planetary boundaries for land-system change, freshwater change and biogeochemical flows, they form the nexus of climate, land, ecosystems and water, and the nutrient elements that are cycled through these domains. The introduction of novel entities can be seen as a direct marker for the Anthroposphere (Persson *et al.*, 2022). The processes of ocean acidification, atmospheric aerosol loading and stratospheric ozone depletion constitute the remaining three boundaries. But despite many scientists' call for action to halt and mitigate environmental pressures, anthropogenic exploitations have already led to the transgression of six planetary boundaries, namely biosphere integrity, biogeochemical flows, land-system change and climate change, novel entities and freshwater water change (Richardson *et al.*, 2023).

1.3. Applications of the framework

Uniting multiple aspects of environmental perturbation into a single and coherent figure (Morseletto, 2017), the planetary boundaries framework has decisively shaped the academic discourse of global sustainability and influenced policy recommendations worldwide (Biermann, 2012; Biermann *et al.*, 2012; Downing *et al.*, 2019, 2020; Biermann and Kim, 2020; Brand *et al.*, 2021). It has helped to foster dialogue in many forums about the integrated human-environment relationship as it frames limits to human resource use (Downing *et al.*, 2020) and provides a more holistic perspective on the deeply entangled environmental challenges of the Anthropocene (Keys *et al.*, 2019). Besides sparking scientific debates (Downing *et al.*, 2019), the planetary boundaries framework has established itself as a valuable basis for guiding discussions and mobilizing action for global sustainability. It has been widely adopted and operationalized by policymakers at different levels of governance (Dearing *et al.*, 2014; Häyhä *et al.*, 2016; Fetting, 2020) and guided efforts for corporate sustainability (Whiteman, Walker and Perego, 2013). It has been taken up in integrative model-based assessments to explore global pathways to achieve the seventeen Sustainable Development Goals (SDGs) within the nine planetary boundaries (Randers *et al.*, 2019), and applied in assessments of resource needs to assure a just and safe life for every human on this planet (Raworth, 2017; O'Neill *et al.*, 2018).

However, all of these applications of the framework rest on a static representation of the planetary boundaries, where the existence of interactions is merely acknowledged but not explicitly accounted for. In many application contexts, conceptual translations are needed and simplifying indicators are used rather than the framework's control variables. For example, the widely used carbon emissions budget is a pragmatic way to inform about the magnitude of action needed on climate change, whereas CO_2 concentrations in the atmosphere cannot be "shared" so simply. Yet sustainability applications also need to consider the scientific insights about Earth system interactions that underlie the framework.

A starting premise of this thesis is that factoring in interactions between planetary boundaries is a crucial prerequisite for using the framework in a dynamic way, both to analyze future impacts of boundary transgressions and also to make systemic risk assessments that are relevant to societal decision-makers operating at global and also sub-global levels.

1.4. Planetary boundary interactions

> *"Because [...] the boundaries are linked, exceeding one will have implications for others in ways that we do not as yet completely understand"*
>
> *– Rockström et al., 2009a*

The above quote from the first planetary boundaries paper highlights that the existence and importance of planetary boundaries interactions was acknowledged ever since the origin of the framework. However, despite their inherently systemic context, anthropogenic pressure levels on individual planetary boundaries are still predominantly analyzed and quantified in isolation (as observed in the 'Boundary interactions' section in Steffen *et al.* (2015)).

The planetary boundaries framework is a representation of a single, integrated, complex, adaptive and highly dynamic Earth system with an embedded Anthroposphere (Steffen *et al.*, 2020). Each of the framework's nine processes is a human-driven perturbation to the Earth system's stability. But the resilience of the Earth system and thus its capacity to withstand further anthropogenic pressures on one boundary can be impaired by intensifying pressures on a different boundary if these Earth system processes are connected. To apply the framework as a dynamic tool, the interconnectedness of the Earth system's "components" and the co-dependency of individual stability indicators in the planetary boundaries framework have to be accounted for by making interactions between planetary boundaries explicit.

In the following, I introduce the core terminology that allows discussion of planetary boundary interactions as provided by the conceptual framework developed by Lade *et al.* (2020):

In a social-ecological system, the mechanisms of planetary boundary interactions can either be *biophysically mediated* (e.g., the impact of changing climate on land, freshwater etc.) or *reactive human-mediated.* The latter depicts human agency and accounts for adjustments in human behavior, values and norms as a response to changing environmental conditions which in turn affects the pressure levels on planetary boundaries (e.g., changes in agricultural management practices as a response to dietary changes or precipitation variability). Both mechanisms (biophysical and human-mediated) could result in two types of interactions in the framework with different consequences, *interactions between planetary boundaries* and *changes in a planetary boundary*, respectively.

First, *interactions between planetary boundaries* refers to the connectedness and codependency of control variable values of planetary boundaries. Exerted human pressures changing the control variable value of one boundary (i.e. a change in pressure level) can propagate through the Earth system and result in linked changes in another boundary's control variable value. To illustrate, freshwater availability or forest biome distribution might change as a consequence of human-driven future climate change.

Second, *changes in a planetary boundary* describes the readjustment of the identified boundary position resulting from interaction-induced changes in a boundary's control variable. The resulting changes to the shape and size of the safe operating space (delineated by the planetary boundaries) and risk space (here introduced, delineated by the boundary pressure levels) will be discussed and critiqued in chapter *3.5. The notion of a shrinking safe operating space* and *3.6 Dynamic risk space*.

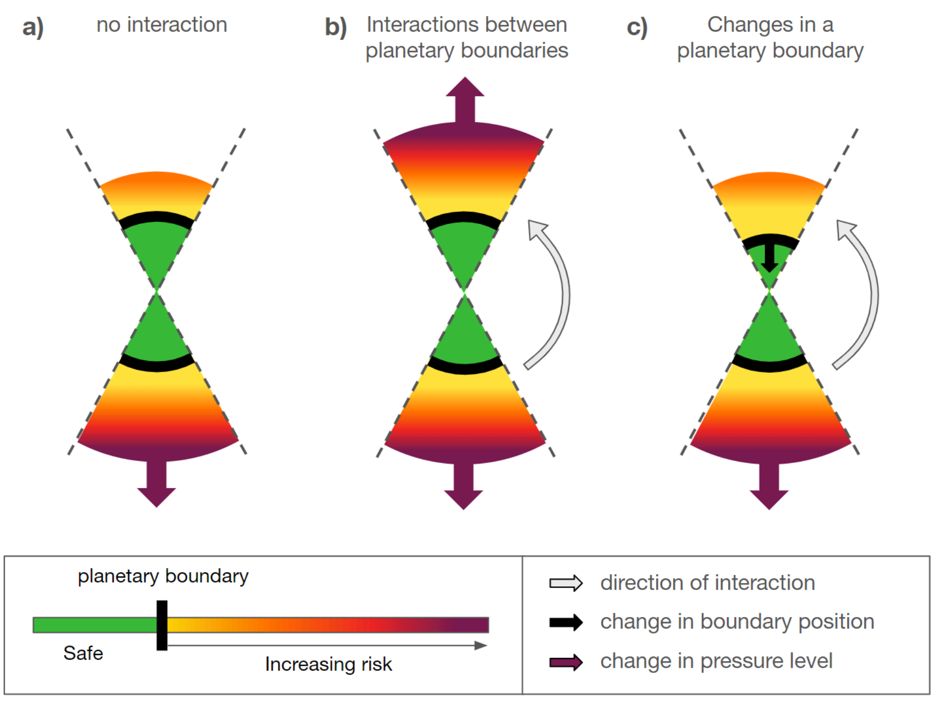

Figure 2. Schematic representation of planetary boundary interactions following Lade *et al.* (2020). Panel a) depicts the absence of a co-dependency between the boundaries, i.e. no interaction occurs; b) shows the control variable value of one boundary shifting when pressure rises on another boundary as a result of the planetary boundary interactions; and c) shows change in a planetary boundary position when pressure changes on another boundary as a result of their interaction. *Interactions between planetary boundaries* would result in changes in the dynamic risk space as the pressure level of the boundaries change (as elaborated in chapter *3.6.*). *Changes in a planetary boundary*, on the other hand, would change the shape of the safe operating space (cf. chapter 3.5.). Note that b) and c) are not exclusive but can occur concurrently. Own graphic, visual interpretation of the interaction terminology introduced by Lade *et al.* (2020), adapted from Paper III.

Decision-makers who employ the framework for their assessments of action and responsibility for global sustainability would benefit from being informed about potential synergies where acting to reduce pressures on one boundary could help relieve pressures on another. A famous example of a policy intervention with positive outcomes across boundaries is the Montreal Protocol to halt stratospheric ozone depletion, which has helped avoid significant additional global warming while protecting the terrestrial biosphere (Young *et al.*, 2021).

On the other hand, collateral transgressions also need to be taken into account. For example, the deployment of bioenergy with carbon capture and storage can help to reduce the pressure on the planetary boundary for climate change via lowering atmospheric CO_2 levels, but there are trade-offs that affect other planetary boundaries. Model-based analysis has shown that the necessary large-scale cultivation of bioenergy crops would increase existing pressures on several other planetary boundaries: freshwater change, land-system change, biosphere integrity and biogeochemical flows (Heck, Gerten, *et al.*, 2018). Irrigation of these bioenergy crops may cause higher levels of water stress than climate change alone (Stenzel *et al.*, 2021).

More fundamentally, a systematic process-based analysis of planetary boundaries interactions could potentially point to a need to re-evaluate the positions of the boundaries themselves, which to date have been based primarily on expert assessment, grounded in a co-evolutionary and complex systems understanding of Earth system dynamics, derived from data, models and theory. Since 2009, new control variables have been proposed for several planetary boundaries (Richardson *et al.*, 2023), and these capture different aspects of Earth's dynamics and seek to be better oriented towards policy and action contexts. However, the quantitative coherence of the framework as a whole has not been cross-checked because modeling tools have so far been lacking that cover the diverse set of human-perturbed processes.

The above examples illustrate why a more systemic quantitative understanding of both biophysical and human-mediated planetary boundary interactions provides critical information for effective operationalization of the framework. The possibility to take synergies and trade-offs into consideration links back to the aforementioned "whole Earth system” approach to global sustainability, which implies the need for better stewardship of the entire planet. Humanity cannot solve one dimension of the environmental crisis of the Anthropocene at the expense of others. Exploring and revealing the complex, adaptive, dynamic interactions within the planetary boundaries framework is an important role for science that informs pathways for human development on a changing planet.

2 Aim and scope of the thesis

My research addresses the need to advance the representation of interactions among planetary boundaries in the framework. The interconnectedness of the dynamic Earth system processes represented by individual boundaries has to be made visible to show how impacts of breached planetary boundaries propagate through the Earth system and thereby affect the pressure levels of multiple boundaries.

The central research question guiding this thesis is:

> **How may continued anthropogenic climate change affect the geospatially resolvable land and water planetary boundaries, and what are the implications for human livelihood?**

I use the term "human livelihood" to refer to the fundamental means of supporting people's continued existence, not in the more usual narrower sense of economic activities that generate individual or household income. This is informed by the definition of sustainable livelihood given by Scoones (1998):

> *"A livelihood is sustainable when it can cope with and recover from stresses and shocks, maintain or enhance its capabilities and assets, while not undermining the natural resource base."*

My aim is to tackle the prevailing research gap of an observation-constrained, process-based and scenario-driven understanding of planetary boundary interactions. I describe the overarching system analysis approach in chapter 3.2. *System perspectives in Earth system sciences*, and introduce the focal planetary boundaries in chapter 3.3. *Climate, land, water and ecosystem nexus*. To achieve the objective of closing this gap, I employ the LPJmL dynamic global vegetation model (introduced in chapter 4. *Methodological approach*) as it enables a dynamic and adaptive Earth system perspective on key planetary boundary processes and their interactions. Utilizing this process-based and validated modeling environment facilitates a detailed spatiotemporal analysis, surpassing the capabilities of previously employed conceptual models.

This analysis is a vital step for the practical application of the planetary boundaries framework, as its insights have potential to help anticipate and manage future conditions more effectively. The research can provide valuable insights into the consequences of actions across various boundaries, thereby contributing to the operationalization of the framework in contexts of climate and sustainability policy and action.

A specific focus of my research is green water, encompassing terrestrial precipitation, evapotranspiration, and plant-available soil moisture. I assess how planetary boundary interactions could affect human livelihood in terms of green water scarcity and food security, thereby highlighting the importance of accounting better for planetary boundary interactions in future-oriented application contexts.

The specific research questions and sub-questions that have guided my scientific contributions are:

RQ 1: How can green water be effectively integrated into the planetary boundaries framework? What is an appropriate, monitorable and encompassing control variable that provides a comprehensive assessment of human impacts on Earth system dynamics? Where is the planetary boundary for green water? Has it been crossed? **(Paper I)**

RQ 2: How does the control variable value (pressure level) of the land-system change boundary shift under climate stabilization and destabilization scenarios? What spatiotemporal planetary boundary interaction patterns emerge? Are other planetary boundaries affected? Are there gaps or shortcomings in the current land-system change boundary definition? Is there a difference in short vs. long term interactions? (**Paper II)**

RQ 3: Where is future climate change projected to affect the green water component of the freshwater change boundary as a result of climate-land-water interactions? Are dry deviations linked to green water scarcity? How is human livelihood affected in terms of food security and the attainment of SDG 2 ‘Zero Hunger’? (**Paper III)**

RQ 4: What is the relationship between the SDGs and the planetary boundaries framework? Do the SDGs sufficiently consider planetary stability? Which trade-offs and synergies exist between the SDGs and the planetary boundaries? **(Paper IV)**

RQ 5: How can modeled human land-use be rearranged to meet scenario requirements provided by the definition of the land-system change boundary? How can such a rearrangement be technically implemented to be reproducible and easily adjustable? **(Paper V)**

In summary, my thesis seeks to advance the science of planetary boundary interactions and their implications for human livelihood, providing a crucial foundation for informed decision-making in the context of sustainable development. RQs 1-3 explicitly investigate the interactions as such, while RQs 4 and 5 turn respectively to the contexts of global sustainability policy and the wider land-use and global change science community. In the next chapter, I introduce the theoretical foundation that enabled and guided my research.

3 Background

3.1. Roots in sustainability sciences

The planetary boundaries framework is guided by and builds on various major concepts from Earth system and sustainability sciences. The framework advances on earlier discourses on “tolerable windows” (Petschel-Held *et al.*, 1999) and the “guard rails concept” (German Advisory Council on Global Change (WBGU), 2000) which are integrated assessment schemes of tolerable risk towards anthropogenic climate change. Acknowledging the plurality of ecological crises and human drivers, the planetary boundaries framework has extended the climate guardrail to a holistic Earth system guardrails discourse.

The concept of resilience lies at the heart of the planetary boundaries framework. It characterizes a system’s biogeochemical and physical capacity to thrive under changing circumstances and to uphold its key structure and functions (Folke, 2006). The premise of the framework is that by taming anthropogenic pressure to stay within the safe operating space, a Holocene-like stability domain can be assured for generations to come. Breaching boundaries and leaving the safe operating space, in turn, results in an erosion of resilience, thereby threatening the functioning of the Earth system and its capacity to uphold the life support systems that humanity relies on. Especially breaching the two core boundaries, climate change and biosphere integrity, is deemed to increase the risk of the establishment of a new Earth system state. The other seven boundaries and their respective breaching contributes to the overall loss of Earth system resilience as they are regulating key Earth system functions, i.e. biogeochemical flows, moisture recycling, maintaining the terrestrial carbon sink, habitat provision etc (Steffen *et al.*, 2015).

Breaching boundaries and eroding resilience, in turn, can lead to the emergence of ecological regime shifts and tipping points (Folke *et al.*, 2004). Regime shifts between alternative stable ecological states are defined as *“large, abrupt, and persistent critical* *transitions in the function and structure of ecosystems" (Rocha et al., 2018)*. Examples of shifting stable states, such as forest to savannah transition, arctic sea ice loss or coral reef loss, flag the susceptibility of ecosystems to undergo abrupt and massive transitions as a response to changes in a key variable (nutrient loading, temperature etc). Shifts can emerge as a consequence of ecological resilience loss (Holling, 1973) and often involve the loss of ecosystem services. Tipping points are defined as a threshold where *"a small additional perturbation [...] causes a qualitative change [...] in the future state of a system"* (McKay *et al.*, 2022). To illustrate, climate tipping points, such as the thawing of the boreal permafrost or the collapse of the west Antarctic ice sheet, are potentially triggered once the warming threshold of 1.5°C is exceeded (McKay *et al.*, 2022). Exceeding tipping points would decisively push the Earth system's trajectory in the Anthropocene away from the Holocene-like conditions of the safe operating space. Regimes shift when tipping points are crossed; however, it may not be that case that all regime changes have a tipping point. Rather, they are all based on the idea that natural systems do not always respond to change linearly, but occasionally abruptly and irreversibly. Leaving the safe operating space increases the risk of resilience loss which could cause the emergence of non-linear regime shifts and tipping points.

In summary, the planetary boundaries and the safe operating space they delineate are an effort to separate the relative stability of a Holocene-like Earth system capable of upholding the life support systems humanity relies on from a risk space characterized by uncertainty and non-linear change. The planetary boundaries are placed with the recognition that many of the Earth system processes represented in the framework operate predominantly on a local to regional scale and for which tipping elements are difficult to identify, or may not even exist.

3.2. System perspectives in Earth system science

Various analysis systems are deployed in Earth system sciences but each type of numerical representation of the Earth system comes with its own set of assumptions and a particular systems perspective that affects its suitability for studying planetary boundary interactions. The three system perspectives that I want to discuss are: (i) a purely physical climate system, (ii) a biophysical Earth system and (iii) a social-ecological system.

i. **A physical climate system**, as presented by general circulation models (GCM) or conceptual modules focusing on energy transport (Edwards, 2011) feature a very limited and static presentation of the terrestrial biosphere, often only expressed in terms of surface roughness, albedo, thermodynamics (Schneider and Dickinson, 1974). If (plant or human) life and its dynamics is included, it is not equipped with agency. Crucial dimensions of the Earth system and functionalities that are key to the survival of our species are thus not included, rendering this mere climatological system perspective largely impractical for the study of planetary boundary interactions.

ii. **A biogeochemical and biophysical Earth system** view adds this lacking layer of complexity. It describes the coevolution of life and the environment over time where life is interacting with the climate and geochemical cycles of the Earth system. Here, the model family of dynamic global vegetation models (DGVMs) is key. They are capable of simulating the underlying processes that drive the dynamics of the natural vegetation, such as growth, mortality, resource competition, and disturbances like wildfires, as well as the carbon and water fluxes associated with them (Kooijman, 2004; Schaphoff, von Bloh, *et al.*, 2018). DGVMs are thus highly capable of representing the dynamic interaction landscape connecting the (terrestrial) planetary boundaries. By combining a dynamic biosphere to an atmosphere, ocean and other Earth system aspects within a single and cohesive modeling environment, Earth system models (ESMs) are highly promising tools for process-based analysis of planetary boundaries interactions, yet they are constrained by computational costs, which force them to either feature simpler DGVMs (Arora and Boer, 2010; Fisher *et al.*, 2018) or a coarser atmosphere (Drüke *et al.*, 2021). My research is largely framed in a biophysical Earth system perspective, since it helps to study the biophysical conditions of a dynamic safe operating space (left panel, figure 1) and, to some extent, how it could affect human livelihood (central panel, figure 1). Humanity, however, is still exogenous to such a system representation, lacking a dynamic presentation of human responses and societal choices to changes in the environment.

iii. **A whole Earth system approach** sees humanity's choices as an integral part of life in a complex and adaptive Earth system, and thus humanity is endogenous to the system (Donges *et al.*, 2017) as shown by the Anthroposphere in the proposed update to the NASA

Bretherton diagram (Steffen *et al.*, 2020). The symbiosis of humanity and the natural world form an interconnected system, associated with coevolutionary dynamics: a social-ecological system that is both complex and adaptive (Berkes and Folke, 1998). While human activity deteriorates the condition of Earth's ecosystems, the wellbeing and prosperity of human societies depends on continued ecosystem functioning (Fischer *et al.*, 2015). Earth as a complex adaptive social-ecological system is characterized by nonlinear feedbacks, spatiotemporal heterogeneity, regime shifts, tipping points and the emergence of alternative stable states, which constitutes a major challenge for modeling endeavors (Levin *et al.*, 2013). Yet a social-ecological system understanding builds the foundation for navigating the Anthropocene (Reyers *et al.*, 2018). It offers an understanding to reunite the spurious dichotomy of culture and nature which has been the prevailing paradigm of the 20th century (Latour, 2017). The planetary boundaries framework represents a social-ecological system as the foundation for guiding sustainable development in the Anthropocene (Steffen *et al.*, 2015; Reyers *et al.*, 2018). While the placement of boundaries takes the characteristics of a complex adaptive system into account, the representation of these central features and properties of the system, such as tipping points, nonlinear dynamics, self-organization and resilience are difficult to capture in numerical and process-based models of high complexity (Levin *et al.*, 2013). A challenge for integrated human-environment research on global change processes is the scientific community's limited ability to model fully coupled social-ecological systems.

3.3. Climate, land, water and ecosystem nexus

My motivation is to understand the relevant drivers and interactions of selected subsystems of Earth system dynamics as represented by the planetary boundaries framework. In my PhD I focus on the climate, land, water and ecosystem nexus as climate and the biosphere are identified as core boundaries in the framework (Steffen *et al.*, 2015) while water is the enabler of the terrestrial biosphere. Land systems and freshwater can further be seen as proxies for terrestrial and freshwater biodiversity. My choice to study this nexus and its interactions is further motivated as it can be seen as a central component of Earth's capacity to sustain human livelihood, while simultaneously being subject to mounting anthropogenic pressures.

As a consequence, I focus on three planetary boundaries: those for changes in climate, land-systems and freshwater. So far, human actions have caused all three boundaries to be breached (Richardson *et al.*, 2023), flagging the necessity to study the implications of their possible further future breaching and of their interactions. While land-systems (biomes) and the terrestrial water cycle are well represented in DGVMs, changes in climate are obtained externally via using GCM output to force the DGVM model. The simulation of other planetary boundaries involves additional challenges which are outside the scope of my PhD project. To illustrate, anthropogenic perturbations of the phosphorus cycle (a macronutrient essential for plant growth) is represented in the planetary boundaries framework but lacking in the DGVM of my choice, LPJmL (the model will be described in greater detail in chapter 4, *Methodological approach*). Another example is the planetary boundary of biosphere integrity which operates on scales that are smaller than the resolution of the model, thereby posing a grand challenge for simulation-based analysis. I have tried to accommodate the challenge and proposed a simple *habitat intactness index* in Paper II which accounts for ecosystem changes in areas currently classified with a Biosphere Integrity Index value which is deemed to be within the planetary boundary for biosphere integrity (Newbold *et al.*, 2016). However, work from colleagues at the Potsdam Institute of Climate Impact Research and elsewhere, not included in my thesis, is pushing for a better representation of additional boundaries despite the constraints of the model.

3.3.1. Climate change

The continuous release of greenhouse gasses has resulted in an unprecedented concentration of atmospheric CO_2, reaching levels not seen in the planet's past 23 million years (Cui, Schubert and Jahren, 2020). As a consequence, humanity has breached the planetary boundary for climate change, marked by the 350 ppm CO_2 threshold—an upper limit deemed tolerable for anthropogenic interference with the atmospheric radiation balance (Steffen *et al.*, 2015). Additional emissions will lock humanity into a trajectory that is persistently and substantially breaching the climate change boundary. Global warming may have already set several tipping points in motion (McKay *et al.*, 2022), heightening the likelihood of the emergence of a new, stable yet undesirable Earth system state known as “hothouse Earth” (Steffen *et al.*, 2018). The critical role of climate change in maintaining Earth system stability is underscored by its classification as one of the two “core” boundaries, alongside the boundary for biosphere integrity (Steffen *et al.*, 2015). Lade et al. (2020) further stress that climate change is densely connected to other planetary boundaries, providing additional incentive to study planetary boundary interactions.

3.3.2. Land-system change

By converting forests and other terrestrial biomes to agricultural land, humanity is driving landscape transformations that imperil biodiversity and disrupt ecosystem functioning. The land-system change planetary boundary, originally defined by the ‘percentage of global land cover converted to cropland’ (Rockström *et al.*, 2009b), encapsulates this transformation. In the updated assessment by Steffen et al. (2015), the paramount role of forest biomes in climate regulation led to an update in the control variable of the land-system change boundary which focuses on the remaining amount of forest cover. Despite their importance for regulating the Earth system, forests are subject to mounting human pressures. Especially agricultural practices, such as burning, grazing and cultivation have provoked a sharp decline in global forest cover extent (Bhagwat, Kettle and Koh, 2014; Campbell *et al.*, 2017). To illustrate, agriculture-driven deforestation in the pantropics is estimated to occur at a rate of 6.4 to 8.8 Mha per year in 2011-2015 (Pendrill *et al.*, 2022).
Roughly a third of Earth's terrestrial surface is currently covered by forest biomes which provide critical habitats to more than half of all known plant and animal species (Potapov *et al.*, 2008). Forests contribute to various fundamental Earth system functions (Bonan, 2008), operating across various spatiotemporal scales (Ellison *et al.*, 2017). These functions range from sustaining moisture recycling to land surface cooling, terrestrial carbon sequestration, biogeochemical nutrient cycling and albedo control. Most of these functions can be simulated in contemporary DGVMs, making them suited for studying the effects of changes of this boundary.

The land-system change boundary marks the spatial extent of the three major forest biomes – temperate, tropical and boreal – that need to be maintained to minimize the risk of planetary destabilization. Analyses indicate that this boundary is being transgressed in most areas in the world (Steffen *et al.*, 2015), jeopardizing the functions mentioned above. The required intact area is individually specified for each biome, considering both its strength of land-surface climate coupling (Snyder, Delire and Foley, 2004; West *et al.*, 2011; Steffen *et* *al.*, 2015) and potential tipping points, such as boreal forest dieback and Amazon forest decline (Lenton *et al.*, 2008, 2019; McKay *et al.*, 2022).

3.3.3. Freshwater change

The planetary boundary for freshwater change attests to the pivotal role of the terrestrial water cycle in sustaining key Earth system processes. Core Earth system functions of water, as highlighted by (Gleeson, Wang-Erlandsson, *et al.*, 2020), encompass critical aspects such as the energy exchange with the atmosphere, the facilitation and sustenance of terrestrial ecosystems and the terrestrial carbon sink, moisture recycling, albedo changes, nutrient transport and cycling, freshwater storage, among others.

Originally, the freshwater-use boundary was defined by global blue water consumption levels, thus streamflow (Rockström *et al.*, 2009b) but has later been reconceptualised by incorporating environmental flow requirements of riverine ecosystems (Gerten *et al.*, 2013). In a recent study, we highlighted the necessity to account for the large scale historical changes of green water (rootzone soil moisture) and have complemented the original definition with a green water planetary boundary (Wang-Erlandsson *et al.*, 2022) which has been priorly identified as a major conceptual gap (Gerten *et al.*, 2015; Jaramillo and Destouni, 2015; Heistermann, 2017; Tobian, 2019; Gleeson, Wang-Erlandsson, *et al.*, 2020; Gleeson, Wang-Erlandsson, *et al.*, 2020). It replaces the original freshwater-use boundary and together with blue water creates an integrated planetary boundary for freshwater change (Porkka *et al.*, 2023), emphasizing the diverse water functions mentioned earlier.

This integrated planetary boundary for freshwater change has set the new standard definition of anthropogenic changes in the latest update of the framework (Richardson *et al.*, 2023).

Moreover, it marks a conceptual shift in the planetary boundary for freshwater: while the original boundary quantification focused on a resource depletion problem, the maximum allowable perturbation of the freshwater cycle through blue water withdrawals, the refined quantification complements this perspective by addressing changes that are beyond the Holocene maximum variability range. In the context of my PhD thesis, I aim to promote the latter systemic understanding. First, it includes humanity as being part of the system which is changed, thereby advancing a social-ecological system understanding. Second, this perspective is crucial for incorporating planetary boundary interactions into the framework, recognizing that transgressions of interconnected boundaries can either amplify or dampen existing anthropogenic changes to the system - an insight previously discussed by Lade et al. (2020), as will be explored in greater detail below.

3.4. Current status of interaction studies

As early as in (2013), Anderies et al. employed a conceptual and heuristic model of the carbon cycle, simulating dynamic feedbacks and interactions between atmospheric, maritime and terrestrial carbon stocks. They translated their findings into the planetary boundaries framework and found that boundaries are in fact linked. However, their analysis lacks a spatiotemporal dimension, a process-based implementation and, by focusing exclusively on the carbon cycle, it is resting on a purely physical system, lacking a dynamic and process-based biosphere.

In an extensive literature survey, Lade et al. (2020) provisionally estimated the strength and direction of interactions between almost all nine planetary boundaries, highlighting the co-(de)stabilizing nature of planetary boundary interactions. The predominant type of planetary boundary interactions in the Earth system was found to be of self-amplifying and reciprocally destabilizing nature, thereby causing human impacts on the planetary boundaries to be amplified. It must be questioned however, if destabilizing and stabilizing feedbacks are represented to the same extent in the analysis and stated that their feedback model is linear and employed to *"illustrate possible consequences of the interactions"*. Moreover, they acknowledge that their *"estimates of interaction strengths and the subsequent model are highly simplified and, in many cases, highly uncertain representations of complex Earth system processes"*, calling for additional *"research on the magnitude and consequences of planetary boundary interactions"* (Lade *et al.*, 2020). Overall, the study provides a major advancement in the discourse of planetary boundary interactions and establishes the terminology that my research builds on.

In the following year, Lade et al. (2021) advanced on this front by using LPJmL as the foundation for a prototype Earth system impact metric, sensitive to planetary boundary interactions. The metric takes changes in runoff, vegetation cover, and climate change into account (as proxies for planetary boundaries) and calculates their interactions strengths using the LPJmL dynamic global vegetation model. The found interactions strengths are subsequently fed into the simplified and linear external feedback model from (Lade *et al.*, 2020). While this study constitutes an advancement in the science of planetary boundary interactions (being the first study to incorporate a process-based modeling framework featuring a dynamic and adaptive biosphere), it is pragmatically simplified and lacks the representation of scenario-driven transgressions of planetary boundaries which would improve the understanding of the Earth system processes at play.

In a recent study where I was invited to participate, an expert knowledge elicitation has been conducted to derive qualitative and quantitative knowledge about PB interactions in the context of food production (Chrysafi *et al.*, 2022). This is a novel approach in the context of planetary boundary interactions which is, however, not free of its own limitations and biases: The estimates made by the experts are difficult to compare and do not constitute a simulation-based analysis. It is not clear whether all of the chosen experts have the same understanding of a complex adaptive earth system (cf. chapter 3.2. *System perspectives in Earth system sciences*) and the quantitative values provided are estimates which are only partially supported by literature. Lastly the spatially explicit nature of the dynamics of planetary boundary interactions was not being accounted for. Nevertheless, the study underscores the relevance of planetary boundary interactions for sustainable food production and shed light on the large uncertainty behind the processes involved.

My PhD project further gave me the chance to contribute to the latest planetary boundary assessment by Richardson *et al.* (2023). Advancing on the analysis in Steffen *et al.* (2015), this article expanded its representation of Earth system modeling, by including an analysis of planetary boundary interactions. In particular, different combinations of varying pressure levels of the climate and land-system change boundary were simulated by the POEM Earth model (Drüke *et al.*, 2021). My main contribution was the development and deployment of the land-system change reallocation tool, described in Paper V. The analysis showcases that keeping the pressure level at the boundaries for climate change and land-system change would result in maintaining stable Earth system conditions for the terrestrial carbon sink and global land surface temperature for centuries to come. A simulated future transgression, however, would lead to severe surface warming and carbon leakage from the terrestrial ecosystems, despite the model's strong CO_2 fertilization effect, highlighting the systemic context in which human pressures on individual components of the planetary boundaries framework operate. In a recent paper by Drüke *et al.* (2023), we elaborate further on these findings by unfolding the spatiotemporal dimensions of the interactions that were beyond the scope of the study by Richardson *et al.* (2023).

3.5. The notion of a shrinking safe operating space

This and the following section 3.6. are largely based on the discussion of Paper III but provide more detailed background information and justification of the terminology. Moreover, additional figures are drawn to guide the reader.

As discussed in chapter 1.4. *Planetary boundary interactions* (Fig 2), incorporating interactions could potentially result in changes to planetary boundary positions. Already at the inception of the framework (Rockström *et al.*, 2009b) state that *“interactions among planetary boundaries may shift the safe level of one or several boundaries”* and provide a long list of positive feedback loops that create reinforcing links between planetary boundaries. They conclude that interactions have the potential to amplify anthropogenic pressures exerted on the Earth system. This has implications for the safe operating space and they conclude that *“many of these interactions will reduce rather than expand the boundary levels we propose, thereby shrinking the safe operating space for humanity”*. The resulting notion of a safe operating space whose shape is dynamic and changing as a consequence of pairing anthropogenic pressures with planetary boundary interactions has subsequently been dominating the discourse. This includes both studies that study the biophysical basis of these interactions (Anderies *et al.*, 2013; Lade *et al.*, 2020, 2021) or the potential implications for humanity (Gerten and Kummu, 2021; Chrysafi *et al.*, 2022).

Based on their literature survey, Lade *et al.* (2020) distinctively conclude that *“along most planetary boundaries, interactions do indeed shrink the safe operating space”*. They thereby call for a readjustment of individual boundary positions and, provided that the predominant type of interaction was found to be reinforcing, the resulting changes in individual planetary boundary positions that account for interactions (both biophysical and human-mediated) would be substantially more conservative. This notably smaller safe space would in turn exacerbate the sustainability challenges of the Anthropocene such as food production (Gerten and Kummu, 2021).

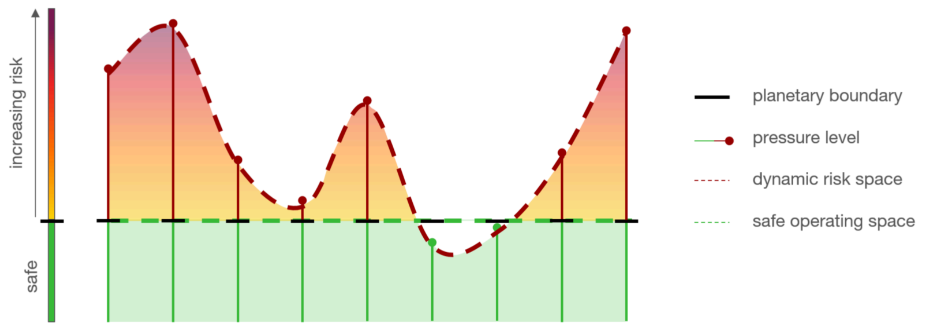

Figure 3. The planetary boundaries framework. The horizontal black bar symbolizes the position of the planetary boundary for each of the nine Earth system processes. Delineated by the nine planetary boundaries, the green dashed line separates the safe operating space (green) from the increasing risk territory (orange to red). The anthropogenic pressure level for each boundary is represented by the length of each of the nine vertical bars. A planetary boundary is breached if the pressure level exceeds the safe boundary position, pushing the Earth system into increasing risk territory. Taken together, the pressure levels of all boundaries form the risk space (dashed red line). Note that the position of the boundaries are arbitrary and chosen for illustrative purposes. The standard cartesian diagram style was chosen over the traditional radial planetary boundaries plot as it is easier to assess the integral of both the safe operating space (under the green dashed line) and the *risk space* (between the green and red dashed lines).

The safe operating space is strictly delineated by the nine planetary boundaries (black bars and the dashed green line in Fig 3). Each boundary represents a crucial Earth system process and is placed at a level that assures to remain in a Holocene-like safe state. Figure 3 is a schematic depiction of the nine planetary boundaries and their pressure levels (the depicted positions are arbitrary and chosen for illustrative purposes only). The notion of a shrinking or narrowing safe operating space is only accounting for one of the two core interaction terminologies by Lade *et al.* (2020) mentioned above, namely *changes in a planetary boundary* (Fig 2c). *Interactions between planetary boundaries*, i.e. the interaction-induced shifts in a boundary's pressure level are a central aspect of planetary boundary interactions but not captured by the current discourse (Fig 2b). A central terminological gap remains.

3.6. Towards an understanding of a dynamic risk space

Planetary boundary interactions affect the assessment of planetary risk. Future transgressions of boundaries could destabilize linked components of the Earth system, thereby amplifying existing human impacts. Societal risk guardrails in terms of one boundary cannot be quantified in isolation of existing pressures on other linked planetary boundaries.

How interactions change the distance between the status quo and the safe operating space is only poorly resolved by the currently dominating discourse of a more conservative placement of planetary boundaries in a shrinking safe operating space. In other words, focusing on a shrinking safe operating space alone limits the perspective on changing the placement of planetary boundaries but is blind to linking the pressure levels as denoted by boundary control variable values.

Hence I have introduced the term *dynamic risk space* to refer to the space delineated by the pressure levels of all planetary boundaries (dashed red line in Fig 3). My choice of terminology extends the boundary-specific one-dimensional zone of increasing risk and high risk (yellow to red color in Fig 1) which was introduced by Steffen *et al.* (2015). It builds on the holistic understanding that the increasing risk gradient for one boundary cannot be analyzed in isolation of human interferences with interlinked Earth system processes.

Unlike the notion of the dynamically shrinking safe operating space, the dynamic risk space is sensitive to *Interactions between planetary boundaries* as they co-determine the pressure levels of individual boundaries. The dynamic risk space is the product of pressure levels on individual boundaries and how those are propagating through the interconnected Earth system and affect the pressure levels of other boundaries. This understanding is both novel and useful as it promotes the holistic operationalization of the boundaries in concert. Based on this understanding, increasing or decreasing pressures on one boundary would not only affect the particular boundary but also affect linked planetary boundaries in a dynamic and integrative fashion (outlined in Fig 4). The resulting integral between the risk space and the safe operating space indicates the overall distance of how far humanity has been breaching individual planetary boundaries and pushing the Earth system into the zone of increasing and high risk. The larger this integral, the further humanity departs from the accommodating Holocene-like Earth system conditions of the safe operating space and into poorly predictable and highly uncertain conditions. The term dynamic is not only referring to the shape but also the time component, a critical factor for the establishment of state shifts (cf.

timeframe discussion on Earth system feedbacks in Steffen *et al.* (2018)). The time dimension of change is accounted for in the long-term impact studied by Drüke et al. (2023) and in Paper II of this PhD thesis.

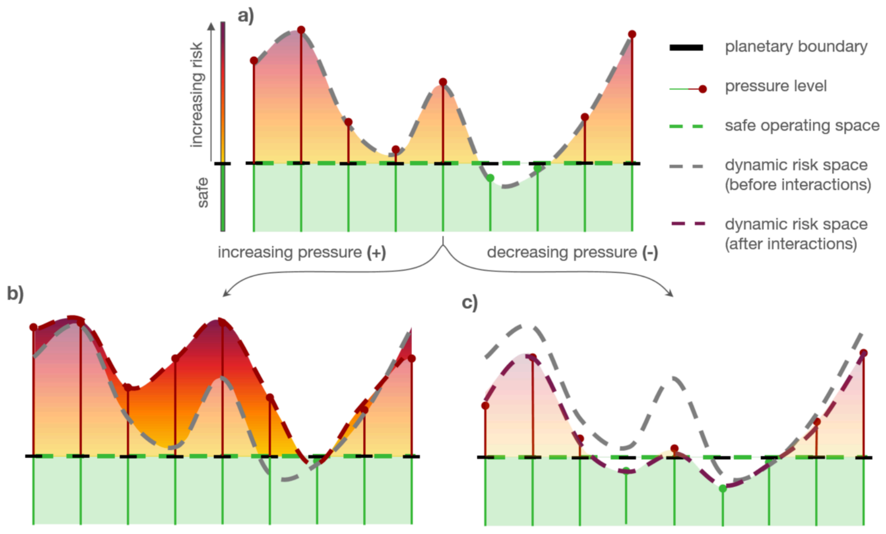

Figure 4. The dynamic risk space is the collective product of the pressure level on all nine planetary boundaries Earth system processes (vertical bars) and their interactions. The safe operating space is delineated by the nine planetary boundaries (black horizontal lines), each representative of an Earth system process crucial for maintaining Earth system stability. The integral between the dynamic risk space (dashed gray and red line) and the safe operating space (dashed green line) depicts how far humanity has been pushing the Earth system into the zone of increasing risk of the individual yet interconnected planetary boundaries. Panel (a) depicts the starting position (here, assumed to be in a quasi-equilibrium state). Panel (b) shows how increasing pressures on one boundary could affect the status of other planetary boundaries. If reinforcing feedbacks dominate, the risk space would move further away from the safe operating space, as highlighted by the additional saturated color space underneath the red dashed line. The opposite scenario can be seen in panel (c) where a decreasing pressure could contribute to a reduction in the pressure on other linked planetary boundaries. Here, the dynamic risk space is moving closer to the safe operating space. Note that just like in Fig 4, the position of the boundaries and the strength and direction of their interactions are arbitrary and chosen for illustrative purposes.

3.7. Research gap

Previous investigations of planetary boundary interactions are generally scarce and often limited to simplified modeling, literature surveys and expert elicitation studies. Lade *et al.*

(2020) has established the core terminology that underpins my thesis (cf. chapter 1.4. *Planetary boundary interactions)* and gleaned literature emphasizing the existence of a comprehensive web of planetary boundary interactions that need to be unpicked and analyzed in greater detail. However, by being built on a literature survey and simplified feedback model, Lade *et al.* (2020) do not address the spatiotemporal heterogeneity of the interactions they found. Subsequently, it is not possible to use the method and analytical foundation of this paper at sub-global spatial scales where societal decision-makers operate. By not building on a scenario-based assessment (i.e. studying the interactions under scenarios of increasing or decreasing human pressures on individual boundaries), the findings of the paper can only be used to inform policy makers in a limited context and are not suitable for future assessments.

Recent efforts by Lade *et al.* (2021), Richardson *et al. (2023)* and Drüke *et al. (2023)* have strongly advanced the quantitative and simulation-based understanding of planetary boundary interactions. But despite these aforementioned important efforts, the general lack of a systematic, bottom-up, process-based and scenario-driven understanding of non-linear planetary boundary interactions in an observation-constrained modeling environment largely remains. Moreover, impact studies on how these interactions would affect human well-being and the attainment of global sustainable development goals are largely missing (with the exception of the perspective article by Gerten and Kummu (2021) on food security).

The SDGs represent a comprehensive framework adopted by the United Nations to address pressing global challenges and achieve sustainable development by 2030 (UN, 2015). The 17 SDGs encompass a wide range of social, economic, and environmental dimensions, aiming to eradicate poverty, promote prosperity, and safeguard the environment. The goals are strongly interdependent and their achievement requires large-scale transformations (Sachs *et al.*, 2019). A recent study by Fanning et al. (2022) shows that currently no country is meeting its inhabitants basic needs at a sustainability level that is in accordance with the planetary boundaries. Interactions between planetary boundaries were not even part of their equation.

4 Methodological approach

"In order to understand the world, one has to turn away from it on occasion."
-- Albert Camus

Given the immense size and long time scales of the research object, the employment of equation-based numerical computer models is one of the principal tools in climate science (Edwards, 2011) and Earth system science (Steffen *et al.*, 2020). Models are necessary to simulate and quantify global processes under shifting future conditions. They link the locally observable to the globally possible by building on an observation-based understanding of processes in the biophysical world. I have therefore not observed nature in a direct manner, nor collected data in the field, but used a synthetic and experimental numerical computer model-based research strategy to gain new insights about crucial Earth system processes linking the planetary boundaries and their implications for human societies.

Focusing on the interactions of the planetary boundaries for climate change, land-system change and freshwater change, DGVMs are a highly suitable tool, as they are capable of dynamically simulating the terrestrial biosphere, the hydrological cycle, biogeochemical cycles and wild fires under changing climate. LPJmL (Lund-Potsdam-Jena with managed Land) is a state of the art DGVM capable of simulating not only naturally occurring vegetation (represented by plant functional types) but also human land-use (rainfed and irrigated crop functional types). It operates in daily timesteps and resolves a dynamic vegetation and changes into fluxes and pools of water and carbon in a 0.5° x 0.5° grid. It is comprehensively described (Schaphoff, von Bloh, *et al.*, 2018) and validated (Schaphoff, Forkel, *et al.*, 2018), thereby providing an observation-constrained modeling environment for the study of planetary boundary interactions. In my research, I have employed LPJmL5 - the latest version - featuring a dynamic nitrogen cycle (von Bloh *et al.*, 2018) which is a crucial aspect in light of estimating the CO_2 fertilization effect of the terrestrial carbon sink under future climate change (Wang *et al.*, 2020). The combination being a state of the art model, combined with a strong publication history, extensive validation, in-depth representation of human land-use and nitrogen cycle gives LPJmL an edge over other DGVMs. DGVMs do not feature a dynamically coupled atmosphere model and have to be externally forced using climate model outputs. Here, I force LPJmL using multi-model climate projections derived from a range of global circulation models of the CMIP6 project (Eyring *et al.*, 2016).

LPJmL has a long record of model improvements and validations (Sitch *et al.*, 2003; Gerten *et al.*, 2004; Bondeau *et al.*, 2007; Schaphoff, Forkel, *et al.*, 2018; Schaphoff, von Bloh, *et al.*, 2018; von Bloh *et al.*, 2018). It has been proven to be suitable for studying the planetary boundaries framework, especially in terms of the freshwater change boundary (Gerten *et al.*, 2013; Wang-Erlandsson *et al.*, 2022; Porkka *et al.*, 2023) and the land-system change boundary (Heck, Gerten, *et al.*, 2018; Heck, Hoff, *et al.*, 2018; Gerten *et al.*, 2020).

5 Summary of papers

This thesis contains five interrelated scientific Papers. These consist of four research articles (two as pre-submission manuscripts) and one book chapter, presented in the same order as in the *List of Papers*. Here, I summarize the major results and key contributions of each Paper.

Paper I - A planetary boundary for green water

Green water constitutes a major part of the freshwater cycle, making it fundamental to Earth system dynamics. It sustains terrestrial ecosystems, helps vegetation to sequester carbon and enables agriculture, so it also plays a critically important role for global sustainability. At the same time, it is subject to extensive human perturbations. The vital role of green water combined with its susceptibility to anthropogenic pressures led to various calls for its inclusion in the planetary boundaries framework (Jaramillo and Destouni, 2015; Heistermann, 2017; Gleeson, Wang-Erlandsson, *et al.*, 2020; Gleeson, Wang-Erlandsson, *et al.*, 2020). In my master's thesis, I began to conceptualize green water within the planetary boundaries framework (Tobian, 2019). I have now contributed to filling this major conceptual gap by co-authoring *"A planetary boundary for green water"* (Wang-Erlandsson *et al.*, 2022), published in *Nature Reviews Earth & Environment*.

In this paper we reviewed and highlighted the various roles of green water in the Earth system, many of which show complex dynamics, associated with non-linear relationships with ecological, biogeochemical and physical atmospheric change. We further conducted a consensus-based multicriteria qualitative evaluation to find an adequate control variable for green water. The outcome was the decision to use root-zone - thus plant-available - soil moisture.

I ran historical simulations of green water departures from long-term baseline variability using LPJmL forced by climate output from an ensemble of 10 different GCMs in the climate model intercomparison project CMIP6 (Eyring *et al.*, 2016), combined with root-zone soil moisture data obtained from the Earth system model MPI-ESM1.2-LR (Wieners *et al.*, 2019). Analyzing outputs of these simulations, we found that humanity has been affecting green water to an ever increasing extent. In particular, we found that root-zone soil moisture availability deviates from Holocene variability (in any month of a modelled year) on an increasing percentage of terrestrial ice-free area. These deviations were found to occur both as dry and wet departures. We subsequently proposed a planetary boundary for green water, using a percentile-based quantification. This approach provides the basis for the analysis of the recent Freshwater change assessment article (Porkka *et al.*, 2023) and has been applied with some adaptation in the latest planetary boundary framework update article (Richardson *et al.*, 2023). I co-authored both of these subsequent papers.

Paper II - Climate change critically affects the status of the land-system change planetary boundary

In this Paper, I and my co-authors have analyzed how long-term climate stabilization as well as destabilization scenarios result in planetary boundary interactions. In the study, we again employed LPJmL (version 5.1) forced by the climate output of an ensemble of 10 GCMs from CMIP6 (Eyring *et al.*, 2016). Simulations were conducted for both the historical and future period, ranging until the year 3000 to account for long-term dynamics in the studied planetary boundary interactions. The climate output was transposed, following the "warming slice" approach by Schleussner *et al.* (2016), representing CO_2 ppm levels that match different stages of the planetary boundary for climate change. Our scenarios ranged from returning to the planetary boundary at 350 ppm to extreme transgression scenarios of 1000 ppm. While our results indicate widespread changes to the position of various terrestrial planetary boundaries, we primarily focused on the interactions between the planetary boundaries of climate change and land system change.

First, we found that maintaining climate change at the planetary boundary level (350 ppm) would lead to a co-stabilization of the land system-change boundary by upholding forest biomes in their current position over the course of the millennium. The climate change boundary is thus well placed, with respect to the land-system change boundary. Breaching the climate change boundary, on the other hand, would critically affect the world's major forest biomes. Our simulations show that on entering the high risk zone for climate change

(>450 ppm), the boreal forest is subject to a severe dieback at the southern fringe, losing nearly all its ground under the most extreme scenarios, and it shifts polewards, replacing existing ecosystems and contributing to polar warming amplification. The temperate forest would tend to migrate into today's boreal zone. The tropical belt would expand while the tropical forest undergoes structural changes. The structural composition of a forest biome is currently not accounted for in the definition of the planetary boundary for land-system change but can be seen as part of the biosphere integrity boundary, as we discuss in Richardson et al. (2023). Future climate change would thus be contributing to pushing the Earth system further beyond the already transgressed planetary boundary of land-system change, with greater biome disruptions the higher the CO_2 concentration climbs.

This study thus demonstrates the existence of planetary boundary interactions and illustrates the scale of possible co-destabilization. It highlights the necessity to study planetary boundary interactions and to account for them in the framework dynamically, systematically and in an explicitly process-based manner for future-oriented studies.

In addition, our results indicate that other planetary boundaries, like the ones for freshwater change and biosphere integrity, and even the climate change boundary itself (through both physical and biogeochemical feedbacks) are critically affected by climate change. This means that we were able to provide an analysis-based justification for the position of the climate change boundary in the framework, since an atmospheric CO_2 concentration of 450 ppm already exerts additional pressures on the land-system change boundary.

Paper III - Planetary boundaries interactions and food production: Exploring the dynamic risk space

My third paper is written in close collaboration with my PhD colleague Maganizo Kruger Nyasulu, who has a background in economics and development. Currently a working manuscript, it is set out to be an interdisciplinary perspective piece in which we combine the study of planetary boundary interactions with insights from the analysis of the green water planetary boundary (Wang-Erlandsson *et al.*, 2022) and consideration of the role of green water in the grand challenge of food security in the Anthropocene. We describe how agriculture is responsible for large environmental burdens globally and has contributed to the historical transgression of several planetary boundaries. And we briefly review studies that show that food security is at risk in a narrowing safe operating space.

By providing a first estimate of climate change-induced shifts in green water, we shed light on arguably the most critical planetary boundary interactions affecting food security. We have employed LPJmL to assess which areas of the world are prone to a significant increase in dry deviations of green water under the RCP7.0 climate change scenario by the end of the century. A dry deviation in green water occurs when any month of the year is holding less plant-available soil moisture (green water) than the 5th percentile of the preindustrial baseline period (as introduced in Paper I). The significance of change has subsequently been tested using the prop.test function in R, following Porkka et al. (2023).

Our simulations show widespread future increases in dry deviations, especially in the Amazon basin, central and southern America, parts of western North America, and the Mediterranean region. Many of these areas are already currently highly dependent on green water. These climate-land-freshwater planetary boundary interactions are putting the reliability of rainfed agriculture at risk, implying soaring social costs in future if no mitigation and adaptation action is taken. In our manuscript, we show how many people are living in areas of dry departures today. We assess the fraction of green water in the total water consumption, and assess the share of agriculture in national GDPs. We discuss the concept of green water scarcity, and suggest that our approach could be used as part of predictive assessments of future food security risk. We are seeking to argue for a better understanding of a “dynamic risk space”, in contexts where scientific analysis points to a world increasingly outside of a “safe operating space”. Finally, we discuss our analyses in light of the Sustainable Development Goals, where we highlight the prevailing gap of an integrative representation of green water in the Agenda 2030 goals and indicators.

Paper IV - The planetary boundaries buttress the Sustainable Development Goals

In this invited book chapter, we have emphasized the urgent need to align the United Nations' 17 Sustainable Development Goals with planetary boundaries to ensure the long-term stability and resilience of the Earth system as the foundation for human well-being. We have argued that the current development paradigm comes at the expense of planetary boundary transgressions, noting recent analyses (Fanning *et al.*, 2022) that show that no country in the world is able to meet the basic needs of its citizens at a resource use level consistent with the planetary boundaries and that could thus be extended to all people globally. Following Griggs *et al.* (2013), we have argued that the transgression of planetary boundaries puts planetary stability and resilience at risk, and that this undermining of the biosphere's foundation for human well-being necessitates a reevaluation of the conventional development paradigm.

The Paper has included a first assessment of the systemic intertwinedness of biophysical and socio-techno-economic conditions, showing how planetary boundaries build the foundation for reaching Sustainable Development Goals. A novel analysis in this Paper is the demonstration of bidirectional misalignments where actions towards SDGs may intensify pressures on the Earth system, leading to further transgressions of planetary boundaries. Conversely, existing pressures on planetary boundaries can hinder progress on SDGs. We have also underscored the potential for interactions among planetary boundaries to magnify detrimental effects over time. Our closing call to action is for the international community to seek synergies between achieving SDGs and mitigating pressures on planetary boundaries.

Paper V - The Land-Use Change Allocation Tool (*lucatoo*) and its application to the planetary boundary of land system change

In this Paper, I and my co-authors introduce the *land-system change reallocation tool*, an algorithm that allows for the scenario-based rearrangement of anthropogenic land cover to depict various pressure levels on the land-system change boundary. Land use change stands out as a prominent catalyst for global environmental change in the Anthropocene era, significantly impacting the overall functioning of the socio-ecological system (Verburg *et al.*, 2015). The planetary boundary for land-system change highlights the anthropogenic modifications and alterations of terrestrial ecosystems via land-use transformation and intensification (Richardson *et al.*, 2023), and establishes the 'safe' planetary conditions in terms of the extent of remaining forest cover in the three primary forest biomes across temperate, tropical, and boreal climatic zones. However, existing future scenarios of land use change are not aligned with this land-system change boundary definition, and are therefore not suitable for studying the implications of a further breaching of the boundary through human-induced land cover changes, in terms of planetary boundary interactions and altered Earth system resilience.

We formulate the technical description for the tool, with the aim of making the underlying code publicly available and adaptable. The *lucatoo* algorithm has already been used in the context of studying climate warming potentials from land-use change with the POEM Earth model (Drüke *et al.*, 2021) both in the most recent planetary boundary assessment (Richardson *et al.*, 2023) and in an application paper studying the long-term transgression of the climate change and land-system change boundary (Drüke *et al.*, 2023).

6 Contributions and reflections

6.1. Positioning my research in the context of sustainability science

I understand my work to be situated in the interdisciplinary domain of sustainability research encompassing both the biophysical and social domains while ensuring both methodological groundedness and applicability (Haider *et al.*, 2018). In Fig 5, I have mapped my Papers along the social-biophysical and theoretical-applied axes following the social-ecological systems framework, adapted from McPhearson *et al.* (2022). The term ”social” refers to the human system spanning culture, economy and governance. “Biophysical” encompasses the ecology, climate and biogeochemistry. Interdependencies between the social and biophysical systems are explicitly acknowledged. Following de Gooyert and Größler (2018), theoretical research is conducted to increase the understanding of a scientific theory or framework by making it subject to critical scrutiny employing adequate methods. Applied research, on the other hand, is set up with the intention to solve concrete problems.

Most of my work is situated in the theoretical biophysical quadrant, but my academic journey is taking me progressively towards issues requiring more integrative and societally-relevant inquiry. This also applies to my co-authored papers which are outside this PhD thesis.

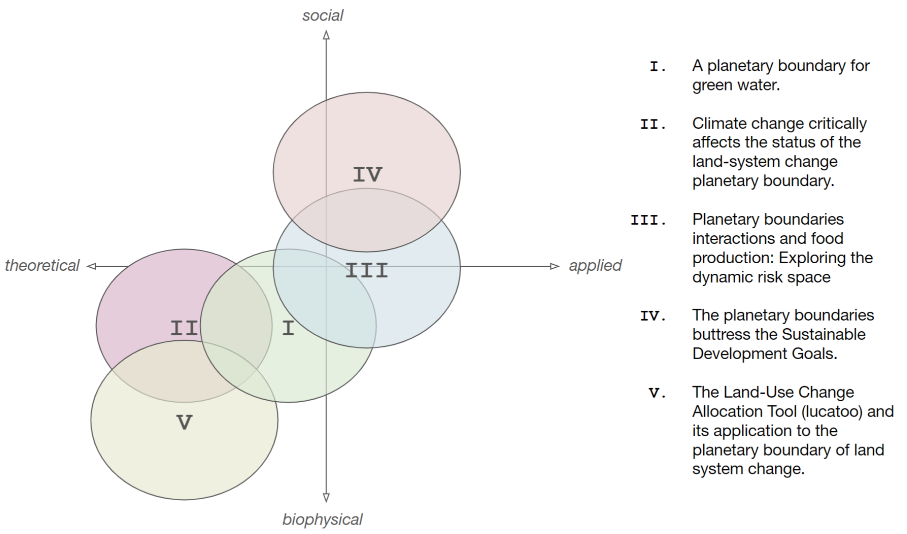

Figure 5. Mapping my interdisciplinary sustainability science papers along the social-biophysical and theoretical-applied axes. The method Paper V, provides a theoretical and methodological foundation which is deeply grounded in the biophysical system understanding. Paper I and II scrutinize the planetary boundaries framework via biophysical analysis to include (I) green water as a sub-boundary or (II) a scenario-driven understanding of interactions and their spatial and temporal resolution. Paper III is placed within the social-biophysical and theoretical-applied continua as it applies the theoretical biophysical foundation of planetary boundary interactions to the social and applied question of food security. Paper IV stresses the link between the planetary boundaries framework, its interactions and the SDGs.

In my research, I have studied planetary boundary interactions predominantly through a biophysical and biogeochemical Earth system lens. This is a *necessary but not sufficient* part of an integrated social-ecological systems understanding. Understanding, defining and quantifying biophysical planetary boundary interactions helps to delineate the safe operating space – and its evolution over geographic space and time as a dynamic risk space (left panel, Fig 6; Papers I and II). This understanding is a critical precondition for human development in the Anthropocene and, despite not dynamically including human agency, it allows for studying impacts on human livelihood (central panel, Fig 6), as I show in Paper III.

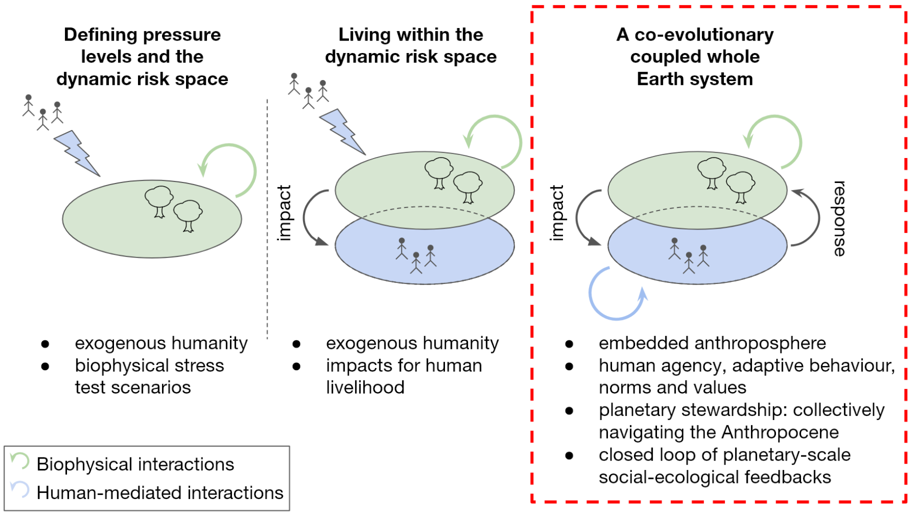

Figure 6. Different stages of realizing human agency with the planetary boundaries framework. The panel on the left accounts for biophysical interactions of the nature component of the Earth system alone. Humanity is an external driver. The central figure adds impact arising from planetary boundary interactions on human livelihood (e.g. changes in ecosystem services, food security). The panel on the right depicts a fully coupled whole Earth system approach where human behavior leads to human-mediated interactions. The red square highlights that an integrative inclusion of the anthroposphere is beyond the scope of this thesis. Own graphic, inspired by the taxonomy of subsystems in World–Earth systems models by Donges *et al.* (2021).

The right-hand panel in Fig 6 depicts a "whole Earth system" approach where the complexities and co-evolutionary dependencies of the human and natural systems are accounted for (Liu *et al.*, 2007). In the subsystem taxonomy introduced by Donges *et al.* (2021), this would mean an analysis and modeling approach where the Anthroposphere is fully dynamically coupled to the biophysical domain of the Earth system (which is already well captured in models such as LPJmL, as my Papers I-III show). The copan:CORE World–Earth framework is an example of a model with endogenous humanity, represented as heterogeneous social actors and global-scale adaptive networks (Donges *et al.*, 2020). In the context of my research on the climate-land-water-ecosystems nexus, adaptive human behavior encompasses, for example, changes in land-use, dietary changes, changes in norms, policy interventions, emission reductions, technological solutions, human migration and flows of capital in response to environmental changes. These reactive human-mediated interactions result in shifting pressures on Earth system processes (Lade *et al.*, 2020), presenting difficult challenges for those seeking to put the planetary boundaries framework into practice as a quantitative or spatially-resolved tool. This panel is highlighted in red because although it was far beyond the scope of my project to implement such a fully coupled system, my research is contributing to this dynamic integrative understanding.

6.2. Contributions of my research

In summary, my thesis contributes to the advancement of the planetary boundaries framework on three fronts (a summary of each paper's key contributions can be found under table 1):

I. The representation of green water (Papers I & III)
II. Biophysical understanding of planetary boundary interactions (Papers II, III & V)
III. Connecting planetary boundaries to food security and the sustainable development goals (Papers III & IV)

Table 1. Summary of the key findings and contributions of the included Papers.

	Key contributions
Paper I A planetary boundary for green water	• establishes green water as a sub-boundary for freshwater change • highlights its various roles in Earth system dynamics • demonstrates how green water is subject to increasing human perturbations since the preindustrial period • provides a quantification scheme as the basis for future research (e.g. Paper III of this thesis and adapted for Porkka *et al.* (2023) and Richardson *et al. (2023)*.
Paper II Climate change critically affects the status of the land-system change planetary boundary	• assesses and maps climate change driven changes in the transgression level of land-system change (both by the end of the century and end of millennium) • discusses mechanisms of other planetary boundary interactions (e.g. green water, biosphere integrity and climate change itself) • finds that major biome shifts and a boreal dieback are emergent in our simulations using 10 GCMs of CMIP6 • finds changes in biome composition in the tropics

	(evergreen to deciduous forest), highlighting gaps and operational shortcomings in the current land-system change boundary definition ● provides supporting evidence that the climate change boundary is well placed in relation to the land-system change boundary
Paper III Planetary boundaries interactions and food production: Exploring the dynamic risk space	● a demonstration of how a planetary boundary interaction study has sustainability application, showing how future climate change (RCP 7.0) affects the transgression level of the green water sub-boundary. ● analysis shows an increase of climate change-induced dry deviations of plant-available soil moisture ● highlights how boundary interactions could affect human livelihood in terms of food security ● introduces the concept of the 'dynamic risk space' to account for interaction induced changes in control variable values ● highlights the gap of green water in the 2030 Agenda's goals and indicators
Paper IV The planetary boundaries buttress the Sustainable Development Goals	● emphazises the dependency of the SDGs on a stable and resilient planet as defined by the planetary boundaries framework ● calls for their future alignment, with a focus on achieving human prosperity and equity within planetary boundaries ● highlights the perils of a bidirectional misalignment between the nature and people components of the global social-ecological system ● highlights pathways and solutions aligned with influential integrative global systems modeling initiatives: the five Earth4All turnarounds and The World In 2050 transformations
Paper V The Land-Use Change Allocation Tool (lucatoo) and its application to the planetary boundary of land system change	● highlights the various links of land-use change to several planetary boundaries (other than land-system change) ● provides a methodological and technical description of an algorithm to readjust spatially explicit anthropogenic land-use change scenarios to meet the land-system change planetary boundary definition ● created land-use datasets for wider scientific use (already used in Richardson *et al.* (2023) and Drüke *et al.*

	(2023)) ● enables future research on planetary boundary interactions prompted by shifting pressure levels on the land-system change boundary ● can be easily adapted and used outside the planetary boundaries context

The contributions of my individual papers are all linked to my overarching research question: **How may continued anthropogenic climate change affect the geospatially resolvable land and water planetary boundaries, and what are the implications for human livelihood?**

By establishing green water as a planetary boundary, **Paper I** paves the way for assessing the impacts of climate change on rainfed agriculture (which relies exclusively on green water) and provides a quantification scheme for the assessment. The in-depth analysis in **Paper II** constitutes a crucial advancement in the assessment of climate change-driven planetary boundary interactions. **Paper III** shows how continued climate change affects the green water planetary boundary and provides quantitative assessments of the interaction that extend into a discussion of implications for SDGs and food security (strong indicators for human livelihood). **Paper IV** expands the discussion from climate change to discuss how all planetary boundaries and their interactions relate to the attainment of the SDGs. Lastly, **Paper V** fills a key research gap as it builds the methodological foundation for combined assessments of ongoing climate change and land-system change and their implications for the planetary safe operating space.

My work has tackled the research gap of *"the general lack of a systematic, bottom-up, process-based and scenario-driven understanding of non-linear planetary boundary interactions in an observation-constrained modeling environment"* as well as the lack of *"impact studies on how these interactions would affect human well-being and the attainment of the SDGs"* (as set out in chapter 3.7). As shown in Fig 5, my research has predominantly focused on the theoretical biophysical quadrant. I chose the opening quote by Alexander von Humboldt as it highlights that these open research gaps are too large to be addressed in a single PhD project. This is also a rapidly evolving research area, as society becomes more aware of the urgency of climate action and the complex trade-offs in navigating sustainable climate mitigation options. Many applied social questions arise from my research, and they also need to be addressed with the best available understanding of the ways that biophysical changes play out dynamically at all scales from local to global. In other words, what are the social implications of entering the dynamic risk space? I am confident that my research renders useful for future research that extends the research undertaken here and applies it with the intention of solving concrete real-world problems. In the next section, I want to point the reader to the challenges ahead.

6.3. Limitations and possibilities for future directions

In my research, I have primarily studied interactions between three planetary boundaries (climate change, land system change and freshwater change). Even with just these three, many other potential links among these boundaries could be analysed, using different models and data sources. This work needs to be extended to shed light on the complex interaction landscape underneath the planetary boundaries framework. Continuing with DGVMs and climate change scenarios, this programme of work could include the study of additional boundaries (e.g. biosphere integrity, nitrogen flows), design of relevant forcing scenarios (systematic land-use change based on my method described in Paper V, nitrogen loading scenarios) and further model development (e.g., for representation of phosphorus flows). All in all, my work presented here provides a first stage towards the development of a planetary boundary simulator, a model design that allows for the comprehensive study of the dynamic risk space.

The land-use change allocation tool presented in Paper V and applied in Richardson *et al.* (2023) and Drüke *et al.* (2023) could enable further research. Example studies range from analysis of land use change driven changes in blue and green water to investigating how deforestation affects moisture recycling, building on insights by Nyasulu *et al. (2024)* who have shown that tropical rainforest moisture is crucial to support agricultural precipitation in Africa.

The robustness of the simulations conducted could also further be improved. A valuable next step would be to include multiple DGVMs to run an ensemble simulation to account for inter-model uncertainties and biases (Hempel *et al.*, 2013; Warszawski *et al.*, 2014). However, setting up multiple DGVMs to run systematic scenarios would require major collaborative efforts and involve very high computational costs. Also current scenarios are limited to combined forcings of future land-use and climate change, making it difficult to disentangle drivers of change.

Ultimately, simulating and studying the co-evolutionary coupled whole Earth system with an integrated Anthroposphere (right panel, Fig 6) with process-based biophysical and socio-cultural dimensions poses a grand challenge in the endeavor to model social-ecological systems. However, human agency is not part of the model's equations used in this thesis and can instead be seen as an external driver, exogenously forcing a biophysical Earth system. Exciting new research frontiers have started coupling the LPJmL DGVM to an agent-based model to account for human processes as mandated by the whole Earth system approach (Donges *et al.*, 2020). However, given the early stages of the development, they could not be included in my thesis but provide an exciting avenue for future research. Adaptive behavior of human societies, i.e. reactive human-mediated interactions, could result in changes in carbon emissions, land-use or water withdrawals, which could be linked back to a DGVM to assess the resulting changes in the biophysical domain. This would constitute a necessary step to holistically investigate Earth system dynamics and planetary boundary interactions in a whole Earth system approach.

7 Conclusions

In this thesis I have shown that characterizing, analyzing and mapping interactions between planetary boundaries has strong potential for using the framework in a dynamic way. It allows us to assess the scientific coherence of the positioning of boundaries in the framework, and to better analyze future impacts of boundary transgressions. It shows promise for making systemic risk assessments that are relevant to societal decision-makers operating locally and regionally as well as in the global sustainability context.

Planetary stability is a prerequisite for long-term human prosperity. The proposed safe operating space for humanity has been breached in six of its nine dimensions but the impacts of this breaching are far from being fully understood. My analysis shows that interactions between planetary boundaries bear the potential to accelerate non-linear change and systemic risk if boundaries are significantly and persistently breached. Many of the processes at play operate on local to regional scales. Highly resolved analyses thus enable to identify and highlight priority areas for integrating other research for mitigating Earth system risks and maintaining Earth resilience.

The interactions between climate change, land-use change and water system change are comprehensively depicted in DGVMs when coupled with climate model output. The utilization of these models enables investigations of the safe operating space and dynamic risk space to extend beyond conjectures, conceptual models, literature survey-based narratives and semiquantitative expert opinions. The examination of these interrelationships on a spatially and temporally resolved scale represents a pivotal step in improving the precision of the planetary boundaries framework as a guide to define and deal with societal risk guardrails and operational targets for reducing planetary pressures.

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