Stepping back from the precipice: Transforming land management to stay within planetary boundaries

SPECIAL REPORT ON LAND

Potsdam Institute for
Climate Impact Research

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Table of contents

Preface

Prof. Dr. Johan Rockström
Director of the Potsdam Institute for Climate Impact Research (PIK)

Ibrahim Thiaw
Executive Secretary of the United Nations Convention to Combat Desertification (UNCCD)

As we mark the 30th anniversary of the United Nations Convention to Combat Desertification (UNCCD) and head into the 16th Conference of the Parties (COP16) in Riyadh, the stakes could not be higher. We stand at a precipice and must decide whether to step back and take transformative action, or continue on a path of irreversible environmental change.

Land is the cornerstone of our existence, providing the essential resources we rely on for food, water and shelter, while sustaining our climate and supporting biodiversity. Yet, despite its essential functions, land, along with other critical Earth system components, is under unprecedented pressure from human activities. Overexploitation of natural resources, unsustainable agricultural practices, deforestation and urbanisation have resulted in the breaching of six of the nine planetary boundaries, which mark the safe operating space for maintaining Earth's stability, resilience and life support. Trade-offs between different land uses and functions exacerbate land degradation and related challenges: the expansion of agricultural land may feed more people in the short term, but it can accelerate soil degradation, biodiversity loss, and thus food insecurity in the long term.

This special report on land comes at a time when the scientific evidence is unambiguous: the way we manage our land will directly determine the future of life on Earth. The planetary boundaries framework, highlighted in this report, is a critical scientific tool to understand the complex interdependencies between land, climate, biodiversity and water, among other Earth system components, offering policymakers a focused lens through which to view the potential risks and rewards of different land-use decisions. Science is uniquely positioned to provide the evidence for understanding land degradation, its linkages to other environmental challenges and opportunities for action. By providing reliable data and insights, science can guide policymakers and other actors to make informed decisions, prioritise investments in key areas and design more targeted interventions.

We must recognise that in protecting and restoring land, we also restore hope and resilience. The synergies between the three Rio conventions – on climate, biodiversity and desertification – show that addressing land degradation can amplify efforts to protect ecosystems and mitigate climate change, while improving human wellbeing. This report highlights transformative actions towards that vision, where both people and the environment can prosper within planetary boundaries.

Executive summary

Background

Land is vital to Earth system processes, most directly those related to climate, biodiversity and freshwater. It is also fundamental to economic development, provides shelter and shapes cultural identity. However, human activities are driving land degradation worldwide, putting many of these essential functions and services at risk.

This special report on land – Stepping back from the precipice: Transforming land management to stay within planetary boundaries – draws on an extensive literature review to present a planetary boundaries perspective on land degradation. Land is central to seven of the nine planetary boundaries, referred to as the land-based planetary boundaries. The report focuses on their current status, their interlinkages and opportunities for action.

Planetary boundaries are scientifically determined thresholds within which humanity can operate safely. Crossing these thresholds can lead to catastrophic environmental change and destabilize the Earth system with serious consequences for economic development and equity.

Understanding land degradation in connection to other challenges like climate change and biodiversity loss, as well as human needs, is key for transforming land management in a way that considers people and nature, steering us away from irreversible harm from local to global scales.

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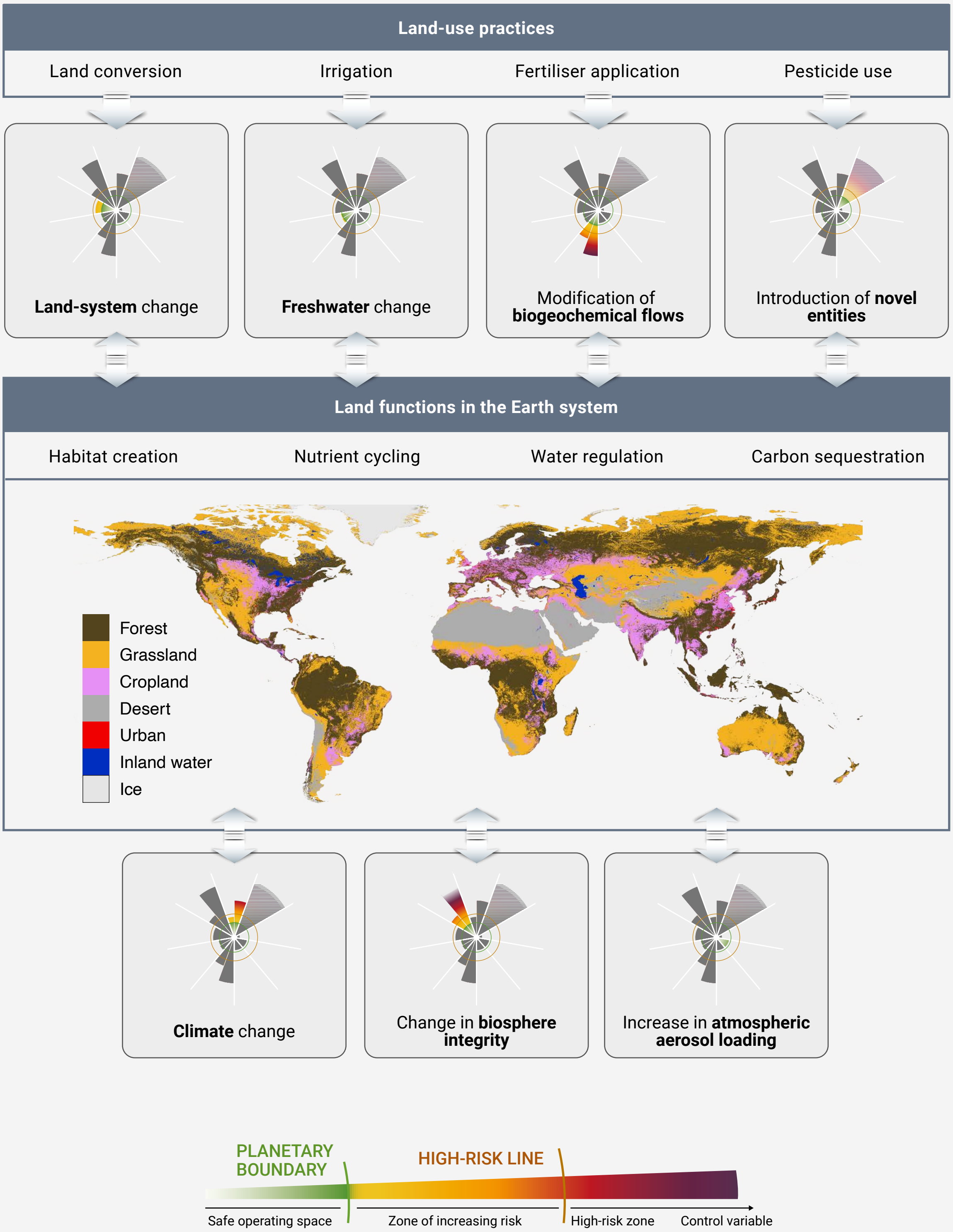
Interaction between land-use practices, land-based planetary boundaries and the global state of land.

Source: Own illustration, based on Richardson et al. (2023). Land cover map based on Buchhorn et al. (2020).



Key messages

1. Land is central to people and nature

Land is an integral component of the Earth system and central to the processes, functions and services that support environmental and human wellbeing. Recognising the centrality of land is essential for maintaining environmental stability and promoting sustainable development for current and future generations.

1.1 Land supports and connects critical Earth system processes defined in the planetary boundaries framework. It is home to diverse ecosystems, regulates climate, and ensures water flow and nutrient cycling.

1.2 Land is also essential for human survival, serving as the foundation for food production and providing clean water and shelter. Furthermore, land sustains livelihoods through agriculture and forestry, and can contribute to social equity and cultural identity.

2. Land is increasingly under threat

Land is increasingly threatened by current land use and management practices, which are driving land degradation and other environmental challenges globally, ultimately compromising the ability of the planet to sustain current and future human wellbeing.

2.1 Land degradation is driven by human activities, such as unsustainable agricultural practices, conversion of natural ecosystems, deforestation and urbanisation.

2.2 Other environmental challenges such as climate change and biodiversity loss are closely linked to land degradation. These issues further exacerbate land degradation, creating a vicious cycle and pushing the limits of global sustainability.

2.3 Recognising these limits, the planetary boundaries framework defines critical thresholds for Earth system processes that, if exceeded, pose a risk to environmental and human wellbeing. Seven of the nine planetary boundaries are substantially affected by human land use and six of these have been crossed, highlighting the critical role of land management in maintaining planetary stability.

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3. Transformative actions can halt land degradation

Transformative actions to combat land degradation can facilitate a return to the safe operating space for the land-based planetary boundaries, while yielding further benefits. Just as the planetary boundaries are interconnected, so must be the actions to prevent or slow their transgression.

3.1 Returning to the safe operating space requires efforts to avoid, reduce and reverse land degradation.

3.2 Transformative actions exist that can address land degradation, while respecting the land-based planetary boundaries and yielding further socioeconomic co-benefits, such as income diversification or food security. In this way, land can act as a lever for driving positive change across environmental and social dimensions.

3.3 Principles of fairness and justice are key when designing and implementing transformative actions to stop land degradation, ensuring that benefits and burdens are equitably distributed.

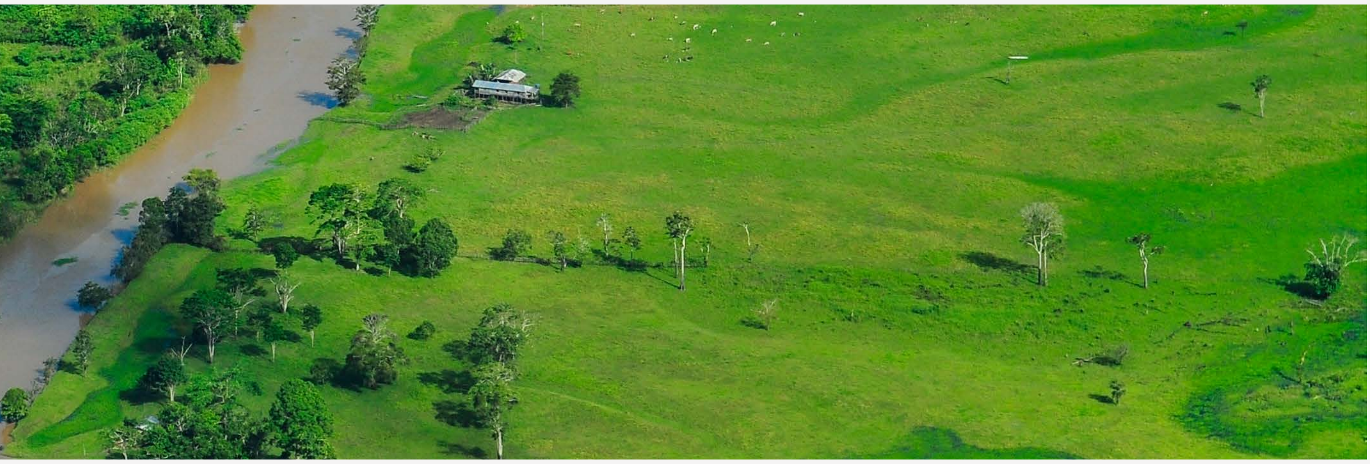
4. Evidence-based policies are crucial for transformative action

Effective evidence-based policies are crucial for transformative action, and ultimately for environmental and human wellbeing. They must be supported by an enabling environment, substantial public and private investments, and a closer collaboration between science and policy.

4.1 Enabling factors such as supportive frameworks, economic incentives, clear property and resource-use rights, and effective coordination between actors and scales can create a conducive environment for adopting, scaling up and sustaining transformative actions for sustainable land use.

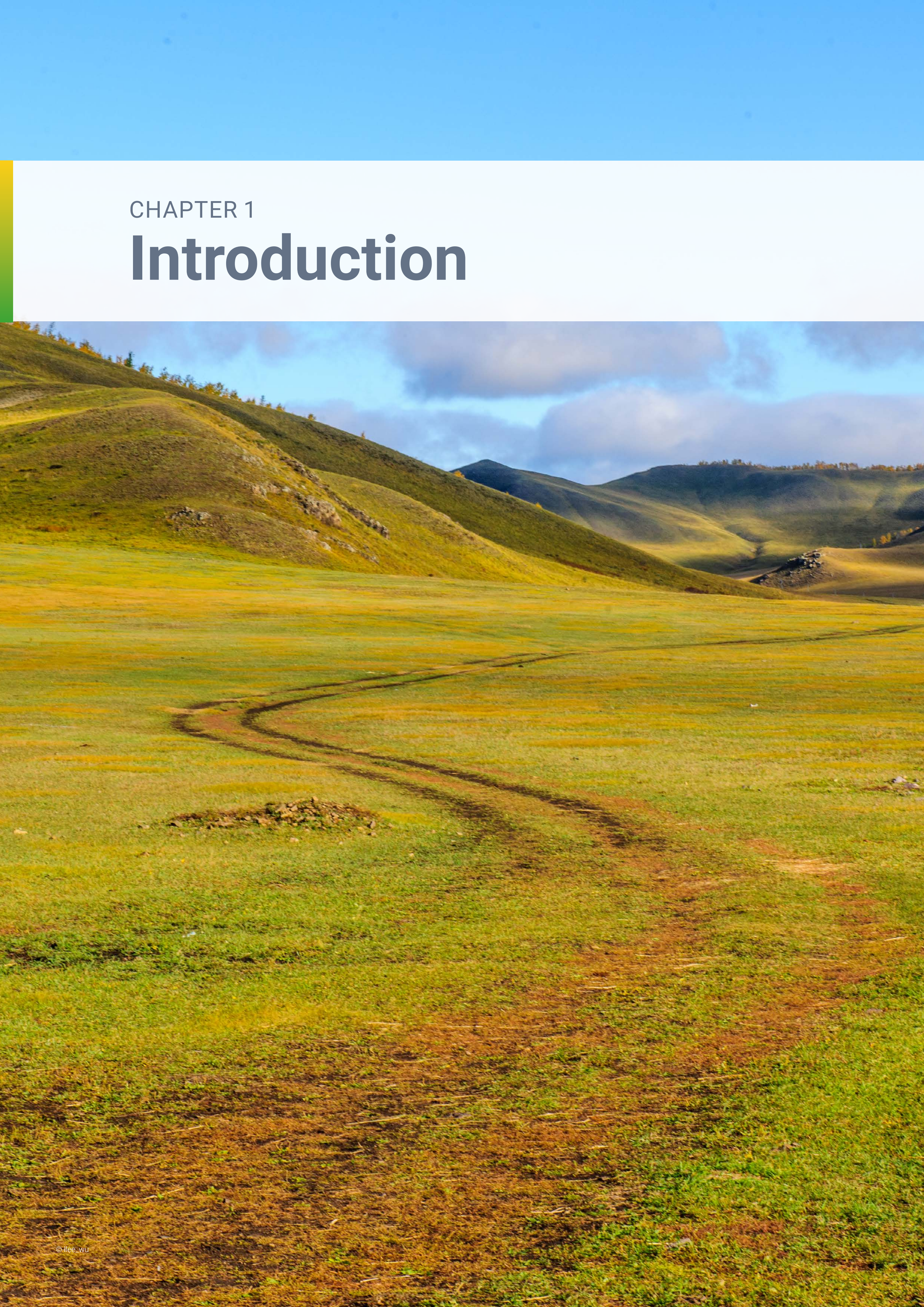
4.2 Substantial public and private investments, in particular a better integration and prioritisation of sustainable land use in all national and international funding, are needed for more comprehensive and effective action.

4.3 Scientific frameworks like the planetary boundaries can serve as a practical guide for policymakers to evaluate the sustainability of land-use measures and make evidence-based decisions in the context of multiple interconnected challenges.



CHAPTER 1

Introduction



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Land holds global importance due to its key role in supporting and connecting critical Earth system[1] processes related to biodiversity, climate change and freshwater, among others, thereby sustaining human life on Earth. As a central element, land is home to diverse ecosystems that contribute to the planet's ecological balance. It regulates climate, ensures water filtration and nutrient cycling, and is the basis for agricultural production and thus food security. Additionally, land is vital for economic development, shelter and cultural identity. However, human activities such as unsustainable[2] agricultural practices, deforestation and urbanisation are driving land degradation worldwide, thereby threatening these essential functions.

Land degradation

Land degradation is "the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices" (UNCCD, 1994). The United Nations Sustainable Development Goal (SDG) Target 15.3 – to achieve land degradation neutrality (LDN) – addresses land degradation through a structured response hierarchy: namely, the prevention of land degradation, reduction of existing degradation, and restoration of land that has been significantly degraded.

1.1 A planetary boundaries perspective on land

The planetary boundaries framework defines Earth system thresholds that, once transgressed, can lead to irreversible environmental damage and threaten the stability of the entire planet. They delineate a space within which humanity can operate safely. The concept of the planetary boundaries was first introduced by Rockström et al. (2009), who identified nine critical Earth system processes along with associated boundaries for each: land-system change, climate change, change in biosphere integrity, freshwater change, biogeochemical flows, atmospheric aerosol loading, novel entities, ocean acidification and stratospheric ozone depletion. These planetary boundaries are interrelated; transgressing one boundary may affect the state of other boundaries and lead more easily to their transgression. According to the latest update of the planetary boundaries framework, six out of nine planetary boundaries have already been crossed, including the boundary for land-system change defined by global forest cover: only 60% of original global forest cover remains, with the boundary defined at 75% (Richardson et al., 2023).

Planetary boundaries

Planetary boundaries are scientifically determined thresholds within which humanity can operate safely. Crossing these thresholds can lead to catastrophic environmental change and destabilise the Earth system with serious consequences for economic development and equity (Rockström et al., 2009; Richardson et al., 2023).

Land is a central aspect in seven of the nine planetary boundaries: land-system change, climate change, change in biosphere integrity, freshwater change, biogeochemical flows, novel entities and atmospheric aerosol loading. Unabated land degradation will directly or indirectly lead to further pressure on these planetary boundaries, whereas sustainable land management can lead to greater systems resilience (Qiao et al., 2022). In this report, we place a special emphasis on these seven land-based planetary boundaries and focus on socioeconomic needs identified as crucial in the context of land degradation, based on the Doughnut economic model (Raworth, 2017) (see Figure 1 and Chapter 3).

Given the transgression of these planetary boundaries, there is an urgent need for transformative action to protect and restore land and other critical Earth system processes, and effectively achieve the targets enshrined in the three Rio conventions – the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the United Nations Convention to Combat Desertification (UNCCD). Transformative action involves systematic efforts to prevent land degradation, reduce existing degradation and restore ecosystems that have been significantly degraded, while also mitigating climate change, making land resilient to climate impacts, and reversing biodiversity loss. These efforts need to expand the traditional focus on forests and agricultural lands to consider the unique role of drylands, savannas and grasslands in land-based solutions.

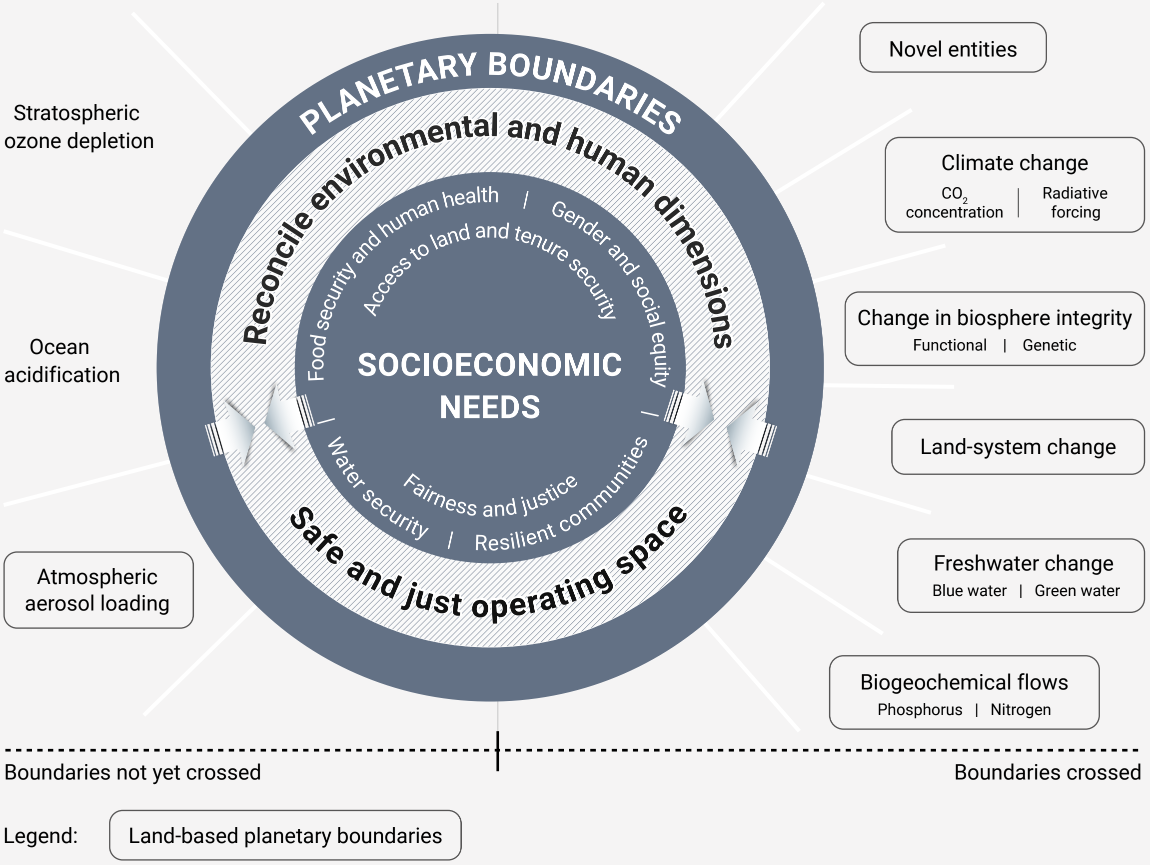
Sustainable land management

Sustainable land management is understood in a broad sense, encompassing local practices related to agricultural production or ecosystem restoration, as well as land-based policies and investments. It enables various societal needs, including food, health and shelter, to be met within the safe operating space of the Earth system.

Many cost-effective practices already exist and could be readily implemented or upscaled, but concerted action is needed to channel investments into these solutions. At the same time, sustainable land management must be part of a just transition and address the

Figure 1

The safe operating space for humanity needs to reconcile environmental limits and human requirements. These are represented as the planetary boundaries (outer circle) and socioeconomic needs (inner circle). Seven of the nine planetary boundaries are substantially affected by human land use and are therefore referred to as the land-based planetary boundaries, six of which have already been crossed. Source: adapted from UNCCD, 2022; see Chapter 3 in this report.



question of how to fairly distribute responsibilities and benefits. Concepts like “actor fair shares” or “environmental footprints” can play a crucial role in achieving environmental objectives related to land degradation without compromising equity and justice.

1.2 The special report on land

The special report on land highlights the critical issue of land degradation by taking a planetary boundaries perspective, and discussing the many ways in which land degradation affects and interacts with other global challenges. It considers opportunities for transformative action towards sustainable land management and planetary resilience by placing a specific focus on the land-based planetary boundaries.

Various UN-led initiatives, in particular the three Rio conventions, have explored land degradation and restoration, and their interdependence with biodiversity loss and climate change. In addition, seminal reports like the Global Land Outlook (UNCCD, 2017, 2022b) provide comprehensive overviews of the challenges and opportunities related to sustainable land management. The IPBES Report on Land Degradation and Restoration (2018b) and the IPCC Special Report on Climate Change and Land (2019) examine the complex interactions between land degradation and other environmental challenges.

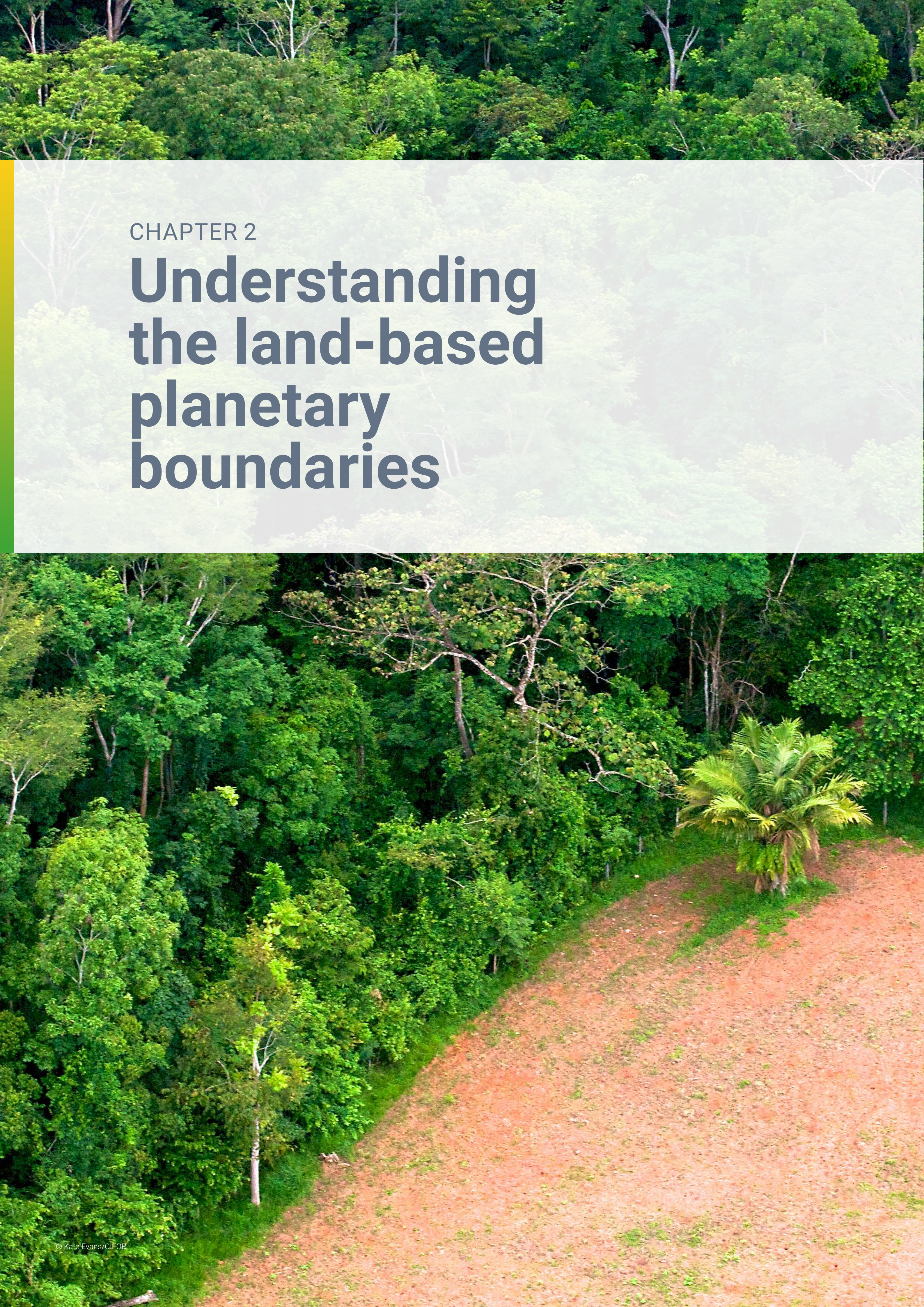
The special report on land is motivated by the following questions: How is the current state of the land-based planetary boundaries linked to land and land degradation globally? In what ways do human activities contribute to and bear the impacts of land degradation? What actions are needed to prevent land degradation and mitigate its impacts on the environment and human wellbeing? How would combating land degradation contribute to avoiding planetary boundary transgressions? How can sustainable land management be implemented in a manner that is just and fair?

Methodologically, the report is based on an extensive literature review, synthesising existing research and assessments on land degradation, the land-based planetary boundaries and opportunities for action. The literature review conducted for this report is not systematic in nature, but provides an overview of carefully selected research and an update of previous assessments. Examples from different regions of the world were selected to ensure that they adequately and meaningfully represent land degradation in its various forms and contexts, and showcase a variety of transformative actions to inspire actors from different domains to join forces in combating land degradation.

The special report is divided into five chapters, with this introduction constituting the first chapter. Chapter 2 follows with an overview of the planetary boundaries framework, focusing on the land-based boundaries. Chapter 3 explores socioeconomic dimensions of land degradation in a planetary boundaries context. Chapter 4 focuses on transformative actions to combat land degradation, including enabling factors, policies, investment strategies, and principles of fairness and justice. The report concludes in Chapter 5 with recommendations for action and future research needs.

CHAPTER 2

Understanding the land-based planetary boundaries



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The past 11,700 years, known as the Holocene, has been a period of unusually stable environmental conditions on Earth, which fostered the development of contemporary human societies (Steffen et al., 2015). However, since the Industrial Revolution, the accelerating impact of human activities has initiated a transition to the Anthropocene.[3] This new epoch is marked by humanity's dominant influence on various Earth system processes.

The key drivers of this transition are the energy sector, with its heavy reliance on fossil fuels, as well as agricultural expansion and land-use change (Rockström et al., 2009). While human land-use and management practices have shaped terrestrial landscapes and ecosystems throughout the Holocene period (Ellis et al., 2021), agriculture has increasingly been threatening the stability of the Earth system since the Industrial Revolution (Campbell et al., 2017). The planetary boundaries framework responds to this shift by offering a way to understand the critical thresholds that maintain Earth's stability, highlighting the urgent need for humanity to take action to remain within a safe operating space.

This chapter outlines the rationale for considering land degradation trends from a planetary boundaries perspective. It provides detail on the conceptual framework, including its origin, evolution and key components, followed by the current state of the land-based planetary boundaries. The chapter concludes with a discussion of the land-mediated interactions between these boundaries, underscoring the need for an integrated approach to preventing multiple transgressions.

2.1 Land degradation and the planetary boundaries

Land-use change and agriculture are the major drivers of the transgression of the planetary boundaries for land-system change, change in biosphere integrity, freshwater change and biogeochemical flows. They also contribute significantly to the human-induced perturbation of the planetary boundaries for climate change, novel entities and atmospheric aerosol loading (Campbell et al., 2017). These transgressions are intimately linked to land degradation and the resulting loss of land productivity and complexity. Conversely, sustainable land management can help alleviate pressures on several planetary boundaries.

The ecological integrity of land and its components (soil, water and biodiversity) is important for both human wellbeing and Earth system stability (Prăvălie, 2021). Land degradation therefore threatens both environmental resilience and the livelihoods of those communities that are directly dependent on the land. Land is key to many economic activities, yet fundamentally differs from other natural resources or capital components (such as water or energy) as it cannot be moved and it cannot be augmented or newly created (with very few exceptions). Hence, the only sensible approach is to conserve, sustainably manage and restore land resources. The Economics of Land Degradation (ELD) initiative studies the true value of land and its connected ecosystem services. Estimates suggest that ecosystem service losses from land degradation range between USD 6.3 and USD 10.6 trillion annually (ELD Initiative, 2015).

Examining land degradation from a planetary boundaries perspective highlights its wide-reaching and long-term implications, as well as its interconnectedness with other pressing environmental issues. Although land degradation manifests on a local scale, it is a global phenomenon that can affect environmental conditions in distant areas. This is illustrated by the impact of deforestation on river flow in distant regions (Wang-Erlandsson et al., 2018), the role of soil erosion as a source of atmospheric CO_2 (Lal, 2019), and the long-range atmospheric transport of pesticides (Meijer et al., 2003).

The planetary boundaries framework also considers the impacts of land degradation over a wide range of time scales. While some planetary boundaries, such as the boundary for aerosol loading, respond to land degradation within days or weeks, others such as the climate change boundary act on timescales of years to decades, or even centuries. This is consistent with the time horizons over which soil formation occurs and reflects the long-term impacts of land degradation.

Global extent of land degradation

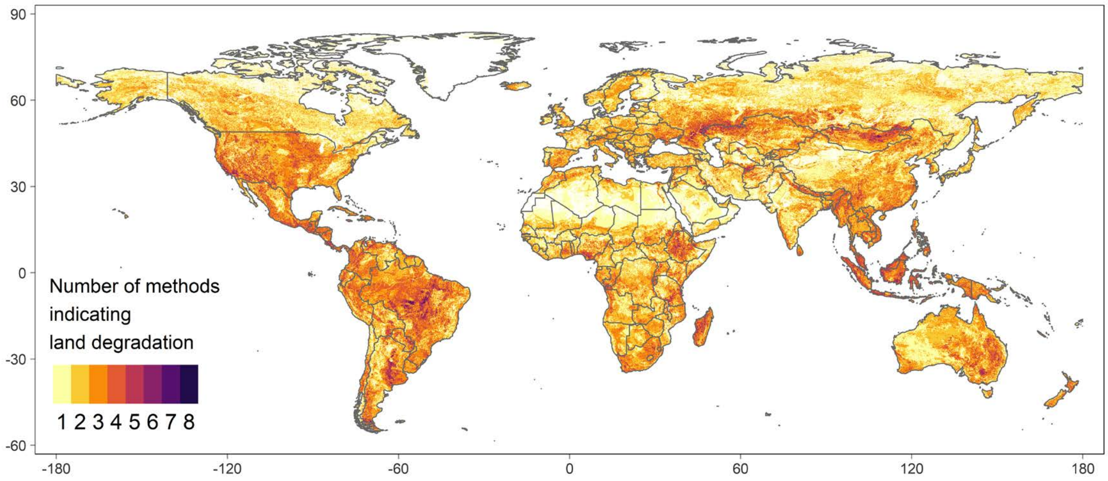
There are conflicting figures on the status and extent of global land degradation, due to differences in definitions and indicators (Jiang et al., 2024). National reports to the UNCCD indicate that at least 1.2 billion people, and an area of 1.5 billion hectares (ha), are affected by land degradation, with an estimated annual increase of 100 million ha (UNCCD, 2023).

Finding a universal indicator of land degradation is difficult because the processes involved are highly context-dependent (Prăvălie et al., 2021a). In addition, studies can focus on the end condition of the land, the ongoing degradation process, or the risk of future degradation. As a result, different studies are more likely to agree on areas of healthy land than on the extent and degree of land degradation (Gibbs and Salmon, 2015).

The good-practice guidance published by the UNCCD recommends the use of trends in land cover, land productivity and soil organic carbon stocks as indicators of land degradation (Sims et al., 2021). A comparison of these indicators, other indicators commonly used in land degradation research, and two influential global maps of land degradation reveal a low level of congruence (Figure 2). Most methods can capture land degradation in semi-arid regions well, while vegetation-index-based methods are better suited for tropical regions, and soil organic carbon for high latitudes (Jiang et al., 2024).

Figure 2

Global extent of land degradation based on eight different methodological approaches.
The colours indicate the number of methods or indicators that show the area as degraded.
Source: adapted from Jiang et al. (2024).



Land is an integral component of the Earth system and a central aspect of seven planetary boundaries, which we call the land-based planetary boundaries:

- **Land-system change** refers to the conversion of natural ecosystems to human-dominated landscapes, such as agriculture, urban areas and infrastructure development. Agriculture is the primary driver of this change due to the expansion of cropland and livestock grazing (FAO, 2022b).
- **Climate change** is significantly influenced by land as forests, grasslands and soils act as important carbon sinks, sequestering carbon dioxide (CO_2) from the atmosphere. Conversely, activities like deforestation and soil degradation release stored carbon back into the atmosphere, contributing to climate change (Nabuurs et al., 2022).
- **Change in biosphere integrity** and ecosystem health are directly impacted by land-based human activities like deforestation, urbanisation and agricultural expansion, which can result in loss of natural habitats and a reduction of species richness (Gerten et al., 2020; Leclère et al., 2020; Richardson et al., 2023).
- **Freshwater change** is influenced by land-use changes, which affect the availability and distribution of freshwater. Human activities like irrigation and land conversion for agriculture can alter surface water flows, groundwater recharge and soil infiltration (Wang-Erlandsson et al., 2022; Porkka et al., 2024).
- **Biogeochemical flows** are significantly impacted by land-use change. For example, the conversion of forests to cropland or the application of fertilisers can lead to alterations in the nitrogen and phosphorus cycles, nutrient runoff, and a higher risk of eutrophication and dead zone formation in water bodies (Mekonnen and Hoekstra, 2018; Schulte-Uebbing et al., 2022).
- **Novel entities** refer to new and potentially dangerous substances in the Earth system. In the context of land use, the accumulation of toxic and long-lived substances in soils is of particular importance. This includes a wide range of pesticides as well as antibiotics from livestock production (Jørgensen et al., 2022; Persson et al., 2022).
- **Atmospheric aerosol loading** is the emission of liquid and particulate matter into the atmosphere. It is driven by land-based activities, including agriculture, deforestation and biomass burning. In turn, atmospheric aerosols can alter cloud formation and precipitation patterns, affecting the climate system (Casazza et al., 2018; Richardson et al., 2023).

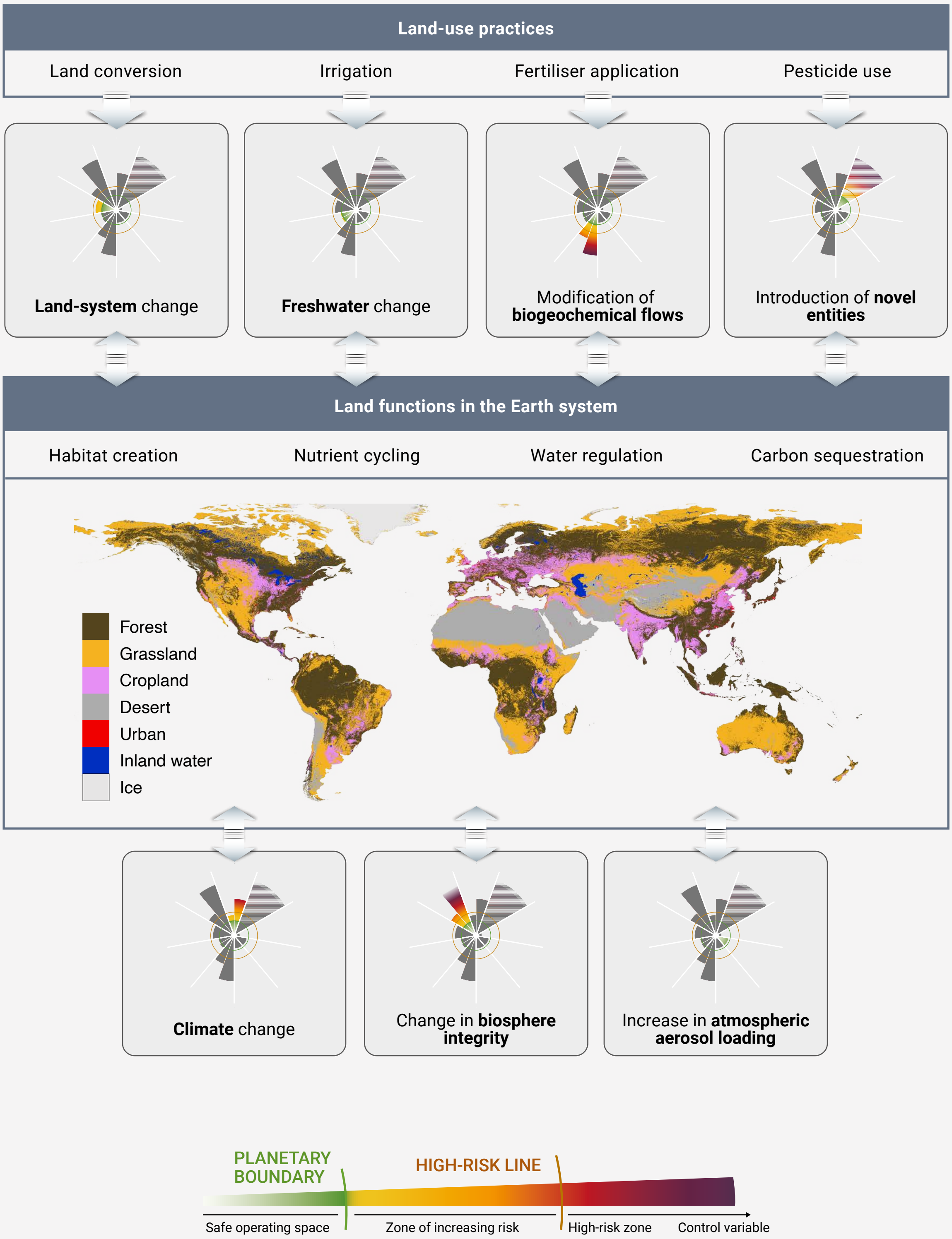
The linkage between land degradation and the land-based planetary boundaries is depicted in Figure 3. Land-use practices that increase agricultural productivity can directly affect the planetary boundaries for land-system change, freshwater change, biogeochemical flows and novel entities. These practices can result in a loss of land functionality, leading to various forms of land degradation, which exert pressure on two core planetary boundaries – climate change and change in biosphere integrity – as well as aerosol loading. Transgressing these boundaries, in turn, further amplifies the loss of land functionality and ultimately feeds back to land-system change and other land-based planetary boundaries.

The planetary boundaries set absolute outer limits within which sustainable land use can occur. This framework can be used to select transformative actions that meet the twin objectives of feeding a growing population while staying within safe environmental limits (Rockström et al., 2017). By emphasising the interactions and large-scale consequences of land-use change and management practices, the planetary boundaries framework calls for a holistic approach. It encourages integration across sectors such as agriculture, water and conservation planning. In this way, it can help identify measures that avoid, reduce and reverse land degradation while enhancing environmental stability and human wellbeing.

Finally, the planetary boundaries framework is a valuable tool in communicating the urgency of combating land degradation, reinforcing the call for greater investment and efforts to scale up sustainable land management. In the context of climate change discussions, the planetary boundaries framework

Figure 3

Interaction between land-use practices, land-based planetary boundaries, and the global state of land.
Source: Own illustration, based on Richardson et al. (2023). Land cover map based on Buchhorn et al. (2020).



served to focus policymakers and the public on the need to act in a synergistic and integrated manner to limit global temperature rise. The framework could become an equally important tool for implementing the global land restoration agenda and raising awareness on the centrality of land to other sustainability targets.

2.2 The planetary boundaries framework

The concept of the planetary boundaries is based on Earth system science, which was founded as a new science in the 1980s (Steffen et al., 2020). It studies the Earth as an integrated entity (the Earth system) and has given rise to several new concepts, including the Anthropocene, tipping points and planetary boundaries. The aim of the planetary boundaries framework is to provide a measure of how much human perturbation can be absorbed by the Earth system, linking global policy and governance communities to the biophysical understanding of the planet.

The planetary boundaries are biophysical thresholds for nine processes that together regulate the state of the Earth system. They delineate a safe operating space that would allow the planet to remain within relatively stable Holocene-like conditions. Overstepping these boundaries risks pushing the planet into alternative states with conditions that humanity has never before experienced (Steffen et al., 2018).

Each planetary boundary is assigned a measurable control variable that captures the most important anthropogenic influence(s) on that boundary (Richardson et al., 2023). For the biogeochemical flows boundary, for example, the control variable for nitrogen (N) fixation captures the anthropogenic input of new reactive N into the Earth system. Some planetary boundaries consist of two components with distinct control variables. For example, change in biosphere integrity is assessed by looking at genetic diversity on the one hand, and functional integrity on the other. Some boundaries, like climate change and ozone depletion, have global control variables, while others, like land-system change or change in biosphere integrity, are composed of changes at local and regional levels that affect the resilience of the Earth system as a whole.

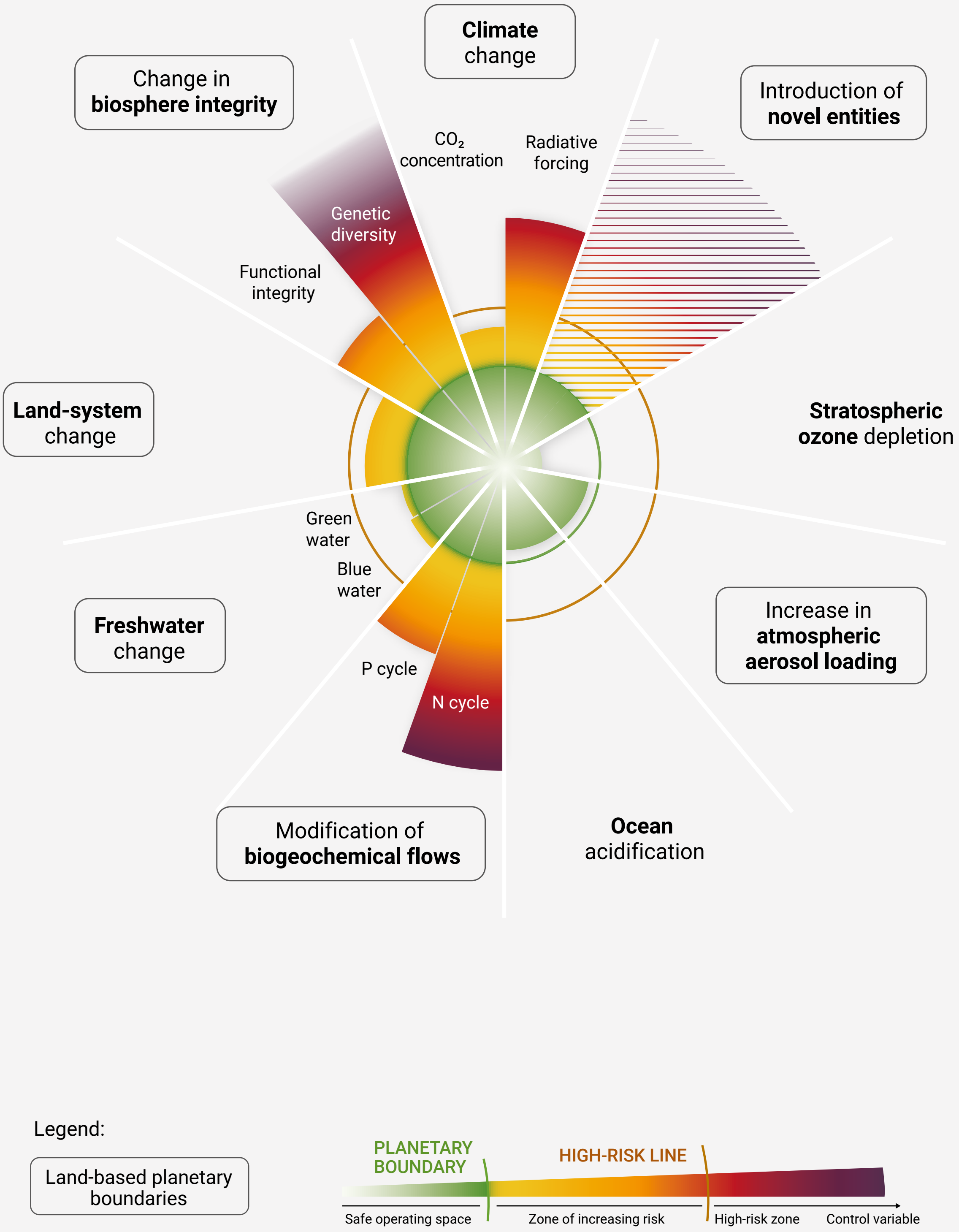
The planetary boundaries framework differentiates between the safe operating space, a zone of increasing risk, and a high-risk zone. The safe operating space is defined by the limits outside of which the Earth system cannot continue to function in a stable, Holocene-like state. This approach is in line with the precautionary principle, which advocates for preventive action in contexts of uncertainty and potential irreversible harm to the environment and humanity. The transition between zones of “increasing” and “high” risk is gradual, but the boundary is usually placed at a point beyond which scientific assessments find evidence for non-linear, irreversible changes that can fundamentally change the state of the Earth system. Figure 4 shows the current state of all planetary boundaries: a total of six planetary boundaries have been transgressed, with four of those being in the “high-risk” zone.

The planetary boundaries framework is a dynamic concept and has undergone several changes since its first introduction by Rockström et al. (2009). While the core concept has stayed the same, several individual boundaries have been reassessed to incorporate new scientific findings, leading to the boundary updates by Steffen et al. (2015) and Richardson et al. (2023). The Planetary Health Check initiative now aims to update the boundaries annually, beginning with their first report in 2024 (Caesar et al., 2024).

The first of these updates identified climate change and change in biosphere integrity as two core boundaries because they are highly connected to all the other planetary boundaries; most significantly, changes in one of these boundaries can alter the state of the entire Earth system (Steffen et al., 2015). This update also emphasised the importance of disaggregating global control variables and introducing sub-global values for several planetary boundaries. The second update proposed a quantification of all nine planetary boundaries, including atmospheric aerosol loading and novel entities (Richardson et al., 2023).

Figure 4

The planetary boundaries and their current status (based on Richardson et al., 2023).
The dashed area represents the uncertainty associated with the novel entities boundary.



Building on the planetary boundaries, the Earth Commission recently introduced the concept of Earth system boundaries, which aims to define a safe and just corridor for people and the planet (Rockström et al., 2021; Gupta et al., 2024). In addition to the inclusion of social and equity dimensions, the Earth system boundaries deviate from planetary boundaries in several ways: Land-system change is no longer a separate boundary, but is included in two newly introduced boundaries for the biosphere (DeClerck et al., 2023; Mohamed et al., 2024). In addition, the Earth system boundaries place a stronger emphasis on sub-global thresholds and tipping elements (Rockström et al., 2023).

While this report centres on the planetary boundaries framework, the complexity of land degradation and its role in the Earth system require consideration of social and equity dimensions. This report duly considers the contribution of land to livelihoods, as well as the planetary boundary assessment of human activities on land. It also addresses tipping points, which are not explicitly considered in the planetary boundaries framework (Anderies et al., 2013). The increasing and high-risk zones of the planetary boundaries framework indicate states where tipping dynamics are more likely to occur, which can be highly relevant for land-use governance and planning (Lenton et al., 2023).

2.3 The current status of the land-based planetary boundaries

To understand the relevance of unsustainable land use, it is necessary to identify the significance of land for each planetary boundary. What follows is an in-depth analysis of the seven land-based planetary boundaries and their importance in the context of land degradation.

2.3.1 Land-system change

Land ecosystems are critical for the continued resilience of the Earth system in the face of increasing anthropogenic impacts. The land system interacts with aquatic systems and the atmosphere, and is involved in regulating climate, biodiversity and water flows on a global scale (Verburg et al., 2015). Land has absorbed 32% of all anthropogenic CO_2 emissions since 1850, with tropical forests contributing the most to this land carbon sink (Friedlingstein et al., 2023). Forests also play an important role in regulating atmospheric water transport through moisture recycling (Wang-Erlandsson et al., 2018), while the extent and distribution of natural ecosystems largely determines the state of biodiversity on land (DeClerck et al., 2023).

Land-system change – the large-scale conversion of terrestrial ecosystems – is a major pressure on the Earth system and influences several other land-based planetary boundaries. The destruction of these ecosystems undermines the Earth's capacity to support biodiversity, regulate freshwater and biogeochemical flows, and maintain a stable climate (Jung et al., 2021). The landscapes that replace these natural ecosystems often exacerbate the damage: unsustainable agricultural practices frequently extract more water than can be naturally replenished, pollute waterways and contaminate groundwater through overuse of fertilisers, and support the production of high-emission ruminant meat. Land conversion at the landscape level is also associated with a global increase in soil erosion, as well as vulnerabilities to a range of natural disasters (Remondo et al., 2024).

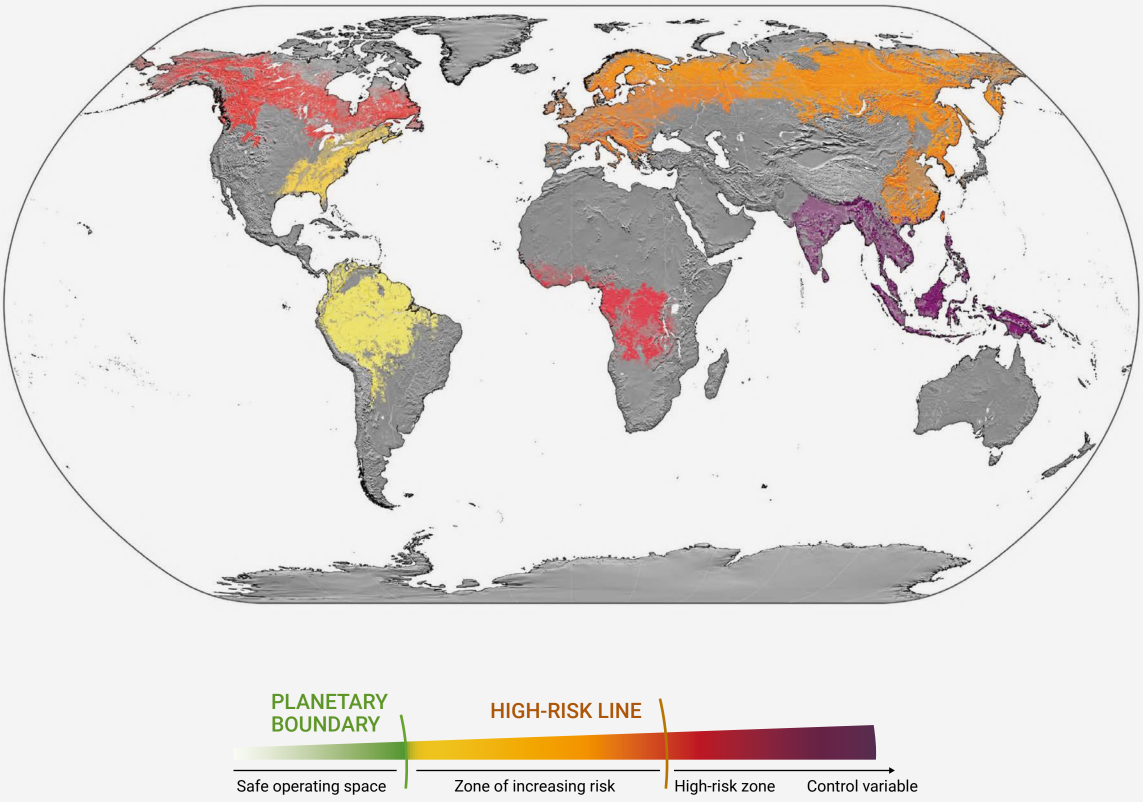
In the planetary boundaries framework, land-system change is measured by the current proportion of global and regional forest area relative to its potential extent during the Holocene epoch (Richardson et al., 2023). Forests were chosen as the focal control variable because model simulations indicate that they have had the strongest functional coupling with the climate system among land biomes during the Holocene (Snyder, Delire and Foley, 2004). The three major forest biomes – tropical, temperate and boreal – are assessed separately due to their different roles in the Earth system. The global area-weighted average of these boundaries suggests that 75% of the Holocene's potential forest area must be preserved (Steffen et al., 2015). However, this indicator only captures part of the land system and it might also be necessary to include other ecosystems as a control variable (Rockström et al. 2023).

The planetary boundary for land-system change has likely been transgressed since 1990, and only 60% of the original forest cover currently remains (Richardson et al., 2023). Almost 90% of direct deforestation in recent years can be attributed to agriculture, with cropland expansion dominating in Africa and Asia, and expansion of livestock grazing in South America and Oceania (FAO, 2022b). Regionally, cumulative land-system change in the Amazon is particularly concerning because deforestation reduces transpiration and could trigger self-reinforcing feedbacks, leading to further forest loss (Berenguer et al., 2021). This could potentially transform large areas of intact forest into a degraded, open-canopy state (Drüke et al., 2023), constituting a central tipping point in the Earth system. Figure 5 shows the current status of the land-system change boundary, by forest biome and world region.

Savannas and grasslands are major biomes threatened by land-system change, although they do not currently feature as a control variable for this planetary boundary. Similar to forests, there are indications that land-system change could lead to tipping dynamics in these ecosystems (Lenton et al., 2023). For example, savannas cover approximately 20% of the Earth's land surface and are a major store of terrestrial biodiversity and carbon (Murphy, Andersen and Parr, 2016; Bai and Cotrufo, 2022). However, they are increasingly being lost to both cropland expansion and misguided afforestation initiatives (Williams et

Figure 5

Current status of the land-system change planetary boundary.
This map shows the extent of transgression among all major contiguous forest biomes. Source: Caesar et al. (2024).



al., 2022). While woody encroachment into grassland ecosystems tends to increase above-ground carbon storage, it is also associated with a substantial decline in biodiversity (Wieczorkowski and Lehmann, 2022); the overall climate impact is unclear due to uncertainty regarding the below-ground carbon pool response to woody cover (Zhou et al., 2023).

Finally, land-use change and climate change in recent decades have contributed to the desertification of large areas of dryland (Burrell, Evans and De Kauwe, 2020). There is evidence that these important ecosystems, at intermediate levels of aridity, can exist in two alternative stable states: high multifunctionality with higher vegetation cover, soil fertility and nutrient cycling; and low multifunctionality (Berdugo et al., 2017). When climatic stressors such as drought are accompanied by land-use stressors, such as overgrazing, this can lead to permanent regime shifts in dryland ecosystems, even after the climatic stressor has disappeared (Bestelmeyer et al., 2011; Vicente-Serrano et al., 2012).

2.3.2 Climate change

Climate – the state of the atmosphere over long periods of time – controls the conditions for life on the Earth's surface. During the Holocene period, global mean surface temperatures have varied within a narrow range of 0.5°C (Osman et al., 2021). However, anthropogenic impacts on the climate system now demonstrate the potential to shift the Earth to a substantially altered new stable state (Steffen et al., 2018). The relatively stable Holocene climate is thought to have enabled the development of agriculture and complex human societies, and there are serious doubts as to whether humanity can thrive under drastically altered climatic conditions (Rockström et al., 2021).

The climate change boundary's control variables are atmospheric CO_2 concentrations and radiative forcing (Rockström et al., 2009). Atmospheric CO_2 concentration, measured in parts per million (ppm) is the main driver of anthropogenic climate change.

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Radiative forcing, measured in watts per square metre (W m^{-2}), comprises all human activities that affect the Earth's energy balance, not just CO_2 emissions. It also includes other greenhouse gases and changes in the reflectivity (albedo) of the Earth's surface. The safe operating space is set at a CO_2 concentration of 350 ppm and a radiative forcing increase of 1 W m^{-2} relative to 1750 levels (Richardson et al., 2023). These boundaries are consistent with the Paris Agreement goal of holding global temperature rise well below 2°C.

Currently, atmospheric CO_2 concentration is 419 ppm and the estimated anthropogenic radiative forcing is 2.79 W m^{-2} (Forster et al., 2024). Therefore, both control variables indicate that the planetary boundary for climate change is being transgressed. This increases the risk of climate tipping points causing abrupt and irreversible changes, and altering the overall state of the Earth system (Rockström et al., 2023). With the current global warming of ~1.2°C (Forster et al., 2024), there is already a possibility that the Greenland and West Antarctic ice sheets will collapse, and that the global land carbon sink will be substantially weakened (Armstrong McKay et al., 2022).

Land systems are linked to climate change through multiple pathways. As a major component of the Earth system, they are involved in several feedback loops with the atmosphere (Schlesinger and Bernhardt, 2020) and act as both a source and a sink for greenhouse gases, with the sink becoming weaker and the source more pronounced as climate change progresses (Jia et al., 2019). Land use is both affected by and contributes to climate change, such that several mitigation strategies rely on land-related responses (Smith et al., 2019).

Land ecosystems currently absorb about one-third of anthropogenic CO_2 emissions, but unsustainable land management and increasing climate variability are jeopardising this mitigation potential (Nabuurs et al., 2022). The magnitude of the land carbon sink has increased in line with CO_2 emissions, more than doubling since the 1960s. This is attributed mainly to the beneficial effects of CO_2 on plant growth and increased temperatures at higher latitudes (Ruehr et al., 2023). However, increasing climate variability and change may counterbalance these effects. Over the past decade, climate change has reduced the strength of the land sink by 20% (Friedlingstein et al., 2023). If deforestation and land degradation continue unabated, this could potentially trigger a reversal from land being a net sink to a net source (IPCC, 2019).

Land-use activities are a major contributor to climate change. Agriculture, forestry and other land uses contribute about 23% of net anthropogenic greenhouse gas emissions, including CO_2, methane (CH_4) and nitrous oxide (N_2O) (Jia et al., 2019). The biggest culprits are methane emissions from livestock and rice production, and nitrous oxide emissions from mineral fertiliser and manure application. The net contribution of CO_2, on the other hand, is negative because carbon uptake in soils and forests offsets emissions from land cover change and timber harvesting.

A major impact of climate change will be a redistribution of climatic zones and a corresponding shift in the land biomes adapted to these zones (Beck et al., 2023). For land use, this will put pressure on existing crop and livestock production, with poorer farmers being the most vulnerable to these changes (Bezner Kerr et al., 2022). Food security is already threatened by growing climate variability and extreme weather events, such as droughts and floods, and will be increasingly affected by future climate change (Mbow et al., 2019). Finally, climate change is also known to exacerbate soil erosion through an increase in extreme precipitation events (Borrelli et al., 2020).

2.3.3 Change in biosphere integrity

The terrestrial biosphere comprises all ecosystems and living organisms on land. It provides many of nature's contributions to people (NCP), including flood regulation, feed and fodder production, and opportunities for recreation (IPBES, 2019; Neugarten et al., 2024). In terms of Earth system stability, the regulating services provided by terrestrial ecosystems are most important. These include soil fertility, with its impacts on carbon sequestration and nutrient cycling (IPBES, 2019; Jiao, Lu and Wei, 2022), water quality and water flow regulation (IPBES, 2019; Wang-Erlandsson et al., 2022), pollination (IPBES, 2016), and the control of pests and diseases (Beillouin et al., 2021). Only a largely intact biosphere, acting as both a stock and a flow regulator of carbon, water and nutrients, can adapt to external pressures and ensure that the Earth system continues to function (Gupta et al., 2024).

The planetary boundaries framework identifies change in biosphere integrity as one of the two core boundaries critical to maintaining Earth system stability. Originally referred to as "biodiversity loss", change in biosphere integrity better accounts for impacts on both genetic diversity and functional integrity, which provide the two control variables for this planetary boundary (Steffen et al., 2015). Rather than an absence of change, functional integrity is understood as the ability of the biosphere to adapt and maintain overall interactions with the Earth system (Richardson et al., 2023). This adaptive capacity is ultimately determined by genetic diversity, whose recent losses undermine the ability of the biosphere to co-evolve with the abiotic component of the Earth system (Exposito-Alonso et al., 2022).

Genetic diversity is represented by the extinction rate of species, measured as the number of extinctions per million species per year (E/MSY). The rate of extinction over the past few million years is assumed to be around 1 E/MSY, but due to a high degree of uncertainty, the boundary for the safe operating space is set at 10 E/MSY (Rockström et al., 2009; Caesar et al., 2024). Because the extinction rate is only a very coarse measure of genetic diversity, there is a risk of underestimating the impact of declines in functionally important species (Steffen et al., 2015).

Functional integrity is measured as the human appropriation of net primary production (HANPP). This metric indicates the extent to which human activities, such as agriculture and forestry, alter ecosystem productivity and extract energy through biomass harvesting (Caesar et al., 2024).


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The boundary for the safe operating space is set at less than 10% of the pre-industrial net primary production, leaving energy and material flows in the biosphere largely intact (Richardson et al., 2023). Efforts are under way to further refine this control variable to better capture the different facets of biosphere integrity (Caesar et al., 2024).

The control variables for genetic diversity and functional integrity show that the planetary boundary for change in biosphere integrity is being transgressed. The current rate of species extinction is estimated to be over 100 E/MSY, which is 10–100 times higher than the Holocene value, and will increase further if currently endangered species are not protected (Ceballos et al., 2015; Ceballos and Ehrlich, 2023). The control variable for functional integrity shows a boundary transgression dating back to the late 19th century – a period of accelerated land-use change and ecosystem transformation (Klein Goldewijk et al., 2017). Current HANPP is estimated to be 30% of Holocene mean net primary production, and thus well beyond the safe operating space (Richardson et al., 2023).

Land-use pressures, including the conversion of natural ecosystems, overexploitation of natural resources and environmental pollution, pose an even greater threat to global biodiversity than climate change does (Jaureguiberry et al., 2022). The resulting land degradation endangers vital ecosystem functions, ultimately leading to mass species extinctions and the loss of essential regulatory services (IPBES, 2018b). Habitat conversion is a major threat to terrestrial biodiversity (Leclère et al., 2020), but habitat fragmentation and the decline of semi-natural elements in agricultural landscapes also contribute to the diminishment of NCP (Mohamed et al., 2024). In addition, irrigation and the drainage of wetlands have led to a severe crisis in freshwater biodiversity worldwide, resulting in the degradation of freshwater ecosystems at an even faster rate than that of terrestrial ecosystems (Albert et al., 2021).


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2.3.4 Freshwater change

Freshwater accounts for only 3% of Earth's water resources, and most of it is stored in ice caps and groundwater reservoirs (Schlesinger and Bernhardt, 2020). Yet, life on land depends on this scarce resource and its ecological functions. Freshwater is the basis for biological production in terrestrial and aquatic ecosystems, it is involved in numerous regulatory interactions with regional and global climate, and it connects and shapes landscapes through the transport of matter (Falkenmark, Wang-Erlandsson and Rockström, 2019; Gleeson et al., 2020). Important stores in the global water cycle include atmospheric water, soil moisture, surface water, groundwater and frozen water, all of which are being affected by human actions (Mekonnen, Gerbens-Leenes and Hoekstra, 2015; Gleeson et al., 2020).

Human interventions in the water cycle are driven by demands for energy (Mekonnen, Gerbens-Leenes and Hoekstra, 2015) and agricultural production (Rockström et al., 2014). The construction of dams for water storage has disrupted the connectivity of more than half of the world's major rivers, and is associated with declining biodiversity and shrinking river deltas (Grill et al., 2019). In addition, increasing withdrawals of surface and groundwater (Wada, Wisser and Bierkens, 2014) may induce local-scale tipping points in aquatic ecosystems (Bogan and Lytle, 2011). Changes in soil moisture are associated with a variety of impacts, including ecosystem shifts following land degradation and soil moisture loss (Karssenberg, Bierkens and Rietkerk, 2017), as well as the salinisation of soils through irrigation (Rosa, 2022).

Throughout history, human civilisations have depended on the sustainable use of surface and soil water resources (Falkenmark, Wang-Erlandsson and Rockström, 2019). Recent examples of regional societal collapses induced or exacerbated by water stress include the US Dust Bowl of the 1930s (Schubert et al., 2004), the devastation of the Aral Sea (Micklin, Aladin and Plotnikov, 2014) and the long-term drought preceding the Syrian civil war (Gleick, 2014). With increasing water demand due to population growth, and increasing pressure from climate change (Vörösmarty et al., 2000), the boundary for freshwater change can help guide sustainable water use on a planetary scale (Zipper et al., 2020).

The boundary for freshwater change consists of two control variables: one for blue water and one for green water (Richardson et al., 2023). Blue water refers to the flow of surface and groundwater critical for sustaining aquatic biodiversity and transport functions. Green water refers to the combined effects of terrestrial precipitation, evaporation and soil moisture (Wang-Erlandsson et al., 2022), which underpin biological productivity and climate regulation at local to global scales. Freshwater change includes wet events, such as extreme precipitation or flooding, and drought.

Blue water change is represented by changes in surface water streamflow (Porkka et al., 2024), while green water change is represented by changes in soil moisture (Wang-Erlandsson et al., 2022). Locally, the boundary for both variables is transgressed if changes in streamflow or soil moisture in a given area exceed pre-industrial variability. On a global scale, the safe operating space for blue and green water is exceeded when these transgressions occur over more than 10% and 11% of the global land area, respectively (Richardson et al., 2023). The zone of high risk for both variables is entered when transgressions occur over more than 50% of the global land area, which could trigger global-scale ecosystem shifts (Barnosky et al., 2012).

Currently, 18.2% (blue water) and 15.8% (green water) of global land area is experiencing significant deviations from pre-industrial conditions (Porkka et al., 2024). Thus, the boundary for freshwater change has been transgressed for both blue and green water (Richardson et al., 2023). These results are consistent with reported increases in extreme precipitation (Fowler et al., 2021), changes in surface water flows (Gudmundsson et al., 2021), and the occurrence and severity of drought (Spinoni et al., 2014). Spatially, the boundary transgression for freshwater change is associated with increased dry extremes in the tropics and subtropics, and increased wet extremes in temperate and sub-polar regions (Porkka et al., 2024).

Groundwater is currently accounted for indirectly in the boundary for freshwater change through its interactions with soil moisture and streamflow (Condon and Maxwell, 2019). This captures the supply function of groundwater to streams and soils (Gleeson et al., 2020), but not its storage function. Groundwater is a finite resource and the current rate of extraction exceeds replenishment in 47% of global aquifers (Rockström et al., 2023). It is estimated that groundwater pumping will peak around 2050 as aquifers become increasingly depleted, putting further pressure on water availability and food production in many countries (Niazi et al., 2024).

Since blue and green water are both components of the global water cycle, they are closely interconnected. The withdrawal of irrigation water decreases river streamflow and increases soil moisture in many heavily irrigated regions (Porkka et al., 2024). At the same time, large-scale irrigation can induce changes in precipitation patterns (Kim et al., 2023) which in turn can affect soil moisture and surface water flows (Zhang et al., 2022).

2.3.5 Biogeochemical flows

Biogeochemical flows refer to chemical elements that circulate throughout the Earth system and that are essential for life. Currently, the planetary boundary for biogeochemical flows takes nitrogen (N) and phosphorus (P) into consideration, but other chemical elements may be included as the science advances (Richardson et al., 2023). Both N and P are required for fundamental biological functions, forming part of nucleic acids, proteins, cell membranes and contributing to energy transduction in cells (Kamerlin et al., 2013; Zhang, Ward and Sigman, 2020). Their availability in soils and the ocean is the main limiting factor for biological productivity on Earth (Harpole et al., 2011).

In the 20th century, the increased application of N and P fertilisers alleviated these natural limitations on croplands (Lu and Tian, 2017), allowing global food production to increase in line with population growth (Erisman et al., 2008). At the same time, agriculture has had low nutrient use efficiency leading to


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a release of large quantities of both nutrients into the environment, which is likely to continue in the future (Beusen et al., 2022). It is estimated that only 46% of N (Zhang et al., 2021) and 66% of P (Zou, Zhang and Davidson, 2022) currently applied as fertiliser is actually taken up by crops, and only a fraction of these nutrients is recycled in the system via the reuse of wastewater (Jones et al., 2021).

Once released into the environment, reactive forms of N "cascade" through adjacent ecosystems (Galloway et al., 2003) and can contribute to biodiversity loss, global warming, groundwater contamination and the eutrophication of water bodies (De Vries et al., 2024). P is less mobile because it is strongly attached to the soil, where it can accumulate over time (Rowe et al., 2016). However, it enters streams via soil erosion or poor wastewater management, leading to the eutrophication of aquatic ecosystems (Mekonnen and Hoekstra, 2018).

The planetary boundary for biogeochemical flows is based on the impacts of N and P on surface water eutrophication (Steffen et al., 2015). In the last few decades, there has been an increase in the eutrophication of streams (Dodds and Smith, 2016), lakes (Jane et al., 2021) and coastal areas (Malone and Newton, 2020), leading to the emergence of anoxic zones (Breitburg et al., 2018) and a dramatic loss of biodiversity (Tickner et al., 2020). In addition, there is geological evidence that a sustained input of nutrients to the oceans can lead to large-scale ocean anoxia (Watson, Lenton and Mills, 2017).

To avoid eutrophication, N and P in surface waters need to be held below critical thresholds (Richardson et al., 2023; Rockström et al., 2023). The planetary boundary for biogeochemical flows is therefore based either on the total input of N and P to global croplands (Richardson et al., 2023) or on the surplus of nutrients after harvest (Rockström et al., 2023). While the former approach assumes a constant flux from agricultural fields to water bodies, the latter can account for management practices that increase nutrient use efficiency or decrease erosion. However, neither approach considers the potential of improved wastewater reuse (Rosemarin et al., 2020).

Based on nutrient input, the planetary boundaries for N and P are set to 62 teragrams (Tg) N per year and 6.2 Tg P per year, equivalent to approximately 48 kg and 4.8 kg per hectare per year, respectively (Steffen et al., 2015; Richardson et al., 2023). When calculated from nutrient surplus, the planetary boundaries for N and P indicate a limit on nutrient input to 143 Tg N per year and 16 Tg P per year (Rockström et al., 2023). The higher boundary values are due to the effects of regionally varying nutrient use efficiencies. Currently, inputs to agricultural soils are estimated to be 232 Tg of N per year (Schulte-Uebbing et al., 2022) and 17.8 Tg of P per year (Springmann et al., 2018), thus exceeding global planetary boundaries irrespective of the calculation method.

A key feature of the boundary for biogeochemical flows is that it is a combined value of different regional boundaries (Steffen et al., 2015). While the combined planetary boundary has already been transgressed, countries with low current fertilisation levels can still increase nutrient input to improve yields without exceeding their regional boundaries (Schulte-Uebbing et al., 2022). Conversely, a global redistribution of current N inputs would require a large increase in nutrient use efficiency in regions like Europe, North America and Asia, where regional boundaries have already been transgressed (Kahiluoto et al., 2024). Efficiency gains could also be achieved through the use of accumulated soil P from past over-fertilisation (Sandström et al., 2023).

An additional control variable for P inputs to the ocean has been proposed. To avoid large-scale ocean anoxia, the limit has been set at a sustained flux of no more than 20% above the natural baseline (Rockström et al., 2009), although it should be noted that these processes operate on millennial timescales and are subject to high levels of uncertainty (Kemena et al., 2019). Current estimates suggest excess P inputs to the ocean of ~250% (Beusen et al., 2022).

2.3.6 Novel entities

Novel entities refer to novel substances introduced into the Earth system through human activities. They includes chemicals such as pesticides and antibiotics, genetically modified organisms, radioactive materials and microplastics (Richardson et al., 2023). These novel entities have proliferated over the last 75 years, and now serve as geological markers of the Anthropocene (Waters et al., 2016).

The use of novel entities in agriculture poses a risk to the environment, but has also contributed substantially to increased agricultural productivity. As part of the so-called Green Revolution, synthetic chemicals such as pesticides contributed to yield increases in the 20th Century, and are considered a cornerstone of conventional food production strategies (Jørgensen et al., 2022). However, humanity has repeatedly been surprised by the unintended consequences of novel entities in the environment. A prominent agricultural example is the environmental and human health hazards resulting from the widespread use of the insecticide DDT (Mansouri et al., 2017).

The novel entities boundary can be seen as a placeholder for other currently unrecognised planetary boundaries governed by newly introduced substances. Three conditions have been proposed (Persson et al., 2013) for a novel entity to pose a planetary boundary threat: (1) it has an unknown disruptive effect on the Earth system, (2) the disruptive effect is not discovered until it is a problem at the global scale, and (3) the effect is not readily reversible. The large number of novel entities entering the environment, and our prior ignorance of their disruptive effects, make it challenging to quantify this planetary boundary.

Planetary boundaries are typically defined with respect to the Holocene as a baseline period. This is not possible for novel entities which, by definition, have no precedent in the Holocene. Instead, this boundary is calculated as the proportion of released chemicals that are subject to safety assessment and monitoring. The novel entities boundary is currently considered to have been transgressed, as the rate of chemicals produced and released by far exceeds the global capacity for assessment and monitoring (Richardson et al., 2023). For example, around 80% of registered and used chemicals in the European Union are yet to be assessed (Persson et al., 2022).

Although pesticides are a small part of the overall production of chemicals, they are particularly concerning due to their toxicity and widespread release into the environment. Globally, the production and use of pesticides has increased steadily over the years, although the application rates per hectare are decreasing (UNEP, 2019). Many of these pesticides persist in the environment and accumulate in soils, leading to legacy effects even after they have been banned (Silva et al., 2019). Some pesticides are dispersed by long-range atmospheric transport and can be found in soils around the world (Meijer et al., 2003). Strongly associated with soil organic matter, the dynamic cycling of soil carbon could lead to a secondary release of these pesticides (Jiang et al., 2024). Some effects may only occur under changing environmental conditions. For example, drought can concentrate chemicals in the soil solution, while the application of additional agricultural chemicals can increase the transport of pesticide residues through the soil (Rillig et al., 2021).

Similarly, there is a growing concern about the accumulation of agricultural antibiotics in soils (Khmaissa et al., 2024). The majority of antibiotics are used in livestock production, mostly as a prophylactic treatment or as growth promoters (Van et al., 2020). From there, they enter the soil through manure application and act as pollutants with adverse effects on soil microorganisms and plant growth (Patyra et al., 2023; Zhou et al., 2020). In addition, the relatively low concentrations of residual antibiotics in the soil can allow bacteria to develop antibiotic resistance and lead to the spread of drug-resistant pathogens (Khmaissa et al., 2024). Extensive herbicide application has also been found to impact plants and animals indirectly through shifts in microbial communities. Beneficial microorganisms in the soil and in animals' intestinal tracts are negatively affected, while pathogenic bacteria and fungi are enhanced (Van Bruggen et al., 2021).

Aside from chemicals, genetically modified organisms are also introduced into the environment through agricultural activities. They include crops with genes for herbicide tolerance or insect resistance, and animals with newly introduced traits such as accelerated growth in transgenic Atlantic salmon (Jørgensen et al., 2022). In 2018, more than 10% of the world's arable land was planted with genetically modified crops, including 78% of all soybean yield, 76% of cotton and 30% of maize (ISAAA, 2018). A potential threat arises from the interaction of these transgenic species with organisms in their environment, which could alter the genetic identity of wild populations (Wei et al., 2024).

Besides these known interactions, there is no doubt that science will discover others. In this context, some criteria have been developed to prioritise risk assessments for novel entities with a high-risk profile (MacLeod et al., 2014). These include persistence and long-range transport potential, time lags between exposure and effects, and the dependence of society on the entity.

2.3.7 Atmospheric aerosol loading

Atmospheric aerosol loading is the presence of solid or liquid particles, ranging in size from 0.01 to 10 micrometres, that remain in the atmosphere for several hours (IPCC, 2007). Aerosols originate from natural sources, such as desert dust and forest fires, and human activities including fossil fuel combustion, agriculture and industrial processes (Duvic Paoli and Webster, 2020). These particles significantly influence the Earth system through physical, biogeochemical and biological effects (Richardson et al., 2023). The complexity of aerosols arises from their diverse sources, chemical compositions and variable impacts on climate and ecosystems, making it challenging to quantify a global boundary for aerosol loading (Duvic Paoli and Webster, 2020; Richardson et al., 2023).

Anthropogenic aerosol loading has increased significantly since pre-industrial times and contributes more than 10% of total aerosols, the remainder arising from natural sources (Tsigaridis et al., 2006; Duvic Paoli and Webster, 2020). The primary control


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variable for assessing aerosol loading in the planetary boundaries framework is aerosol optical depth (AOD), which measures the reduction in sunlight reaching the Earth's surface due to absorption and scattering by aerosols (Steffen et al., 2015; Richardson et al., 2023). Measured on a scale of 0 (no aerosols) to 1 or higher (very dense aerosol layer), global AOD values show significant regional variation. AOD values are as high as 0.3 to 0.35 in South Asia and 0.4 in East China, compared to a global mean of 0.14 (Richardson et al., 2023).

High AOD has a profound impact on regional precipitation, particularly in monsoon regions, leading to reduced rainfall and affecting the integrity of the biosphere (Steffen et al., 2015; Richardson et al., 2023). A critical factor is the difference in AOD between the northern and southern hemisphere resulting in shifts in the intertropical convergence zone, which can then affect multiple monsoon systems. Therefore, the safe operating space for the aerosol planetary boundary has been set at a maximum AOD interhemispheric difference of 0.1, with a current value of 0.065 (Caesar et al., 2024). However, there is a high degree of uncertainty involved in establishing this global boundary due to an incomplete understanding of the hydroclimatic, ecological and biogeochemical effects of aerosols.

Agricultural practices are significant sources of atmospheric aerosols, as well as aerosol precursors such as ammonia. It is estimated that the food system accounts for 58% of direct anthropogenic aerosol emissions, mainly due to land-use change and crop residue burning. It also accounts for 72% of ammonia emissions related to manure management, livestock grazing and fertiliser use (Balasubramanian et al., 2021). The interaction between aerosols and agricultural activities can exacerbate soil erosion and reduce productivity, creating a feedback loop that intensifies aerosol emissions (Nissan and Toumi, 2013). This feedback between aerosol emissions and land degradation involves complex interactions between soil, vegetation and atmospheric processes (Casazza et al., 2018).

Land degradation caused by deforestation, overgrazing and unsustainable agricultural practices increases atmospheric dust and aerosols. The infamous Dust Bowl of the 1930s, resulting from large-scale land-use changes and inadequate soil conservation, illustrates the severe consequences of land degradation on atmospheric aerosol loading (Cook, Miller and Seager, 2009). Modern parallels are evident in regions with similar practices, where soil erosion and dust emissions threaten food security and exacerbate climate change (Casazza et al., 2018; Owens, 2020). Sand and dust storms are major natural hazards in arid regions, impacting agriculture and ecosystems at the place of origin and at the place of deposition (Middleton, Tozer and Tozer, 2019).


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2.4 Linkages between the land-based planetary boundaries

The land-based planetary boundaries are linked through a variety of processes in the Earth system, so that changes in one boundary will likely affect the state of other boundaries. Although this has been acknowledged in the framework since its introduction (Rockström et al., 2009; Steffen et al., 2015), quantifying interactions between boundaries remains challenging (Richardson et al., 2023). The interconnections between planetary boundaries can include biophysical linkages as well as human-mediated interdependencies. First quantitative assessments indicate that the majority of interactions amplify human impacts on the Earth system, thereby further constraining the future safe operating space (Lade et al., 2020; Caesar et al., 2024).

Besides pure biophysical feedbacks, altered environmental conditions trigger human adaptation and behavioural changes. For example, land conversion contributes to climate change, but climate change also contributes to land degradation, which in turn will increase the rate of land conversion for crop production (Olsson et al., 2019). A spatially explicit assessment of these social–ecological interactions is challenging, as their incorporation into Earth system models is still in its infancy (Donges et al., 2017).

2.4.1 Impacts of boundary transgressions

At the global scale, the linkages of **land-system change** to other planetary boundaries are dominated by the land–climate interaction, particularly through the loss of the land carbon sink. Since the land system sequesters around 3.7 gigatonnes (Gt) of carbon per year (Friedlingstein et al., 2023), it stabilises the climate system. Failing to reverse further land-system change could, regionally or even globally, undermine the ability of forests to maintain themselves and grow, potentially even transforming a net sink into a net source of emissions (Lenton et al., 2023).

Similarly, the land-system change boundary is closely linked to biodiversity. Natural ecosystems are home to the vast majority of Earth's biodiversity, and land-system change threatens these by destroying habitats and migratory routes, often replacing them with degraded landscapes tailored for human use. Since 1970, land-system change has been the primary driver of terrestrial and freshwater biodiversity loss, with agricultural expansion being the most widespread form of land-use change (IPBES, 2019).

Deforestation impacts freshwater change through reduced moisture recycling, which not only affects local conditions but can also reduce precipitation and river flows in distant regions (Wang-Erlandsson et al., 2018). At the same time, increased deforestation also leads to higher runoff and consequently increased streamflow, especially after extreme precipitation events (Sterling, Ducharne and Polcher, 2013). Finally, vegetation fires and cleared agricultural land emit large amounts of atmospheric aerosols (Lade et al., 2020).

As one of the core planetary boundaries, **climate change** has some form of interaction with all other boundaries (Lade et al., 2020). It is tightly coupled with the land-system change boundary through the carbon cycle. Forest biomes are an important part of the land carbon sink, but they depend on relatively stable climatic conditions. Transgressing the climate change boundary will lead to large-scale shifts in Earth's forest biomes and the transgression of the land-system change boundary (Tobian et al., 2024). Stabilising either boundary will help stabilise the other, while a simultaneous transgression will amplify the negative impacts on both boundaries (Richardson et al., 2023). In a similar way, climate change is increasingly threatening biosphere integrity, including the risk of species extinction, large-scale vegetation shifts and the risk of wildfires. All of these risks significantly increase with higher greenhouse gas emissions (Parmesan et al., 2022).

There are also significant interactions between climate change and the planetary boundaries for freshwater change and atmospheric aerosol loading through atmospheric processes. A warmer atmosphere can hold more water, leading to an intensification of the global water cycle with increased evaporation and precipitation (Huntington, 2006). At the same time, droughts are becoming more frequent and severe (Ault, 2020; Yuan et al., 2023) and are the main driver of land degradation (Prăvălie et al., 2021a). Degraded lands are more likely to contribute to aerosol emissions via sand and dust storms (Middleton, Tozer and Tozer, 2019) and more frequent vegetation fires under climate change will also increase atmospheric aerosol loading (Bowman et al., 2020). Higher temperatures also lead to increased soil organic matter turnover, with the possibility of a secondary release of novel entities that had previously been adsorbed (Nizzetto et al., 2010).

Change in biosphere integrity is closely linked to other land-based planetary boundaries. Species diversity has a positive impact on biological productivity and nutrient cycling in ecosystems, and the dramatic loss in genetic diversity threatens these ecosystem services (Tilman, Isbell and Cowles, 2014). High levels of biodiversity are associated with high levels of above- and below-ground carbon storage in terrestrial ecosystems, and thereby help to mitigate climate change (Liang et al., 2016; Chen et al., 2018). Similarly, soil biodiversity increases nutrient cycling in intensively managed agricultural systems and thereby helps to mitigate the negative effects of nutrient pollution (Jiao, Lu and Wei, 2022). The loss of insect pollinators could lead to increased pressures on land use, as crop yields decline with pollination shortfalls (Aizen et al., 2019).

There are also significant interactions between **freshwater change** and other planetary boundaries due to the involvement of water in many Earth system processes. Blue water change influences the change in biosphere integrity and biogeochemical flows. The alteration of rivers (e.g. dams) and wetlands (e.g. reclamation) is a major cause of biodiversity loss in aquatic ecosystems (Tickner et al., 2020), with significant impacts on biogeochemical cycling (Maavara et al., 2020).

Changes in green water flows are also impacting several other planetary boundaries. Extreme precipitation events affect the boundaries on biogeochemical flows and novel entities, as nutrients and chemicals bound to soil particles are released into streams and the wider environment. At the same time, soil moisture determines biological productivity on land, and thus the size of the terrestrial carbon sink (Humphrey et al., 2018). Increasing soil moisture variability tends to reduce this carbon sink and could even turn land into a net carbon source in the second half of the century (Green et al., 2019).

The transgression of the planetary boundary for **biogeochemical flows** contributes to the reduction in biosphere integrity through the loss of genetic diversity. This is especially dramatic for freshwater bodies (Tickner et al., 2020), but N deposition also contributes to biodiversity loss in terrestrial ecosystems across the globe (Payne et al., 2017). Additionally, N fertilisation in agriculture is responsible for 52% of anthropogenic nitrous oxide emissions (Tian et al., 2020), thereby contributing significantly to climate change. At the same time, the net effect of reactive N on climate change is highly uncertain, as N stimulates carbon uptake in terrestrial and aquatic ecosystems and contributes to aerosol formation through ammonia and nitrogen oxide emissions, both leading to a cooling effect on the climate (Erisman et al., 2011; De Vries et al., 2024).

Agricultural **novel entities** mainly impact the planetary boundary for change in biosphere integrity. Environmental pollution is a major stressor in many ecosystems, surpassing climate change as a threat to biodiversity (Jaureguiberry et al., 2022). The toxicity of agricultural novel entities can have lethal or deleterious effects on a wide range of species, even altering ecosystem compositions due to species' differential sensitivity to toxicants (Sigmund et al., 2023).

Aerosols interact with climate and ecological systems in complex ways, influencing cloud formation, weather patterns and regional precipitation. They affect radiative forcing directly through light scattering, and indirectly through their impact on cloud formation, resulting in a net global cooling effect (Bellouin et al., 2020). More specifically, mineral dust aerosols are reflective (Kok et al., 2023), while aerosols from biomass burning absorb light and increase radiative forcing (Chakrabarty et al., 2023). Aerosols strongly influence cloud formation and can lead to shifts in large-scale precipitation patterns, thereby affecting the planetary boundaries for change in biosphere integrity and freshwater change. Their effect on precipitation at smaller scales is not yet fully understood (Stier et al., 2024). Finally, aerosols interact with the planetary boundary for biogeochemical flows through the deposition of nutrients like N or P (Mahowald et al., 2017).

2.4.2 Feedback loops and cascades

The interactions discussed above are summarised in Figure 6, which illustrates the high degree of interdependence between the land-based planetary boundaries. Some interactions are bidirectional, with amplifying feedback loops between planetary boundaries (Ripple et al., 2023). For example, deforestation leads to carbon emissions that amplify climate change, while disrupting the ability of forests to recycle moisture and cope with drought, causing further forest dieback (Lenton et al., 2023). Similarly, land-use change in drylands can induce a vicious cycle of increased aridity and land degradation (Ravi et al., 2010).

In addition to feedback loops, changes in one boundary can lead to cascading effects for other planetary boundaries. This applies to the external pressures on the land-based planetary boundaries, such as drought, and to the potential of land-based mitigation options for climate change.

For example, higher temperatures due to climate change alter precipitation patterns and increase evaporation from the land surface, leading to more frequent and severe periods of drought (Ault, 2020). Droughts lead to water stress through reductions in soil moisture, and pose a direct threat to biodiversity in terrestrial ecosystems (Pugnaire et al., 2019), while also potentially increasing the concentration of toxic chemicals in the soil to critical levels (Rillig et al., 2021). Furthermore, drought is a major driver of land-system change, with all three major forest biomes and drylands increasingly threatened by drought-related tipping dynamics (Lenton et al., 2023). Atmospheric aerosol loading is also increased by droughts through an increase in sand and dust storms (Middleton, Tozer and Tozer, 2019). Finally, droughts are the largest driver of land degradation (Prăvălie et al., 2021b) and can lead to social feedbacks, including increased land-use intensity and further land degradation (Olsson et al., 2019).

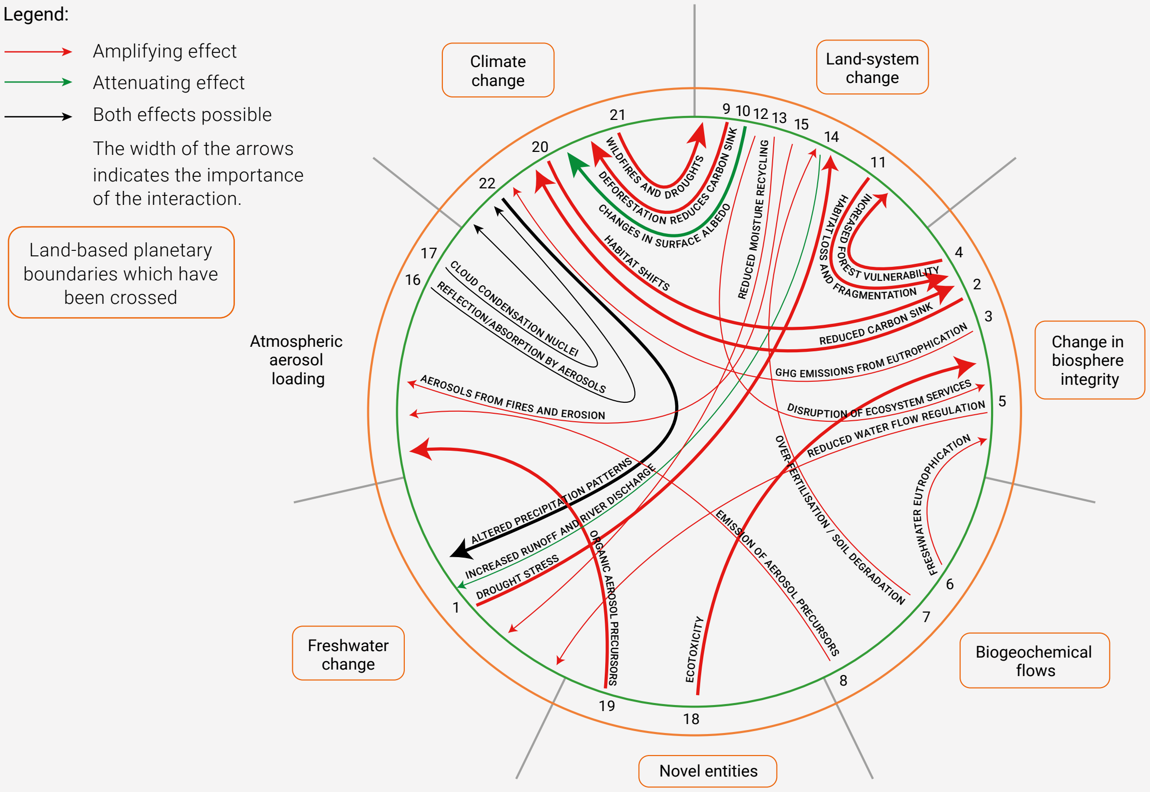
These interdependencies must also be considered in the implementation of measures to address the transgression of individual planetary boundaries. For example, approaches that focus on climate change mitigation in isolation may have negative impacts on other planetary boundaries. Most mitigation scenarios include large amounts of CO_2 removal through bioenergy crop production combined with carbon capture and storage (BECCS) (Popp et al., 2017). However, large-scale expansion of bioenergy could increase land competition, greenhouse gas emissions from land-use change, nutrient leaching and biodiversity loss (Smith et al., 2019). Therefore, context-specific implementation of BECCS is needed to ensure synergistic outcomes with other production and environmental objectives. Careful implementation of BECCS is also needed to avoid rising food prices and food insecurity (Hasegawa et al., 2020).

On the other hand, interactions between planetary boundaries can be used to achieve synergistic outcomes. Climate change mitigation can also be realised through a variety of nature-based solutions that simultaneously contribute to other international objectives, such as the Sustainable Development Goals (SDGs) or land degradation neutrality (LDN) (Roe et al., 2021). The most effective mitigation option is likely to be the protection and restoration of forests, wetlands and other ecosystems. There is also significant potential for carbon sequestration through soil carbon management in croplands and grasslands, and through agroforestry (Nabuurs et al., 2022). These efforts can be complemented by a sustainable

Figure 6

Interactions between the land-based planetary boundaries.

The figure shows the main processes by which impacts on one land-based planetary boundary are transmitted to other boundaries. The width of an arrow indicates the relative importance of the process, and the colour indicates the type of connection (amplifying, attenuating or both). Source: adapted from Caesar et al. (2024).



1 Reduction of soil moisture or green water flow can lead to desertification and land degradation.

2 Loss of biodiversity and ecosystem degradation can reduce the capacity for carbon uptake.

3 Increased productivity due to increased eutrophication can lead to increased greenhouse gas (Methane) emissions.

4 Degraded biosphere integrity can increase the vulnerability of forests to shocks or pests.

5 Loss of ecosystem functions reduces the ability to regulate the hydrological cycle, affecting water availability and quality.

6 Nutrient runoff from agricultural application into freshwater can lead to algal blooms, dead zones and loss of fish.

7 Excessive use of fertilisers can lead to farmland soil degradation.

8 Nitrogen compounds, particularly ammonia from agriculture, can contribute to aerosol formation.

9 Deforestation and land conversion can reduce CO_2 absorption of these systems, increasing atmospheric CO_2 concentrations.

10 Changes in land cover can alter the surface reflectivity (albedo). This affects the radiative forcing.

11 Land conversion can lead to habitat loss. Fragmentation of habitats can isolate populations, reducing genetic diversity.

12 Land-system change can disrupt ecosystem services such as pollination, water purification, and soil stabilisation.

13 Deforestation can impact the hydrological cycle by reducing evapotranspiration and subsequent drying of the atmosphere.

14 Land-system change can increase river discharge through reduced water retention.

15 Forest fires (associated with land clearing) and cleared agricultural land emit large amounts of aerosol.

16 Sulfate aerosols reflect sunlight, cooling the Earth's surface. Black carbon absorbs sunlight, warming the atmosphere.

17 Aerosols influence cloud formation, properties and lifetimes, affecting the energy balance, the hydrological cycle and climate dynamics.

18 Increased release of pesticides and industrial chemicals can harm organisms, reducing diversity and disrupting ecosystem services.

19 The release of volatile organic compounds and persistent organic pollutants can contribute to the formation of secondary aerosols.

20 Changing temperature and precipitation patterns affect habitat loss, species extinction, migration and introduction of invasive species.

21 Climate stress on forests (e.g. increased frequency of wildfires and droughts) can lead to deforestation and land degradation.

22 Precipitation patterns can change due to climate change.

intensification of agriculture, which improves input efficiencies and agricultural resilience and reduces emissions per unit of food produced (Campbell et al., 2014).

Vegetation and soil are the primary components of the land system, and both need to be considered when assessing the state of land and its role in mediating planetary boundary interactions (Gibbs and Salmon, 2015; Verburg et al., 2015). Vegetation is prominently represented in the planetary boundaries framework through the control variables for land-system change and functional biosphere integrity, while soil is only considered in the control variable for green water. Soils and soil-related factors play a pivotal role in interlinking the land-based planetary boundaries (Kopittke et al., 2021). Soils host about one quarter of global biodiversity (Bach and Wall, 2018) and the amount of carbon stored in soils exceeds the total carbon in above-ground biomass and the atmosphere (Scharlemann et al., 2014). At the same time, soils are increasingly under pressure through land use and intensified agricultural production (Smith et al., 2016) and are contributing substantially to the transgression of the planetary boundaries for land-system change, climate change, change in biosphere integrity and biogeochemical flows (Kopittke et al., 2021). The sustainable management of soils is therefore a key factor for staying within the safe limits of several planetary boundaries, leading to the proposal to include soil degradation as an additional component in the planetary boundaries framework (Kraamwinkel et al., 2021).

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CHAPTER 3

Socioeconomic dimensions of land degradation in a planetary boundaries context

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The previous chapter highlighted the critical importance of land within the context of planetary boundaries. Human activities, including unsustainable agricultural practices, deforestation, water overuse, urbanisation and other demographic and economic developments, are clearly driving land degradation (UNCCD, 2022; IPCC, 2019). At the same time, land is essential for human wellbeing, providing critical resources like food, water and raw materials (UNCCD, 2022b). Agriculture, forestry and urban development depend on land, shaping economic livelihoods, human health and social stability (IPCC, 2019). Due to degradation, rural communities, who are especially reliant on land, face reduced agricultural productivity and increased food insecurity (IPCC, 2023). These issues are worsened by insecure land tenure and social inequities, undermining efforts to scale up sustainable land management and ecosystem restoration.

The planetary boundaries framework, however, has been criticised for ignoring the human dimension. Without knowing the specific socioeconomic contexts in which environmental degradation occurs, solutions may be technically sound but often fail to be practical or equitable (Downing et al., 2019). For example, a spatial optimisation of food production may reduce land-system change, but it will not ensure equitable access to the benefits. The consideration of fairness and justice should complement biophysical assessments. By doing so, it may impose stricter boundaries than those based solely on safety concerns (Rockström et al., 2023).

Raworth's (2017) Doughnut Economics model links planetary boundaries to social foundations, aiming for human wellbeing within Earth's ecological limits. It incorporates the social objectives outlined by the SDGs, thereby linking the planetary boundaries framework to these internationally accepted goals (O'Neill et al., 2018). The main socioeconomic dimensions considered by Raworth's model include water, food, health, education, income and work, peace and justice, political voice, social equity, gender equality, housing, networks and energy.

In addition, the model delineates a space between two boundaries: the inner ring represents the social foundation, indicating basic needs such as food, water and energy, while the outer ring denotes the ecological ceiling beyond which environmental degradation occurs. The recent Lancet Planetary Health–Earth Commission report (Gupta et al., 2024) expands on this with the concept of a "safe and just corridor" – the space between the two rings – integrating safe Earth systems with human dignity. The corridor's ceiling represents the strictest safe and just boundaries necessary to avoid harm and maintain planetary stability, while the base sets the minimum access to essential resources required to lift people from poverty. Even within this space, however, justice is not guaranteed. Resource distribution can still be inequitable, worsening environmental and health challenges.

To better assess the key socioeconomic dimensions driving land degradation and the transgression of the land-based planetary boundaries, the model has been adapted (Figure 1). The main socioeconomic dimensions considered in this chapter include food security, human health, gender and social equity, water security, resilient communities, access to land and tenure security, fairness and justice. These dimensions will be discussed by exploring the link between land degradation and agriculture, examining how livelihoods contribute to and are affected by land degradation, with a focus on potential consequences for food security and human health. It also addresses social inequities, particularly those affecting women, youth, Indigenous peoples and local communities, as well as the connections between land degradation and water scarcity due to unsustainable water management. Additionally, land degradation is discussed as a driver of migration and conflict, leading to rural–urban migration and pressures on urban centres. The chapter concludes by analysing how poor land governance and corruption drive land degradation.

3.1 Agriculture, food security and human health

Agriculture and food systems are vital for global economic development and job creation, supporting billions worldwide (Willett et al., 2019; Davis et al., 2023). However, they also drive significant issues such as land degradation, deforestation and land-use change, exacerbating food insecurity, poverty and environmental degradation. These interconnected challenges threaten planetary boundaries and human health, especially as effects of climate change intensify (IPCC, 2022). The Paris Agreement underscores the multiple demands on agriculture to secure food supplies, alleviate hunger, promote climate resilience and reduce greenhouse gas emissions (Zurek et al., 2022).

Agriculture in a changing environment

Current agricultural practices pose risks to both human health and planetary boundaries due to the unsustainable treatment of soil, water and biodiversity in both developed and developing nations. They are major contributors to soil degradation, deforestation and biodiversity loss, which in turn drive land-use changes and exceed planetary boundaries (IPCC, 2022). Agriculture accounts for 80% of global deforestation and 70% of freshwater use. In lower-income countries, over 50% of agricultural emissions stem from forest conversion, compared to only 6% in higher-income nations (Sutton, Lotsch and Prasann, 2024). While the Green Revolution significantly improved crop yields and reduced the need for land conversion (Pingali, 2012; Stevenson et al., 2013), it did not place a strong emphasis on soil health or below-ground biodiversity, resulting in persistent environmental challenges related to soil degradation (Benton et al., 2021). Thus, comprehensive reforms across production, supply chains and consumption are urgently needed to address these wide-ranging issues.

The interconnectedness of agriculture and environmental degradation is most evident among vulnerable rural populations that rely on these land-use systems. In rural communities, 76% of workers living in extreme poverty and 60% of those in moderate poverty are employed in agriculture (Castañeda et al., 2018). Additionally, 85% of pastoralists and 75% of agro-pastoralists live below the extreme poverty line (De Haan et al., 2016). In West Africa, the food system accounts for 66% of employment, with nearly 80% of those jobs in agriculture (Allen, Heinrigs and Heo, 2018). Between 2000 and 2010, the number of rural poor living on degraded land increased in low-income regions, creating a vicious cycle where land degradation reduces productivity, forcing households to intensify land use and further degrade the land (Barbier and Hochard, 2018). On the other side, extensive agricultural land use and expansion, especially through deforestation and other human activities, has been identified as a major driver of environmental degradation (Winkler et al., 2021; AbdelRahman, 2023; Assede et al., 2023). Globally, net forest loss is estimated at 0.8 million km², alongside an expansion of cropland and pasture by 1.0 million km² and 0.9 million km², respectively (Winkler et al., 2021), as well as a significant decline in soil productivity (Eswaran, Lal and Reich, 2001; Assede et al., 2023).

Climate change adds further pressure

Climate change exacerbates agricultural challenges by increasing the frequency of extreme weather events – such as droughts, floods, pests, disease, wildfires and dust storms – that threaten food systems, human health and socioeconomic stability (IPCC, 2022). For example, dust storms can damage crops (Middleton, Tozer and Tozer, 2019) and wildfires increasingly threaten agricultural production in regions like California (Burke et al., 2021; Turco et al., 2023), severely impacting food production and local economies.

Conversely, agricultural activities, particularly livestock farming and rice production, significantly contribute to climate change, especially through the emission of methane and nitrogen oxides (Lynch et al., 2021; Qian et al., 2023). This interaction also complicates efforts to prevent the transgression of the planetary boundary for atmospheric aerosol loading (Richardson et al., 2023).

Looking to the future, the global population is projected to increase by 2 billion by 2050, and the corresponding demand for food will further strain environmental resources (Searchinger et al., 2019; Bodirsky et al., 2020; van Dijk et al., 2021). Without transformative changes in production methods and dietary patterns, land degradation, rising global temperatures and declining agricultural yields are likely to occur (IPCC, 2022; Ruggeri Laderchi et al., 2024). Continuous productivity growth will be needed to alleviate some of this dependency (Wang et al., 2020).

Implications for food security and human health

The relationship between land degradation and food security has direct and indirect consequences. Degraded soils produce less, lower-quality and less-nutritious food (Fanzo et al., 2018), as soil organic matter directly influences food micronutrient content (Joy et al., 2015; Fischer et al., 2020; Gashu et al., 2021; Kihara et al., 2024). Indirectly, land degradation can result in inefficient input use, additional land conversion and reduced income, all of which compromise food security. Land degradation can also lead to pollution and human health issues, reinforcing poverty and triggering conflicts and migration (FAO et al., 2017, 2023). Farmers may abandon their marginal or unproductive land (Gomiero, 2016), creating a negative feedback loop: declining yields increase reliance on inputs and further land conversion, compounding environmental and health challenges.

The impacts of land degradation on human health extend beyond food security. It can impair mental wellbeing, particularly among Indigenous peoples and local communities (IPBES, 2019), and heighten disease transmission risks (IPBES, 2018b). Soil contamination, often from anthropogenic sources, poses direct health risks through contact, and indirect risks via contaminated food and water (Sena, 2019; Nawab et al., 2021); heavy metals, commonly found in contaminated soils, can have serious health implications (Nawab et al., 2021). Studies in Pakistan have revealed cadmium levels that exceed safe thresholds, while research in Turkey highlighted substantial contamination from chemical fertilisers, indicating an urgent need for monitoring (Durdu et al., 2023).

Desertification, land degradation and food security in drylands

Drylands are especially vulnerable to drought, water scarcity and soil erosion, complicating land management and restoration efforts (Jiang et al., 2020). Drylands cover nearly 46% of the world’s land area, with Africa holding the largest share at approximately 75% (Prăvălie, 2016). Notably, more than one third


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of the global population resides in these regions (Chimwamurombe and Mataranyika, 2021) and their share is projected to increase (Heinke et al., 2019). Although essential for agricultural production, drylands – especially in Africa and Asia – face increasing stress from desertification, drought and land degradation, and this is projected to worsen as the global percentage of drylands grows (Prăvălie, 2016; Prăvălie et al., 2019; Chimwamurombe and Mataranyika, 2021), leading to water insecurity, reduced agricultural productivity, increased food insecurity and heightened vulnerability for people living in drylands (IPCC, 2019).

Agriculture plays a crucial role in ensuring food security in drylands, balancing environmental stewardship and reaping the economic benefits from meeting the ever growing demand for food and other land-based commodities (IPCC, 2019; Chimwamurombe and Mataranyika, 2021). Unsustainable use and management practices, like overgrazing and deforestation, are reducing soil fertility and biodiversity. In Zimbabwe's semi-arid regions, about 26.5% of land is degraded due to low soil organic carbon levels (Chisadza, Gwate and Musinguzi, 2024), and further degradation is anticipated as forests are cleared for agriculture and settlements. Similarly, agricultural expansion in Brazil's Caatinga region is reducing ecosystem services, worsening poverty and leading to land abandonment (Araujo et al., 2021). In northern China, restoration efforts have mitigated soil erosion but challenges from drought and vegetation loss highlight the need for tailored restoration strategies (Jiang et al., 2020). Human activities like mining and urbanisation exacerbate dryland degradation, resulting in reduced vegetation, fragmented habitats and diminished ecosystem services (Shen et al., 2021; Wang et al., 2023). Urgent action is required in the form of sustainable agricultural practices, ecosystem restoration initiatives, and financial support to protect natural ecosystems and the livelihoods they sustain (Araujo et al., 2021; Chisadza, Gwate and Musinguzi, 2024).

Food security, human health and the land-based planetary boundaries

Land degradation compromises yields resulting in more chemical inputs and increased inefficiencies, pushing farmers to seek new land (Lal, 2009; Gomiero, 2016) and moving the planet closer to the boundaries for land-system change, novel entities and biogeochemical processes. The expansion of agriculture and deforestation contributes to biodiversity loss (IPCC, 2019), diminishing ecosystem services and adversely affecting human wellbeing (IPBES, 2018b), as well as other planetary boundaries through disruptions to carbon storage and nitrogen cycles (Rockström et al., 2009).

The growing demand for food intensifies pressure to convert land for agriculture, despite the limited opportunities for cropland expansion (Verburg et al., 2013; IPBES, 2019). Caution is necessary when assessing land conversion potential, as studies often overlook the fact that forest land may be more accessible than degraded land, especially in poorly governed areas (Verburg et al., 2013), and converting more land for agricultural purposes risks substantial losses to natural ecosystems, diminishing vital ecological functions like carbon storage and biodiversity (Rockström et al., 2009).

Climate change amplifies multiple pressures on land, impacting livelihoods, biodiversity and human health (IPCC, 2019) through yield reduction, habitat destruction and food crop nutrient depletion. Conversely, maintaining high-quality soils is essential for stabilising crop yields amid increasing climate variability (Qiao et al., 2022). Six interconnected socioeconomic and health consequences have been identified in relation to climate-change-induced land degradation: (1) food and nutritional insecurity, (2) communicable and noncommunicable diseases, (3) livelihood insecurity, (4) physical and mental health, (5) health hazards related to extreme weather events, and (6) migration and conflict (Talukder et al., 2021). Understanding the links between food security, human health and land degradation within the framework of planetary boundaries can help establish sustainable development priorities.

3.2 Gender and social inequities

Demographic characteristics such as gender, age, education and ethnicity shape individual experiences of land degradation, with vulnerable groups particularly impacted by the transgression of land-based planetary boundaries (Twyman, Acosta and Irigoyen, 2022). Ecosystem services, integral to biosphere integrity, hold varied meanings and importance across different social groups shaped by wealth, education and gender (Yang et al., 2018; Fortnam et al., 2019; Pearson, McNamara and Nunn, 2019). Social and economic inequalities can increase both individual and collective vulnerability to the loss of ecosystems by heightening resource dependence or reducing adaptive capacity (Fisher et al., 2014; Berrouet, Machado and Villegas-Palacio, 2018; Laterra et al., 2019).

Climate change further exacerbates existing inequalities. Land surface temperatures contribute to thermal discomfort over large areas, but exposure is often differentiated by wealth. For example, low-income residents in a Dutch study were often overexposed to heat stress due to the suburbanisation of poverty, whereas those in wealthier districts experience less exposure, likely due to the presence of water bodies and green spaces (Mashhoodi, 2021). Locally, immigrants, young adults and women are more affected by heat, reflecting urbanisation trends and labour market dynamics.

Gender and land degradation

The UNCCD's LDN framework illustrates that men and women are affected differently by land degradation due to unequal access to resources and services (Orr et al., 2017; UNCCD, 2022a). A study on three coastal communities in Papua New Guinea, for example, showed that men and women ascribed different levels of importance to various ecosystem services, with men emphasising education and knowledge services, and women highlighting fuelwood and forest materials (Lau et al., 2019). In the Six Nations of the Grand River – the largest First Nations reserve in Canada – women report greater barriers to accessing water due to their caretaking roles. They also express dissatisfaction with water quality, giving rise to further challenges in caregiving as well as health issues, particularly postpartum (Duignan, Moffat and Martin-Hill, 2022). Ecosystem service assessments often overlook gender differences, with women's contributions undervalued at both household and institutional levels, which can serve to perpetuate gender inequities (Kleiber, Harris and Vincent, 2014; UNCCD and FAO, 2024).

Experiences of children and youth

Children and youth, comprising half the world's population, are disproportionately impacted by land degradation and related phenomena (UNCCD, 2024). Younger individuals report practical challenges related to water contamination and inadequate infrastructure, often


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normalising the use of bottled water despite associated costs and logistical difficulties (Duignan, Moffat and Martin-Hill, 2022). Other studies link deforestation to higher infant mortality (Chakrabarti, 2021), increased malaria rates among children (Estifanos et al., 2024), reduced nutritional diversity (Galway, Acharya and Jones, 2018) and adverse health effects from heat exposure (Masuda et al., 2020). They also encounter educational setbacks because of displacement resulting from desertification and land degradation (OCHA, 2022).

Younger populations also tend to suffer more from extreme environmental conditions resulting from climate change (Thiery et al., 2021). This is complicated by the tendency of younger adults to migrate to cities, while individuals aged 65 and older tend to remain in rural areas with less heat exposure (Mashhoodi, 2021). A review of 153 studies indicates that air pollution exacerbates respiratory issues during hot weather, disproportionately impacting children and the elderly, leading to increased hospital visits and mortality rates (Grigorieva and Lukyanets, 2021).

Impacts on Indigenous people and local communities

Indigenous peoples and local communities are significantly affected by climate change and ecosystem degradation, which threatens their cultural heritage as well as livelihoods (IPBES, 2019). The transgression of the land-system change boundary is especially detrimental for groups that rely on forest resources. For example, Indigenous Khyang women in the Chittagong Hill Tracts of Bangladesh need to travel ever greater distances to collect essential items, such as firewood, wild fruits and fodder, due to the decline of forests or restricted access to expanding reserve areas. This increased workload is linked to health problems, such as headaches and fever, and can even result in legal problems, affecting their livelihoods and privacy (Dhali, 2008). Additionally, Indigenous households in Canada are 90 times more likely to lack running water than non-Indigenous households (Duignan, Moffat and Martin-Hill, 2022).

Future directions for addressing social inequities

Despite their crucial role as environmental stewards, and their heightened vulnerability, marginalised groups are often excluded from sustainable land management efforts (Mor, 2018). These groups often possess unique knowledge and can significantly contribute to combating land degradation and climate change, as exemplified by the Great Green Wall initiative. The IPBES Global Assessment report (2019) also emphasises the knowledge and contributions of Indigenous peoples and local communities in the protection and stewardship of ecosystems.

Including vulnerable groups in decision-making processes can also enhance their livelihoods and bargaining power (Löw, 2020). It is crucial to address discriminatory and exclusionary practices across all spheres to ensure equitable representation for women and marginalised groups in decision-making. Supportive environments are necessary to safeguard rights, strengthen leadership capacities, and ensure that marginalised groups can benefit from, rather than only bear the costs of, environmental change (Elias et al., 2021). Innovative research highlights the complex interconnections between gender, environment and climate, advocating for context-sensitive analyses of empowerment and equality. Addressing inequalities through an intersectional gender lens is essential for sustainable development (Mor, 2018; IPBES, 2019; Löw, 2020).

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3.3 Water resources under pressure

Water resources are vital for humans to ensure sufficient drinking water, basic hygiene, sanitation and food production. The transgression of the planetary boundary for freshwater change can negatively impact these functions and exacerbate food insecurity, poverty, gender inequality and conflict (UN, 2023; Gleeson et al., 2020; Gupta et al., 2024).

Global freshwater change has been recognised as a separate planetary boundary due to its central role in maintaining Earth system stability (Rockström et al., 2009; Gerten et al., 2013; Steffen et al., 2015; Gleeson et al., 2020). Recent studies show that this boundary is currently in the high-risk zone due to ongoing over-abstraction, continuing water pollution and severe modifications to hydrological flows (Richardson et al., 2023). In addition, land degradation decreases the water retention capacity of soil, reducing the water available for vegetation, agriculture and human consumption. This is especially dangerous in regions already vulnerable to drought (Sivakumar, Ndiang'ui, and Tansania, 2007). Land degradation is therefore tightly linked to healthy water resources, and a safe and sustainable water supply is crucial for preserving and restoring soils and land (Reichhuber et al., 2019) and guaranteeing human health and wellbeing.

Drought and water scarcity in the context of land degradation

Land degradation hotspots primarily stem from intensive agricultural production and high irrigation demands, particularly in dry regions such as South Asia, northern China, the US High Plains, California and the Mediterranean (McDermid et al., 2023). Extensive irrigation not only affects local water availability but also disrupts large-scale precipitation and moisture patterns. The shift to non-native crop species alters land surface characteristics, including surface roughness and evaporation rates, leading to increased moisture removal and further reducing local water availability.

Agriculture currently accounts for 70% of the world's freshwater use (Alexandratos and Bruinsma, 2012; Fujs and Kashiwase, 2023), with population growth and current dietary patterns intensifying the demand for water and land resources (Willett et al., 2019). The unsustainable pressure on these resources compromises agricultural production and threatens livelihoods. Drylands, in particular, are more susceptible to droughts due to their limited water storage capacity, resulting in heightened demand during critical periods (Reichhuber et al., 2019; Jiang et al., 2020; Chimwamurombe and Mataranyika, 2021). Land degradation exacerbates these issues by disrupting natural water cycles, increasing runoff and soil erosion, and further diminishing water quality and availability. A recent study shows that drylands self-propagate (Koppa et al., 2024): once they are formed, they contribute to their own expansion and their extended aridification. This in turn causes intensified water scarcity and biodiversity loss. The health of water resources is thus closely linked to land degradation, making a sustainable water supply essential for soil and land restoration (Reichhuber et al., 2019).

Human activities, especially as they contribute to climate change, have led to a rise in both the frequency and severity of droughts, significantly impacting human adaptive capacity, ecosystem resilience and agricultural production (Reichhuber et al., 2023). Particularly in mountain regions, water availability during droughts is further compromised by shrinking glaciers and reduced snowmelt due to climate-induced temperature increases (Immerzeel et al., 2020). However, water scarcity is not only the result of physical water availability. It is also a consequence of unequal water allocation, restricted access to water and poor water quality, which is often determined by economic, governmental and institutional factors (Drenkhan et al., 2022). The risk of being affected by water scarcity, therefore, often depends on socioeconomic factors, with lower-income countries being at a higher risk of experiencing water scarcity. This differential vulnerability calls for a better integration of coupled human–natural systems, where socioeconomic vulnerabilities, as well as the natural causes and impacts of water scarcity, are equally addressed (Grey and Sadoff, 2007). One way forward is improved and equitable water governance across multiple scales.

sustainable local water systems, harmonising fair share approaches with a local safe operating space. The European Water Framework Directive (WFD) targets local water resources, for example, but lacks specific boundaries. Downscaled planetary boundaries could complement such policies to ensure ecological balance at both local and global levels (Zipper et al., 2020).

Water, climate and land use in northern Pakistan

The region of northern Pakistan is especially impacted by climate change, and is a hotspot of freshwater boundary transgressions. Research has shown that climate change could substantially reduce agricultural productivity through increasing water demand, yet the main threat to crop yields is increasing heat stress (Becker et al., 2023); even if there was enough water available for irrigation, yield losses would continue. Temperature-related adaptation strategies – such as the selection of more heat-resistant crop varieties or a redesign of agro-ecological zones – should therefore complement water-related adaptation strategies. This, however, might put additional pressure on land resources and further increase the demand for water. Water scarcity problems in this region can therefore only be solved if water, climate and land use are simultaneously considered.

Integrating water governance across scales

Environmental impacts, like water scarcity, often extend beyond the borders of the country where the activity occurs. For instance, over 80% of Germany's blue water consumption is imported, primarily in the form of textiles and agriculture, from countries like India, Pakistan and Egypt (Bunsen et al., 2021). Germany therefore contributes to water scarcity in the Ganges, Indus and Nile River basins, underscoring the need for a global perspective on water insecurity and drought risks.

The challenge is to integrate global sustainability thresholds with local water management and governance. A possible pathway could be to define boundaries for

The redefinition of the planetary boundary for freshwater, which now includes green water (soil and plant moisture), offers a promising guide for sustainable land management (Gleeson et al., 2020; Wang-Erlandsson et al., 2022). This expanded boundary, focusing on soil moisture and its deviation from a Holocene-like state, helps identify local hotspots for land degradation and inform policies for land protection and restoration. It emphasises maintaining healthy vegetation to combat land degradation, with a global framework that supports local efforts in soil conservation, reforestation and watershed management (Wang-Erlandsson et al., 2022).


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3.4 Urbanisation, migration and conflict

Urbanisation, migration and conflict are interconnected challenges that severely affect the land-based planetary boundaries. The rapid expansion of urban areas leads to significant land and forest degradation, intensifying conflicts over access to resources among rural communities (Wassie, 2020). This environmental strain can drive both voluntary and forced migration as communities seek better living conditions and greater security. At the same time, land degradation heightens competition for scarce resources in peri-urban and rural areas, complicating migration dynamics.

Impact of urbanisation on communities and the environment

In 2022, 57% of the global population resided in urban areas (UNCTAD, 2023), with urbanisation rates increasing significantly in African and Asian countries (UN-Habitat, 2022). While urbanisation offers significant benefits, such as increased efficiency, convenience and social integration, uncontrolled or unplanned urbanisation has severe negative impacts on communities (Mahendra et al., 2021). Urban sprawl, overcrowded living conditions, inadequate infrastructure and environmental degradation are some of the consequences of unsustainable urban development (Tafazzoli, Nochian and Karji, 2019).

Rapid urbanisation in Ethiopia has led to the intensive extraction of natural resources, like fuelwood, sand, gravel and water, resulting in accelerated resource degradation and an expanded ecological footprint (Wassie, 2020). In the Brazilian city of João Pessoa, urban sprawl has triggered conflicts over land use, inadequate urban sanitation infrastructure and limited environmental monitoring (de Sousa et al., 2023), resulting in increased land surface temperatures, soil degradation, improper waste disposal, vegetation loss, water pollution and erosive processes. Coastal areas in Romania, Algeria and Vietnam experience land degradation due to urbanisation and tourism pressures, worsened by inadequate national planning and climate impacts. In Italy, urban expansion over the past five decades has heightened vulnerabilities to degradation, transforming peri-urban areas and encroaching upon high-quality productive soils. These examples illustrate how urbanisation particularly affects the planetary boundaries for land-system change, climate change, change in biosphere integrity, freshwater change and atmospheric aerosol loading.

There are several promising initiatives aimed at enhancing urban sustainability, such as Rwanda's Green City Kigali project[4] and efforts in Depok City, Indonesia (Hakim and Endangsih, 2020), as well as the SDG Cities Global Initiative which works to achieve the targets under SDG 11 (sustainable cities and communities) (UN-Habitat, 2023). There are also increased scientific efforts to evaluate cities' progress toward becoming smart, green and sustainable (Bashirpour Bonab, Bellini and Rudko, 2023). These efforts are complemented by frameworks that rank cities based on their sustainability and environmental results, including the Green City Index, the Sustainable Cities Index and the European Green Capital Award (Sáez, Heras-Saizarbitoria and Rodríguez-Núñez, 2020). While these rankings are designed to promote urban sustainability, they often overlook critical interdependencies or lack transparency in their methodologies.

Implications for human mobility

Migration plays a critical role in the dynamics of land-based planetary boundaries, influencing the pressures on land resources and communities' adaptive responses. Land degradation heightens socioeconomic risks, particularly in arid and semi-arid regions (Hermans et al., 2023). For instance, degradation of agricultural land threatens livelihoods and food security, which may ultimately lead to migration (Hermans and McLeman, 2021; Hermans et al., 2023; López-Carr et al., 2023). In addition, non-environmental factors – such as land tenure, family structure, education, income levels and conflict – play a crucial role in shaping how communities adapt to environmental challenges, and whether they choose to migrate (Hermans and McLeman, 2021). In Ethiopia, for example, a lack of institutional support for soil and water conservation measures, and the failure of local government to provide the necessary resources, increases migration pressure (Groth et al., 2021). Alongside socioeconomic factors such as tenure insecurity and population growth, land degradation and deforestation in Burkina Faso correlate with decreasing agricultural profitability (Sanfo et al., 2017), constituting a major driver of rural out-migration.

Migration driven by climate change often involves more immediate and acute factors. For example, climate-related factors in Namibia drive migration from rural to peri-urban settlements in the central regions. Push factors, such as climate-related disasters and declining agricultural productivity, combined with pull factors like higher wages and improved services, significantly influence migration patterns (Thornton, Serraglio and Thornton, 2023). In Morocco, changes in precipitation and temperature, along with drought and desertification, have prompted significant internal migration as well as emigration to Europe (Van Praag, 2021). In Uganda, climate anomalies are more significant than land degradation, constituting the primary drivers of environmental migration (Call and Gray, 2020). While short-term climate pressures – especially heat stress – encourage temporary migration as part of diversified livelihood strategies, prolonged heat stress often triggers permanent migration.

This highlights the need to differentiate between environmental stressors and communities' adaptive responses to them. Generally, migration flows reflect adaptation to changing environmental conditions and the pursuit of improved opportunities (Van Praag, 2021). However, while migration can mitigate some climate risks, it may exacerbate others. Urban migrants, for example, are particularly vulnerable to heat stress as they are prone to living in poverty and overcrowded conditions, and engaging in manual labour. Additionally, migrants often struggle to secure permanent land access, relying instead on the temporary goodwill of host communities. This ultimately hinders long-term investments in land improvement, such as tree planting (Antwi-Agyei, Dougill and Stringer, 2015; Etongo et al., 2015).

Interdependencies between land degradation and conflict

Land degradation and conflict are closely intertwined, creating a vicious cycle that exacerbates environmental and socio-political instability. Armed conflicts significantly impact land-use and land cover changes, leading to severe and long-lasting environmental consequences (Beygi Heidarlou et al., 2020). In Nigeria, desertification-induced migration in ungoverned spaces affects farmer–herder conflicts, endangering livelihoods and human security (Lenshie et al., 2021). Effective governance in this region could help mitigate conflicts and promote


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human security. Globally, armed conflicts in border areas often result in significant land-use and land cover changes, with forest loss during and after conflicts (Zheng, Xiao and Feng, 2023). In Bosnia and Herzegovina, for example, extensive land degradation – largely a consequence of the 1990s civil war – is complicated by intricate institutional frameworks that hinder effective land management, and contribute to ongoing challenges in political stability (Kapović Solomun et al., 2021). Effective political communication and cooperation are therefore crucial for managing land in post-conflict societies.

Considering urbanisation, migration and conflict in sustainable land management

The relationship between land-based planetary boundaries, conflict and migration is multifaceted: transgressing the land-based planetary boundaries can contribute to conflicts over resources, which in turn can drive migration. Although there has been significant progress in understanding the relationship between climate change and drought-driven migration, the effects of land degradation and desertification on human mobility remain insufficiently studied (Hermans and McLeman, 2021; Hermans et al., 2023). The connections between land degradation and migration are not well defined, and few research efforts have directly examined these relationships, even as the significance of environmental migration continues to rise (Hermans et al., 2023). Alternative approaches, such as addressing food insecurity as a possible driver of migration, may offer important insights into these connections (Hermans and McLeman, 2021). Addressing the environmental challenges of urbanisation furthermore requires the integration of sustainable urban planning, migration management and conflict resolution strategies (Coluzzi et al., 2022). Long-term planning is also essential to maintaining a good quality of life in urban areas (Petrişor et al., 2020). Understanding the socioeconomic and environmental dynamics shaping these interactions is crucial for developing effective, context-specific policies that promote resilience and sustainable development.

3.5 Land tenure and governance constraints

Land is a limited resource, but essential to economic activities. Secure access to land is therefore crucial for people and communities around the world. However, land availability is increasingly limited by factors like population growth, changing consumption habits, telecoupling effects (e.g. globalisation of trade), agricultural intensification and climate change. Responsible and inclusive land governance is therefore vital to managing competing interests, and promoting equity and development. Secure land tenure does not automatically ensure equal access to land and the improved functioning of land markets, and special consideration needs to be given to marginalised groups.

Tenure insecurity and unequal access to land

Various multilateral agreements acknowledge the need for good land governance, and especially secure land tenure (UNCCD, 2022; Verburg et al., 2019). While individual private ownership is common in higher-income countries, lower- and middle-income countries tend to have diverse and often overlapping land tenure systems. A survey conducted from 2018 to 2020, covering 140 countries and around 1,000 households per country, revealed that many households lack documentation for their land rights (Prindex, 2020). Extrapolating from this survey, almost 1 billion people are estimated to feel tenure insecure, which means that they fear losing their home or land. The highest rates of tenure insecurity are observed in the Middle East and North Africa (28%), followed by sub-Saharan Africa (26%), while South and East Asia are particularly affected in absolute terms (Prindex, 2020). High rates of tenure insecurity often coincide with low land documentation levels. These vulnerabilities are particularly severe in countries with high poverty rates, and where the agricultural sector contributes significantly to the national economy.

In addition to insecure land tenure, land governance challenges include an increasingly unequal distribution of land in most countries (Anseeuw and Baldinelli, 2022), conflicts arising from land-use and ownership disputes (Deininger and Castagnini, 2006), and large-scale land acquisitions (LSLAs or "land grabs") for the production of food, fodder, fibre and fuel, as well as ecosystem services (Borras et al., 2011). Land grabbing can be defined as "a transfer of the right to own or use the land from local communities to foreign investors through large-scale land acquisitions" (Rulli et al., 2013). It is difficult to quantify the occurrence of land conflicts, as many disputes go unreported and typically do not feature in global conflict databases such as ACLED (Armed Conflict Location and Event Data) or UCDP (Uppsala Conflict Data Program) unless they turn violent. However, it is estimated that small-scale disputes – over land boundaries for instance – are common around the world (Mattsson and Mobarak, 2024). Land investments, some of which qualify as land grabs, accumulated to an estimated 30 million hectares globally by 2020, according to the Global Land Matrix Initiative (Lay et al., 2021; FAO, 2024a). Insecure land rights, land conflicts and external investments in land often occur together or influence each other, making land governance especially complex and urgent.

Land governance and the land-based planetary boundaries

Land tenure and governance are linked to many of the land-based planetary boundaries. Some of these links are well studied, while others warrant more attention. Land tenure insecurity, the lack of formal land rights and LSLAs are important drivers of deforestation and land conversion, directly influencing the land-system change planetary boundary (UNCCD, 2022; Verburg et al., 2019). In particular, protected areas and those with secure land tenure are associated with less deforestation, regardless of the form of tenure (Robinson, Holland and Naughton-Treves, 2014). These dynamics can lead to land governance issues that affect the climate change boundary. Land governance challenges can also increase greenhouse gas emissions, mainly through land conversion and deforestation, driving the transgression of the planetary boundaries for land-system change, climate change and change in biosphere integrity.

Land rights are generally acknowledged to influence investments in land and their management practices, although attempts to quantify this effect


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have been methodologically challenging. Few studies have considered the socioeconomic impacts of weak land governance or insecure land tenure, analysing instead how strengthening land tenure can impact investment in environmental protection and agricultural production (Tseng et al., 2021). One such investment is the application of fertiliser, which can be influenced by secure land tenure under certain conditions (Fenske, 2011; Gao, Sun and Huang, 2017). This represents a direct link between land tenure and the planetary boundary for biogeochemical flows, measured by P and N application rates. Most investments related to strengthening land tenure influence the planetary boundaries for climate change and land-system change, for example through increases in tree planting and environmental conservation due to tenure security (Tseng et al., 2021). Links to the boundaries for change in biosphere integrity and freshwater change are also likely, but have so far received less scientific attention. A prime example of the link between land governance and biosphere integrity is Natura 2000 – a coordinated network of protected areas across the EU, aimed at ensuring the long-term survival of Europe's most valuable and threatened species and habitats (Maiorano et al., 2007).


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There are many indirect links between land governance, especially tenure security, and the land-based planetary boundaries. For example, insecure land rights – especially informal or non-documented land rights – are associated with limited access to credit, markets and extension services. Insecure land rights can also influence migration, although the direction of the effect is context-dependent: empirical studies have found both increases and decreases in rural out-migration as a consequence of insecure land tenure (De Janvry et al., 2015; Ma et al., 2017). All of these impacts can further influence the land-based planetary boundaries, for example through increased pressure on forest or grazing areas, or lower investments in preserving critical land functions.

Tenure security and weather risk in Tanzania

Research in central Tanzania has found that farming households experience higher levels of perceived tenure insecurity and a higher number of land conflicts when exposed to greater weather risk, such as dry spells and precipitation variability (Murken et al., 2024). Conflicts can occur between different actors, such as farming households and pastoralists seeking grazing for their cattle, as well as between farming households and their neighbours – or even within farming households. The nature of the conflict appears to have an impact on households' decisions with regard to formalising their land rights: households that experience weather-driven conflicts with neighbours, private companies or other family members are more likely to acquire formal land certificates, while those that primarily experience disputes with pastoralists do not. A possible explanation is that formal land certificates only hold value in certain settings; while companies, neighbours and family members may honour them, they might not have any meaning for pastoralists who do not contest land boundaries or ownership, but rather seek to use the land temporarily. Overall, this example shows how deeply interconnected land governance and the environment are, with significant implications for the planetary boundaries.

3.6 Corruption and misaligned subsidies

Land degradation is not only influenced by land governance, but also by agricultural policies and institutional arrangements, including corruption. There is no universally accepted definition of corruption, with the UN Convention on Corruption instead recognising the sovereignty of its parties to define it in their respective legislations (Tacconi and Williams, 2020), but Transparency International (2017) defines land corruption as "the abuse of entrusted power for private gain, while carrying out the functions of land administration and land management". Globally, one in every five people had to pay a bribe for land services in 2019, while in sub-Saharan Africa, it was one in every two (Chibamba et al., 2019). Land corruption often results in environmental degradation, social inequality and economic instability, threatening both the planetary boundaries and the achievement of the SDGs.

Land corruption undermines good governance

Land corruption can take many forms, ranging from petty to systemic corruption. An example of petty corruption might be a local forestry officer accepting small bribes from loggers to overlook illegal logging activities. Systemic corruption, on the other hand, could include the manipulation of forest conservation policies to favour large-scale commercial logging operations. Land corruption can also take on different discriminatory layers, including against women, ethnic minorities and other marginalised groups. In Zimbabwe, for example, men were more likely to use financial bribery to gain access to land, while women, who often lack the financial means, would have to resort to offering sexual favours (Mujeyi, 2021). Hence, not only is land access often based on corruption, but it is also highly gendered and can increase sexual exploitation.

Regional examples of land corruption

Several regional studies shed light on the enablers and impacts of land corruption. One study using time series data in Pakistan confirmed a long-term relationship between corruption, income inequality and environmental degradation (Ullah and Ali, 2024). It reveals that corruption worsens the environmental damage associated with unequal income distribution. Several studies have found that higher (perceived) rates of corruption are related to higher rates of deforestation (Cozma et al., 2021; Moreira-Dantas and Söder, 2022). A study of the Río del Carmen watershed in Mexico found that weak water governance, including the prevalence of corruption, has led not only to the overexploitation of water, grassland loss and social conflicts, but also to changes in the behaviour of farmers, who have institutionalised corruption as a strategy to access water (Lopez Porras, Stringer and Quinn, 2019). In Mbarara Municipality in Western Uganda, corrupt actors – including unauthorised garbage truck drivers, public servants and politicians – conspired in the illegal sale of garbage (Gumisiriza and Kugonza, 2020). This multifaceted case of systemic corruption was enabled by poor financing and planning, limited law enforcement and lack of community participation.

Misaligned policies exacerbate land degradation

Although policies have the potential to simultaneously reduce land degradation, biodiversity loss, greenhouse gas emissions and socioeconomic challenges when applied in an integrated manner (IPCC, 2019), many current strategies remain fragmented. These policies often focus narrowly on specific factors, without accounting for the complex environmental, social and economic forces that drive land degradation (IPBES, 2018b; Verburg et al., 2019; UNCCD, 2022b), resulting in siloed and often ineffective solutions (IPBES, 2018b; UNCCD, 2022b). Furthermore, policies are often misaligned across sectors and policy domains, further limiting their impact.

For example, promoting afforestation without considering the complexity of ecosystems can inadvertently accelerate land degradation rather than support restoration (Veldman et al., 2015; Parr, te Beest and Stevens, 2024). Similarly, advancing land restoration efforts without addressing the actions of


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key value chain stakeholders or the growing influence of private actors – along with potential misaligned incentives to investors – can undermine restoration goals. Addressing the problem effectively requires a coordinated, multi-scale policy response that prioritises context-specific solutions instead of a universal approach (Stechemesser et al., 2024). However, the highly localised nature of land degradation makes it difficult to understand how well these policies work (IPCC, 2019), highlighting the need for better alignment and integration of policy tools across different levels and sectors (Verburg et al., 2019).

Agricultural subsidies can have unintended consequences

Agricultural policies and programmes, especially subsidies, can also generate misaligned incentives. Most countries have agricultural policies to support farmers, recognising the importance of food security. But many of these policies can have negative environmental effects, including land degradation, if not coupled with biodiversity, social and environmental protection measures (Lankoski and Thiem, 2020). Subsidies for inputs, such as fertiliser and seeds, are prevalent in many Asian and African countries (Holden, 2018). Other types of agricultural subsidies, such as price incentives for producing specific crops or livestock, or production-based subsidies based on crop yields, are common across the globe. Between 2013 and 2018, an estimated USD 540 billion per year was spent on agricultural subsidies across 88 countries for which data was available, but 87% of this support went to inefficient and inequitable agricultural practices that harmed the environment (FAO, UNDP and UNEP, 2021). The UNCCD Science–Policy Interface Report (Verburg et al., 2019) confirms that agricultural subsidies, as structured by the EU's Common Agricultural Policy, can incentivise unsustainable practices that lead to land degradation. The Dasgupta Review on the Economics of Biodiversity estimates that subsidies cause damage to nature worth USD 4 to USD 6 trillion per year (Dasgupta, 2021).

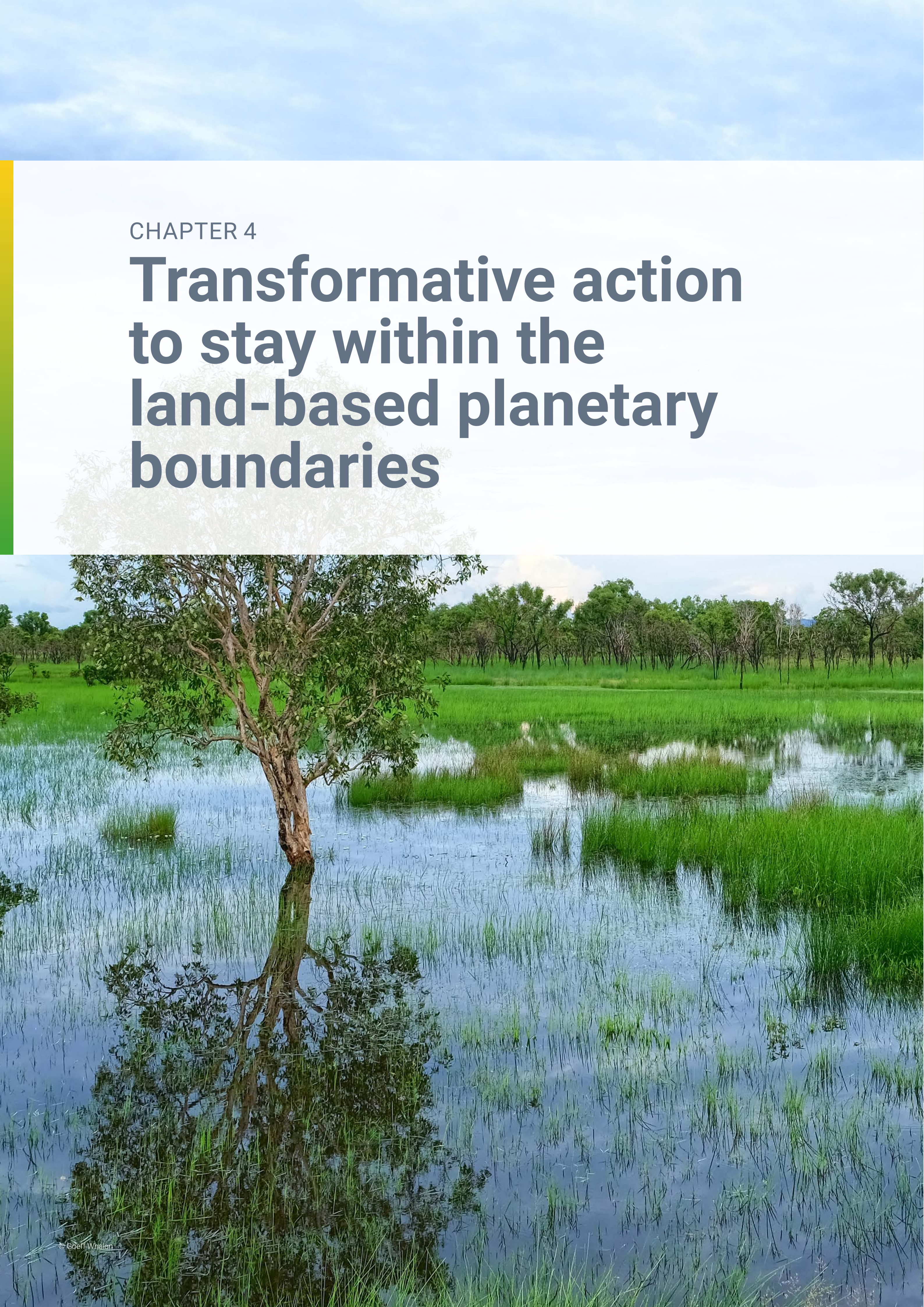
Land corruption, misaligned subsidies and the land-based planetary boundaries

Land corruption is closely linked to land-based environmental crimes: the former enables the latter by allowing activities to go unchecked, while environmental crimes generate profits that fuel further corruption (IPBES, 2018b). This interdependence creates a cycle of exploitation and degradation. Whether on a small or large scale, land corruption undermines good land governance, depletes natural resources and disproportionately affects vulnerable communities who rely on these resources for their livelihoods (IPCC, 2019). In this way, land corruption (indirectly) influences several planetary boundaries, especially the boundaries for land-system change, climate change and freshwater change.

Agricultural subsidies affect the land-based planetary boundaries in various ways. Subsidies for inputs shape agricultural management practices and land-use decision-making, thus influencing the boundaries for land-system change, climate change, freshwater change and biogeochemical flows (IPBES, 2018b; Verburg et al., 2019; Theriault and Smale, 2021). For instance, (inorganic) fertiliser subsidies affect the use of P and N fertiliser (Scholz and Geissler, 2018), which can be harmful in intensively farmed systems with already-high input levels (Gazzani, 2021). This negatively affects soil acidity levels and can pollute water resources through leaching and runoff.

CHAPTER 4

Transformative action to stay within the land-based planetary boundaries



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Transformative action to combat land degradation will facilitate a return to the safe operating space of the land-based planetary boundaries. Transformative actions are those that lead to positive systemic impacts at scale, improving both environmental and human wellbeing. This understanding aligns with the IPBES definition of transformative change (IPBES, 2019). Transformative action includes implementing concrete practices, enhancing governance frameworks and channelling investments into land-based action, while taking fairness and justice into account. Transformative actions require an integrated approach, where institutional, financial and political dimensions align with their objectives. Specific land-based actions in isolation will likely achieve little, unless they are supported by the appropriate enabling environment. Just as the planetary boundaries are interconnected, so too must be the actions for preventing their transgression. Chapter 4 provides a comprehensive overview of the opportunities for transformative actions embedded in an enabling environment, guided by policy objectives, and financed by investments in sustainable land management and ecosystem restoration. It also considers the allocation of benefits to ensure fairness and social justice.

4.1 Opportunities for transformative action

Due to its complex effects on various Earth system processes, land degradation can be addressed through a variety of means: regenerative agriculture and soil protection, integrated water resource management, digital solutions, sustainable or green supply chains, inclusive land governance, and ecosystem conservation and restoration with a focus on forests, grasslands, savannas and peatlands.

4.1.1 Balancing agricultural productivity and environmental sustainability to improve soil health

Extensive agricultural land use and expansion, especially through deforestation and other human activities, has been identified as a major driver of environmental degradation (Winkler et al., 2021; Abdel-Rahman, 2023; Assede et al., 2023). The prevention of soil degradation is crucial for future food security and all other land-based ecosystem services, and requires a transition to sustainable agriculture and food systems that balance increased productivity with reduced environmental impact (Foley et al., 2011).

Soils are crucial for providing food, regulating the climate and supporting biodiversity (FAO and ITPS, 2015; Kopittke et al., 2019), interacting with the planetary boundaries for land-system change, freshwater change and biogeochemical flows, among others (Bhattacharyya et al., 2015; Weil and Brady, 2017; Kopittke et al., 2021). However, the need to expand nature conservation and the growing global demand for food, fibre and fuel drives the unsustainable intensification of farmland and soil quality depletion (Kopittke et al., 2019).

To advance soil health, regenerative agriculture and agroecology are two overarching approaches to sustainable farming that have gained traction in recent years (Giller et al., 2021; Tittonell et al., 2022). Both approaches promote practices like crop residue retention, cover cropping and reduced tillage (Hes, Turbott and Paull, 2019; Giller et al., 2021), but there are also differences. Regenerative agriculture is primarily defined by its outcomes, such as improved soil health, carbon sequestration and biodiversity enhancement (Wilson et al., 2022), allowing farmers the flexibility to determine their preferred mode of implementation. Agroecology, on the other hand, emphasises holistic land management (Hes, Turbott and Paull, 2019; Manshanden et al., 2023) through practices that account for biophysical, socioeconomic and cultural aspects, including the co-creation of knowledge and other participatory processes (Bezner Kerr et al., 2023).

The following subsections take a closer look at various transformative actions that follow an integrated approach to making agricultural production more sustainable. The first two – carbon sequestration and reduced soil erosion – are oriented to specific objectives, while the other two address specific interventions – agroforestry and conservation agriculture. These approaches partly overlap, further highlighting the interconnectedness of land-based sustainability practices.

Carbon sequestration

Carbon sequestration refers to the process of capturing and storing atmospheric CO_2 in a stable form (Lal, 2008). It is most frequently proposed as a means to balancing the global carbon budget (Lal, 2004, 2008), but it is also valuable for combating soil degradation as greater soil organic matter – measured by soil organic carbon – enhances soil structure, soil fertility and biological activity (Lal, 2004). Carbon sequestration can be anthropogenically driven, but it is achieved through natural processes, including biotic sequestration through photosynthesis and carbon storage in vegetation and soils (Jansson et al., 2010; Kambale and Tripathi, 2010).

Promising techniques include woodland regeneration, no-till farming and cover crops, all of which align with principles of conservation agriculture, as well as integrated nutrient management, improved grazing, water conservation and harvesting, efficient irrigation and agroforestry (Lal, 2004; Rabbinge, 2009). Intercropping and the application of organic fertiliser, manure, compost or biochar are also important strategies for enhancing soil organic carbon. These strategies can contribute to sustainable agricultural production, including higher productivity levels, as well as climate change mitigation (Adekiya et al., 2023) through terrestrial CO_2 removal via bioenergy production with carbon capture or afforestation (Heck, Donges and Lucht, 2016). However, if carbon sequestration techniques focus solely on the planetary boundary for climate change, they may lead to the transgression of other boundaries (e.g. land-system or freshwater change) (Rockström et al., 2012; Heck, Donges and Lucht, 2016).


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Soil erosion control

Soil erosion control can be achieved in many ways, including no-till farming (Montgomery, 2007; Lal, 2015), terracing (Nyssen et al., 2004; Rutebuka et al., 2021), cover cropping and crop residue management (Lal, 2015; Adekiya et al., 2023), contour planting (Gilley, 2005) and controlled grazing with appropriate stocking rates (Lal, 2015). Different regions take different approaches: China and Spain aim for vegetation restoration, for example, whereas Brazil and the United States focus on conservation (minimum) tillage (Wen et al., 2023). No-till agriculture is a promising pathway for sustainable agriculture, as it results in erosion rates that are much closer to soil production rates, relative to conventional tillage practices (Montgomery, 2007). Studies from hilly areas like Ethiopia and Rwanda show that terracing is highly effective in combating severe soil erosion, and has thus been widely adopted (Nyssen et al., 2004; Rutebuka et al., 2021). Farmers construct terraces by building stone or soil barriers along the contours of the slope, which reduces the speed of water runoff and allows more water to percolate into the soil. Successful terracing is often reliant on water for irrigation, while labour and maintenance costs also need to be carefully considered (Gebreslassie, 2014).

Contour planting is another effective technique for reducing runoff and combating soil erosion in sloping fields (Gilley, 2005). Crops are planted following the slope contour, forcing surface water to flow perpendicular to the slope, slowing downhill runoff and encouraging soil infiltration (La et al., 2016). Studies have shown that contour farming can decrease annual runoff by 10% and reduce soil and water losses by 49.5% when compared to downslope cultivation (Farahani, Fard and Asoodar, 2016). A study in Zimbabwe showed that contours combined with rainwater harvesting techniques helped increase yields in smallholder farming systems, relative to contours alone (Chiturike et al., 2024). It is important to note that not all contour management methods are equally effective. For instance, contour trenching can harm soil by causing erosion and decreasing water-holding capacity, suggesting that woodland and savanna plantings may be preferable in arid regions (Mussery et al., 2013).

Finally, erosion-reducing plants are widely used to rehabilitate mining areas and to control erosion on steep slopes. The most effective anti-erosion plants are those with high root and stem densities and large leaf areas (Dahanayake et al., 2024). Vetiver grass (Vetiveria zizanioides L.) is commonly chosen for its fast growth rate, deep rooting system and high tolerance for heavy metals, making it suitable for


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stabilising landfills (Truong and Loch, 2004). A study on hill slopes with sandy silt in Bangladesh showed remarkable results, with vetiver reducing soil loss by 94–97%, and reducing runoff by 21% compared to no vegetative cover (Aziz and Islam, 2023).

Multiple benefits of agroforestry

Agroforestry offers multiple benefits including carbon sequestration, improved soil fertility and enhanced physical soil properties (Hillbrand et al., 2017; Raharilaza, 2021; Siarudin et al., 2021; Marques, Anjos and Sanchez Delgado, 2022; Jinger et al., 2023). The practice combines trees or shrubs with agricultural crops and/or livestock in traditional and modern land-use systems to deliver environmental, economic and social benefits (Burgess et al., 2019). By incorporating wood vegetation into farming systems, agroforestry provides a sustainable alternative to low-diversity cropping systems, enhancing the multifunctionality and resilience of landscapes (Nair, 2007; Hillbrand et al., 2017) and contributing to afforestation (Jagoret et al., 2012). The integration of hedges, trees and multi-strata systems enhances soil chemical and physical properties through biological N fixation, deep nutrient uptake, improved soil aggregate stability and increased organic matter, which in turn controls soil erosion (Cooper et al., 1996; Jinger et al., 2023) and improves soil fertility (Cooper et al., 1996; Mbow et al., 2014; Siarudin et al., 2021; Marques, Anjos and Sanchez Delgado, 2022). Leguminous species are especially suited to agroforestry due to their positive effects on soil quality and erosion prevention (Cárceles Rodriguez et al., 2022).

Agroforestry requires knowledge of suitable tree and crop species for a given climate, including an understanding of their water demand, root characteristics and distribution (Ong, Black and Muthuri, 2006; O'Connor et al., 2023). The scientific literature is divided with regard to the water-use efficiency of agroforestry systems. The complementary root distributions of trees and crops can enhance efficient water use (Bayala and Wallace, 2015), increasing soil water content, infiltration and water-holding capacity (Ngaba et al., 2024). However, these benefits may not be achieved in water-scarce climates. For example, in the semi-arid tropics, agroforestry can exacerbate the competition for water and present a challenge for sustaining crop production. At larger scales, trees can positively influence watershed hydrology and help maintain biodiversity, contributing to greater ecosystem resilience (Ellison et al., 2017). Improved fallows enriched with carefully chosen tree species can enhance soil quality while providing firewood and additional food resources for households (Marquardt, Milestad and Salomonsson, 2012).

By enhancing carbon sequestration in above-ground and below-ground biomass, agroforestry can significantly contribute to climate change mitigation (Mbow et al., 2014; Jinger et al., 2023), provided carbon is stored for a long time. Trees can also improve microclimates, mitigating temperature extremes and atmospheric saturation deficits (Mbow et al., 2014; Chemura, Yalew and Gornott, 2021), while increased canopy cover can reduce understory crop temperatures (Middel, Chhetri and Quay, 2015), providing a vital benefit in a warming climate. All things considered, agroforestry is a promising pathway for balancing food security and agricultural sustainability in the long term, but success will rely on careful consideration of the social and ecological conditions (Mbow et al., 2014; Van Noordwijk, 2018) and a thorough assessment of potential sites for implementation (Singh et al., 2022). The effect of agroforestry on soil quality depends on the specific biome (e.g. temperate, tropical, Mediterranean) as well the management practices and tree species selected (Ngaba et al., 2024). Finally, communities need to see the benefits of agroforestry for it to be adopted and maintained in the long run. Policy frameworks can help to ensure land and tree ownership while offering incentives for farmers to adopt agroforestry practices (Hillbrand et al., 2017).

Protecting soils through conservation agriculture

Conservation agriculture enhances soil functions, improving climate resilience and boosting agricultural productivity, particularly in the face of increased rainfall variability (Michler et al., 2019). Soil fertility

Agroforestry, household nutrition and gender in southern Madagascar

Agroforestry can have positive spillover effects beyond agricultural production. One such effect is food and nutrition security, as agroforestry systems often produce a diversity of fruits, nuts or timber, which can be consumed or sold. Preliminary results of a quasi-experimental study in southeastern Madagascar found that agroforestry has a positive effect on some household food security indicators, and their stability over the year (Malevolti et al., 2024). The study also looked at the relationship between agroforestry, food security and the gender of household decisionmakers in terms of production, tree management and food use decisions (consumption or sale), suggesting that agroforestry reduces the vulnerability to food insecurity of households led by women. Therefore, agroforestry can enhance food and nutrition security beyond agricultural productivity, but policies need to account for factors affecting decision-making power within the household.

management and soil water conservation practices are complementary, and can be combined to leverage synergies, increasing their effectiveness (Diop et al., 2022). Reduced tillage – or minimum soil disturbance – is a key component of conservation agriculture (Nasir Ahmad et al., 2020). Protecting and improving soils is crucial to maintaining their role in regulating Earth system processes, contributing significantly to land-system change, climate change and biogeochemical flows (Kopittke et al., 2021).

Other approaches to enhancing soil health include Integrated Soil Fertility Management (ISFM) practices, such as permanent soil cover, crop diversification, rotation and intercropping (FAO, 2022a), and the Zaï technology (Liniger et al., 2011; Danso-Abbeam, Dagunga and Ehiakpor, 2019). The Zaï pit system is an indigenous knowledge-based practice of western Africa, and it has long been considered a form of conservation agriculture for soil fertility management. The practice is based on creating small pits where organic matter (e.g. manure, compost or dry biomass) is embedded before planting (Danso-Abbeam, Dagunga and Ehiakpor, 2019). It improves soil fertility and increases nitrogen-use efficiency, thereby reducing nitrous oxide emissions (Bayu, 2020). The practice has the potential to enhance crop productivity, especially in low-rainfall and low-yield regions, as well as in a changing climate (Arumugam et al., 2023), showing a significant economic impact on household welfare (Ehiakpor et al., 2019). Despite its widely recognised potential, various economic and institutional factors can hamper the adoption of Zaï (Danso-Abbeam, Dagunga and Ehiakpor, 2019), particularly for women farmers, who may face limited access to labour and manure.

Farmer preferences on sustainable adaptation

A study on the adaptation practices of German arable crop farmers revealed a general preference for cultivating resilient crops and varieties, crop rotation, conservation tillage methods and the use of cover crops. The least favoured strategies included insurance, irrigation, mixed cropping and precision farming techniques. This suggests that farmers prefer low-cost, easy-to-implement strategies over more expensive and transformative ones. It also indicates a discrepancy between farmers' preferences and the effectiveness of different practices. Closing this gap will be key to successful climate adaptation at the farm level. Given the diverse preferences of arable crop farmers, policymakers will need to engage farmers and stakeholders in the policy development process, provide targeted information and resources, and promote adaptation through incentives. Additionally, addressing cost barriers and market conditions can enhance the adoption of more effective resource-saving technologies and other sustainable practices (Stetter & Cronauer, 2024).

4.1.2 Restoring ecosystems and their functions

Grasslands, savannas, peatlands and forests all have a role in providing crucial ecosystem services like water purification, flood risk reduction, carbon storage, erosion control, biodiversity conservation and habitat for endangered species (Joosten, Tanneberger and Moen, 2017; IPBES, 2018a; Bengtsson et al., 2019; Worrall et al., 2019). They cover 40% of the Earth's surface and contribute to keeping land within planetary limits through their ecosystem service provision (Bardgett et al., 2021).

Grassland conservation and restoration

Grasslands are often mistaken for recently formed ecosystems, with no need for targeted restoration efforts (Buisson et al., 2022). However, just like forests, grasslands are becoming increasingly degraded and require restoration. There are various grassland restoration methods, including species reintroduction, management of unwanted species (e.g. through topsoil removal or grazing), improved N management to counter eutrophication, and a better understanding and management of plant–microbe interactions (Lyons et al., 2023). Success may depend on the availability of seeds (Slodowicz et al., 2023), how easily native plants can be established at specific sites (Nolan, Dewees and Ma Lucero, 2021) and how different interventions are combined (Resch et al., 2021). In Europe, seed transfer zones, open-source seeds and seed certificates aim to increase the availability of locally adapted seeds, although the supply of rare or endangered species remains insufficient (Slodowicz et al., 2023). An overarching challenge is the monitoring of grassland restoration efforts, which often face resource constraints, making it difficult to provide clear guidance for local actions (Nolan, Dewees and Ma Lucero, 2021; Resch et al., 2021).

Savanna conservation and restoration

Savannas are under severe threat from human-induced land degradation, yet they are essential for ecological and human wellbeing. Restoration methods include the strategic use of fire. In the southeastern United States, the reintroduction of fire into pine savannas has enhanced ecosystem services by increasing plant species diversity and improving soil health (Dixon et al., 2022). Fire helps maintain open canopies, reduces competitive pressure, and promotes the growth of perennial grasses that are critical for soil stabilisation and water regulation. Similarly, in Brazil's Cerrado region, pasture management and the control of exotic grass cover has demonstrated the great potential for savanna regeneration, although natural regeneration outcomes vary depending on biophysical conditions and pasture management practices (Silva et al., 2023). Despite these success stories, challenges remain, particularly in Asia where savannas are often misidentified as degraded forests. This can lead to inappropriate afforestation efforts that harm biodiversity and disrupt water availability, thus a savanna-focused perspective is needed to avoid the unintended displacement of these valuable ecosystems (Kumar et al., 2020).

Peatland conservation and restoration

Peatlands hold great potential for storing greenhouse gases and directly contributing to the planetary boundary for climate change. Provided that 60% of degraded peatlands are rewetted, and intact peatlands are protected, the land system could become a net sink of greenhouse gases by 2100 (Humpenöder et al., 2020). Indonesia, whose vast tropical peatlands face significant degradation, has made restoration a key priority in its National Peatland Strategy (2020–2049). The Indonesian Peatland Restoration Agency (BRG) implemented the 3R approach – Rewetting, Revegetation and Revitalization – to restore peatlands, focusing on fire-prone areas in Sumatra and Kalimantan (Dohong, 2018). Such approaches can be further extended with fire reduction (Harrison et al., 2020) and community-led peatland restoration models (Terzano et al., 2022). Community-led restoration aims to refine and implement effective restoration strategies, while securing local community participation and benefit sharing (Fox and Cundill, 2018). This requires the involvement of Indigenous peoples and local communities to ensure the inclusion of their traditional knowledge and stewardship of peatland ecosystems, while engaging women and youth in restoration activities in view of their significant economic roles in peatland areas (Terzano et al., 2022).

Restoration efforts in Western Europe have primarily focused on protected areas, while larger non-protected peatlands continue to face extraction, drainage for agriculture and forestry, and abandonment (Andersen et al., 2017). The restoration of temperate and boreal Sphagnum-dominated peatlands in 11 European countries has shown varying degrees of success. Passive restoration efforts, involving a cessation of degrading activities, resulted in limited recovery even after decades. Standard techniques, like rewetting, required 45–55 years to regain pre-disturbance levels, but enhanced restoration methods, such as active revegetation, took only 20–35 years (Nordbeck and Hogl, 2023). Other peatland restoration efforts promote greater community participation in management, increasing annual planting areas, diversifying tree species, ensuring post-planting maintenance and promoting natural regeneration with native species (Alam et al., 2022). To enhance the understanding and adaptive management strategies for peatland restoration, more standardised, long-term monitoring schemes across multiple ecosystem services are needed (Andersen et al., 2017; Nordbeck and Hogl, 2023).

Forest conservation and restoration

Forests have received the most attention in restoration and conservation debates so far, and are essential for avoiding planetary boundary transgressions. By capturing and storing carbon, forests contribute significantly to climate change mitigation (Roe et al., 2021). However, the degradation of forests,[5] and land degradation more broadly, compromises their ability to provide critical ecological services, such as carbon sequestration and biodiversity support, which in turn affects environmental and human wellbeing (Mansori et al., 2023). Only a small fraction of the world's forests have a high level of ecological integrity, with many protected areas struggling to meet this standard (Grantham et al., 2020). Key restoration strategies aim to reduce deforestation and forest degradation, and improve conservation measures through protected areas and stronger governance (Smith et al., 2019).

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Good governance is key to effective sustainable forest management, and low-impact supply chain policies and increased monitoring and enforcement can help to mitigate the impacts of commercial activities on forests (Armenteras et al., 2023). In Colombia, weak institutions and poor governance have led to significant forest degradation. Strengthening local governance and promoting sustainable supply chains can address these issues, and involving local actors in forest management can bridge the gap between national policy and implementation (Armenteras et al., 2023). Diversifying income sources is also essential for reducing forest degradation. For example, improved cookstoves or solar photovoltaic systems can provide households with additional income sources, improve livelihoods while reducing their reliance on forest resources (Girma et al., 2023).

Combining different approaches and perspectives into a hybrid governance model can also increase equity, transparency and accountability in forest management (Rana and Chhatre, 2017). Effective forest management must include local communities who have historically relied on forest resources; their involvement will improve policymaking and implementation design, and contribute to objectives such as poverty alleviation and the creation of rural employment opportunities (Kumar, Nisha Phukon and Singh, 2021). Educating communities about forest degradation is critical to conservation efforts. Vietnam is a notable example of successful forest management: Since the 1990s, Vietnam has shifted from net forest loss to forest gain, primarily through restoration, which now accounts for over 84% of total gains (Khuc et al., 2023). Effective policies and programmes, with a focus on land privatisation and improved access to finance, encouraged farmers to invest in forest land and tree planting. The expansion of restored forests in Vietnam is linked to improved incomes, demonstrating that well-designed policies can support both economic growth and environmental sustainability.

Reforestation (the conversion of deforested areas back to forests), forest restoration (the renewal of destroyed forest ecosystems and habitats) and afforestation (the conversion of non-forested areas to forests) are the key pillars of forest protection and restoration. Afforestation, in particular, is often highlighted in international discussions, but it must be carefully managed to avoid negative impacts on existing ecosystems (IPBES, 2019; Smith et al., 2019). Poorly designed afforestation projects, particularly those that involve conversion of non-forested lands, such as grasslands and savannas, can disrupt essential ecosystem services and lead to biodiversity loss (Veldman et al., 2015; Parr, te Beest and Stevens, 2024). In Nigeria's Guinea Savanna, afforestation practices have led to a decline in vegetation and biomass, with about 38% of the area still degraded despite some improvements in land management (Adenle et al., 2020). In Asia, the afforestation of grasslands – misidentified as degraded forest – disrupts biodiversity and water systems (Kumar et al., 2020). Emphasising afforestation over the restoration of savannas and grasslands can exacerbate problems instead of solving them (Dudley et al., 2020), but accurate vegetation mapping and a balanced conservation approach can help mitigate these unintended negative impacts.


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4.1.3 Managing scarce water resources

Reducing water-related risks and reestablishing the health of land resources requires efforts at various scales, from local measures to global policies (Zipper et al., 2020). There are a growing number of water management measures and best practice examples, with increasing attention devoted to those that work with nature, avoiding siloed solutions and keeping the integrity of the larger socio-ecological system in mind (Cassin and Matthews, 2021).

The water sector is in the process of reorienting its thinking from grey infrastructure (e.g. dams, reservoirs, channels or treatment plants) to green infrastructure (e.g. reforestation, floodplain restoration, forest conservation or recharging aquifers) (Browder et al., 2019). These green infrastructure interventions, or nature-based solution (NbS), leverage a range of co-benefits to other Earth system processes. NbS that enhance water availability can simultaneously reduce soil erosion and atmospheric CO_2 concentrations, helping to mitigate land degradation and climate change at the same time. Reforestation, afforestation, wetland creation or floodplain restoration are some of the most popular green water management strategies. In addition to their positive impacts on carbon storage, these measures reduce the impacts of high water flows by increasing infiltration capacities, and prevent critical low flows by storing water and releasing it during dry periods. A dense vegetation cover also helps to maintain soil stability, decrease water and wind erosion, and increase humus layers and the fertility of soils (Vigerstol et al., 2021). Implementing these measures can therefore help to maintain river flows and foster healthy soils.

Yet, expanding forest cover can have negative effects on river discharge by significantly reducing stream flows (Filoso et al., 2017), posing a risk to water availability for ecosystems and human use. This can be mitigated by the selection of less water-hungry trees (Farley, Jobbágy and Jackson, 2005). As the reduction in water flow tends to increase with the size of the afforested area (Dennedy-Frank and Gorelick, 2019), a solution could be to limit these efforts to particularly vulnerable regions (e.g. steep slopes with high erosion potential). It is also crucial to ensure that the new vegetation cover does not have a higher water demand than the vegetation it replaces, and care must be taken to avoid the introduction of invasive species that could threaten native biodiversity (Seddon et al., 2021; Andres et al., 2023).

Because freshwater change is connected to many different Earth system processes, it is crucial to evaluate transformative actions in light of the potential


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Using remote sensing to map smallholder coffee production systems in Vietnam

Digital solutions, like big data and remote sensing, are promising strategies for sustainable land management. A study of smallholder coffee production systems in Dak Lak, Vietnam, used remote sensing to investigate three coffee production systems: open-canopy sun coffee, intercropped and other shaded coffee, and newly planted or young coffee, resulting in a binary coffee/non-coffee map of the area (Maskell et al., 2021). These types of maps, in combination with historical land cover data, can help track deforestation and biodiversity dynamics, coffee replantation or abandonment, and contribute to agricultural planning. In the field of agroforestry implementation, spatial information can support the monitoring of climate adaptation efforts and sustainability certification, which is still mostly done through household surveys.

risks and unintended side effects. The Nature-based Solutions Initiative[6] offers an interactive platform for exploring best practices that combine green and grey infrastructure approaches, which can address various water- and land-related challenges simultaneously. In a harsh dryland area of Morocco, for example, degraded land was passively reforested by protecting the area from overgrazing, which reduced the occurrence of flash floods and soil erosion. In combination, rock dams and water towers can enhance water availability and storage during drought periods, and strengthen the resilience of the local community to climate variability (UNDP, 2013).

In the agricultural sector, the combination of green and grey practices is increasingly gaining attention (Sonneveld et al., 2018). For example, improved natural water storage systems through soil moisture-conserving agricultural practices (e.g. edge-of-field or riparian buffer strips, conservation tillage, cover crops or intercropping) combined with more efficient irrigation techniques, such as surface or sub-surface drip irrigation, could significantly decrease water demand (Thompson, Pang and Li, 2009), reduce soil erosion and prevent further land degradation. Such improved irrigation practices, perhaps in combination with rainwater harvesting, can also help balance production losses if irrigation water is restricted to meet environmental flow requirements (Jägermeyr et al., 2017). Wastewater reuse for irrigation is another way of reducing the level of freshwater abstraction in the agricultural sector. Although wastewater treatment can be costly, it has great potential to respond to water shortages in water-scarce regions (Singh, 2021).

Evidence shows that more efficient water use will not come from changes in technology alone; rather, this needs to be combined with regulation to ensure allocations are sustainable (Perry, Steduto and Karajeh, 2017). Given the complexity and interconnectedness of Earth system processes, the main challenge is to simultaneously consider the impacts of water management on other parts of the system. This means evaluating proposed interventions to identify and quantify any potential side effects, monitoring short-term and small-scale effects, as well as long-term and large-scale impacts, and incorporating a control watershed into the monitoring scheme, where possible, to help isolate the net effects of the selected intervention (Vigerstol et al., 2021).

4.1.4 Digital solutions for sustainable land management

Digital agriculture – also known as smart farming or Agriculture 4.0 – holds great potential for reducing and reversing land degradation. It includes the use of emerging technologies such as precision farming, remote sensing, drones, field robotics, artificial intelligence and big data (Bacco et al., 2019; Abbasi, Martinez and Ahmad, 2022). These technologies can help detect and mitigate land degradation by monitoring land cover change in real time, facilitating the precise application of water, nutrients and pesticides, enhancing crop health through early pest and disease detection, and promoting sustainable land management practices, among others.

Identifying and mapping the extent, severity and types of land degradation are important preconditions for designing and implementing land rehabilitation measures. Remote sensing methods are crucial here, as they can detect the gradual loss of land productivity and cover over time, identifying transgressions of the land-system boundary. Remote sensing can also provide insights into the drivers and impacts of land degradation (Dubovyk, 2017). Images derived from Unmanned Aerial Vehicles (UAVs) (e.g. drones) can increase the efficiency and accuracy of monitoring of site- or species-specific restoration efforts, due to their higher resolution, relatively low costs and cloud-free images (Gómez-Sapiens et al., 2021; Opedes et al., 2023).

Precision farming technologies can be useful in reducing land degradation by enabling farmers to manage fields as heterogeneous entities. In contrast with the uniform application of inputs across large fields (Finger et al., 2019), precision technologies allow farmers to apply water, nutrients and pesticides precisely where and when they are required, and in the correct quantity. One of the most prevalent precision farming technologies involves tractors equipped with a global positioning system (GPS). This helps farmers avoid overlaps and omissions during field operations, optimising input application and reducing the number of machinery passes in the fields. Reduced machinery traffic minimises soil compaction, enhances water infiltration and fosters better root growth, ultimately boosting crop yields and sustainability. In addition to GPS, various sensors – such as electrical, electromagnetic, mechanical, optical and acoustic sensors – can assess site-specific soil conditions like moisture content, organic carbon, nitrogen levels and acidity (pH). Data from these sensors can be used to generate digital soil property maps, capturing soil heterogeneity within the field. These maps facilitate optimal input distribution, mitigate environmental impact, and maximise yield potential across the entire field.

Another emergent technology is solar-powered field robots, equipped with GPS and advanced sensors to precisely plant seeds and manage weeds without the need for herbicides. Using swing-out hoeing knives, they can also keep the area between crops free of weeds (Ramin Shamshiri et al., 2018). Compared to conventional machinery, field robots are much smaller and lighter, causing less damage to plants and soils. Under optimal conditions, one solar-powered robot can manage several hectares per day. The performance of different field robots is currently being tested in landscape experiments to explore the potential of highly diversified cropping systems, which cultivate a mosaic of small, heterogeneous patches within a single field (Grahmann et al., 2024).


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While field robots require high initial investments, and are only affordable to a limited number of well-capitalised farmers, other emerging technologies are more accessible to smallholder farmers in lower-income countries. One example is the Plantix[7] smartphone application, which uses a machine learning approach to detect plant pests and diseases. The app is free and available in 18 different languages, and it can detect approximately 680 different pests and diseases on more than 80 different crops. It has been especially successful in Brazil (Hampf et al., 2021) and among smallholder farmers in India, where nine million geo-located photos of diseased plants have been taken within a two-year period (Wang et al., 2020). The app helps farmers diagnose diseases at an early stage, reducing the need for pesticide application. It can also detect nutrient deficiencies, helping farmers to optimise fertiliser application and avoid overuse.

Although digital agriculture holds significant potential for mitigating land degradation, several limitations must be considered. Currently, precision farming technologies have primarily been adopted on large farms in higher-income countries, with investment costs being a major barrier to uptake. Complex technologies, such as sensor-driven input applications at variable rates, have particularly low adoption rates (Finger et al., 2019). Low internet connectivity in rural areas is also a major obstacle. Moreover, the social impacts of digital agriculture are frequently overlooked. Significant changes in the nature of farm work are expected, including the reduced demand for manual labour and higher unemployment among unskilled rural workers. This transformation may lead farmers and rural workers to feel increasingly disconnected from their land, and more reliant on large tech enterprises (Rose et al., 2021), while the collection of large volumes of data raises concerns about storage, ownership and privacy. Lack of trust in these new technologies could further contribute to resistance.

Taking the costs and benefits into account, agricultural extension services should carefully review emerging technologies and encourage the adoption of easy-to-use and safe innovations that empower small-scale farmers. Additionally, public investments should focus on improving infrastructure and digital connectivity in rural areas.

4.1.5 Considering land degradation in global supply chains

Land plays an important role in global supply chains, serving as the foundation for agricultural production, resource extraction and industrial activities. At the same time, land degradation and biodiversity loss (Owen et al., 2020; Quandt, Lindner and Schüler, 2022), and loss of soil fertility (Sauer, 2021) can be strongly linked to the production and supply of food, energy and raw materials, such as minerals, metals and timber. In response to growing public pressure, companies are increasingly adjusting their production processes and improving efficiencies along global supply chains, from the sourcing of raw materials to the distribution of finished products (Cammarano et al., 2022; Shekarian et al., 2022). The sustainability of each link along global supply chains can be addressed by different transformative actions, including firm-level responses, multi-stakeholder or industry-wide initiatives and government or business regulation.

Firm-level actions for sustainable land management

Individual firms can take action to improve their production or sourcing practices along global supply chains, usually in line with their environmental, social and governance (ESG) standards. These firm-level actions differ significantly in scope, ambition and stage of implementation, and may be focused on different parts of the supply chain (Lambin et al., 2018). When dealing with external actors in their supply chains, such as processors and suppliers, firms have a number of instruments available to address land-related issues. For example, they can impose requirements on suppliers, or source only from suppliers who meet pre-defined sustainability standards; give preference to suppliers who offer third-party certified products; set standards for the products they purchase; audit suppliers' operations against social and environmental standards; or exclude suppliers sourcing from land degradation hotspots or engaging in other poor environmental practices.

Firms engage in sustainability initiatives for different reasons. External drivers include market, societal and regulatory pressure, while internal drivers relate to such factors as the company's corporate strategy, organisational culture, available resources, position in the supply chain or geographical location (Saeed and Kersten, 2019). Many firms use annual sustainability reports to track and publicly disclose the impact of their operations, and highlight the actions they are taking to address socio-environmental challenges in their supply chains. A recent OECD (2024) report shows that a large cohort of firms, representing 86% of global market capitalisation, disclose sustainability-related information. The same report points out, however, that only 66% of these reports are verified by external service providers, potentially reducing their credibility and comparability.

Multi-stakeholder and industry initiatives for sustainable land management

Multi-stakeholder and industry-wide initiatives go beyond individual actors. These initiatives establish sectoral standards to foster alignment among stakeholders within the same sector (Lambin et al., 2014; Delabre, Alexander and Rodrigues, 2020; Yerashevich et al., 2023), and may include positive incentives – such as price premiums for certified products – or sanctions for suppliers engaging in harmful practices (Lambin et al., 2018). Driven largely by civil society and the private sector, these initiatives tackle challenges within supply chains that traditional top-down government regulations struggle to manage, typically due to the geographical dispersion of producers, the scale of their operations and the under-resourcing of regulatory institutions (Cashore, 2002; Buckingham and Jepson, 2013; Wehrmeyer and Mulugetta, 2017).

Existing multi-stakeholder transformative actions, such as the German Initiative on Sustainable Cocoa (GISCO),[8] are often commodity-specific. GISCO is a joint initiative of the German Ministry for Economic Cooperation and Development (BMZ), the German Ministry of Food and Agriculture (BMEL) and the German sweets and confectionery industry, retail grocery trade and civil society. GISCO aims to improve the livelihoods of cocoa farmers and their families, protect natural resources and biodiversity in cocoa-producing countries and increase the cultivation and commercialisation of sustainably sourced cocoa. Similarly, the Roundtable on Sustainable Palm Oil (RSPO) was jointly launched in 2004 by global vegetable oil producer AAK, the Malaysian Palm Oil Association, Migros, Unilever and the Worldwide Fund for Nature (WWF). It provides a forum where stakeholders collaborate to define sustainability standards and assess performance across the palm oil supply chain (RSPO, 2011). With over 4,970 members worldwide, RSPO represents palm oil producers, processors, traders, producers, retailers, banks and non-governmental organisations. In its most recent impact update, the RSPO (2023) claims to have helped conserve more than 360,000 hectares of rainforest, among other positive impacts. Critics have pointed out that RSPO standards are relatively weak and lack enforcement, with some RSPO-certified companies still engaging in deforestation (Millstein, 2024).

Regulatory actions for sustainable land management

Firm-level and multi-stakeholder actions typically operate within the confines of private regulatory frameworks – which themselves are undertaken at different levels and by different actors. On a global level, the three Rio conventions (CBD, UNCCD, UNFCCC) provide frameworks for addressing different but interconnected environmental challenges, with agreements such as the Paris Agreement (UNFCCC, 2015). These conventions and agreements establish overarching goals that influence sustainability criteria and transformative actions at firm or sectoral levels. For example, retail companies are increasingly aligning their energy targets to the Paris Agreement by setting ambitious energy goals, investing in more efficient logistics and integrating life cycle principles in their operations (Ferreira et al., 2019). Regulatory actions can also exist on a regional level, such as the EU's regulation on deforestation-free products (EUDR) to reduce the consumption of products connected to deforestation, and to reduce the EU's contribution to greenhouse gas emissions and biodiversity loss (European Commission, n.d.).

4.1.6 Strengthening land governance

Responsible and inclusive land governance and clear property rights are key building blocks to enable land-based transformative actions. Additionally, land governance interventions are pivotal tools in avoiding land degradation in the first place, promoting fair socioeconomic outcomes for rural communities, and can be seen as transformative actions in their own right.

Strengthening land governance requires effective policy frameworks, long-term planning processes and inclusive institutions. Some promising interventions are land tenure formalisation, participatory and integrated land-use planning, and conflict resolution mechanisms. All of these interventions fall primarily under the authority of national governments, requiring strong political will and public awareness. Non-state-led interventions are also possible. A combination of bottom-up and top-down approaches would likely work best, while state-led approaches appear to be the most sustainable in the medium to long term (Huntington and Shenoy, 2021). The scope for strengthening land governance is global, as eventually all landholdings can – and arguably should – be formalised, with clearly assigned land uses and access to conflict resolution mechanisms.

Land tenure formalisation

Land tenure formalisation – including the recognition of existing legitimate rights – is a key policy and administrative intervention in the field of land governance. Formalising land tenure typically entails clarifying the property rights of landholders, as well as the boundaries of the land in question. This is usually accompanied by some form of official recognition, such as a title or deed. Such interventions hold considerable potential for halting land degradation, incentivising land restoration and improving human wellbeing (Holden and Ghebru, 2016; Higgins et al., 2018; Tseng et al., 2021). In Madagascar, for example, at least 67% of land with high restoration potential is without formal land title, which highlights the importance of securing land rights to scale up forest restoration (Rakotonarivo et al., 2023). A randomised controlled trial in Benin found that mapping and registering land led to approximately a 20% reduction in tree cover loss, and a 5% reduction in forest fires (Wren-Lewis, Becerra-Valbuena and Houngbedji, 2020).

Yet, empirical results are often mixed and nuanced (Sjaastad and Cousins, 2009). Land tenure formalisation primarily aims to strengthen tenure security and bring land to the market, allowing landowners to use it as collateral for credit (Besley, 1995), with increased investment and conservation efforts expected to follow. But the positive outcomes commonly attributed to land tenure formalisation are not always realised (Huntington & Shenoy, 2021; Tseng et al., 2021). There are many reasons for this, such as large regional differences in tenure reform effectiveness and other contextual factors, such as the specific tenure regimes in place (Lawry et al., 2017). Nor is secure land tenure relevant for all types of investment, or in all circumstances. In West Africa, for instance, secure land tenure is associated with leaving land fallow and tree planting, with no effect on the use of manure or chemical fertilisers (Fenske, 2011).

While most land in high-income countries is fully mapped and its tenure formalised, this is not the case in low and middle-income countries. National governments, often with the support of donors such as the World Bank, have been trying to formalise land tenure in these countries for decades, but much of the land – in African countries among others – remains undocumented (i.e. not formally mapped and registered). The formalisation process for communities has been described as time-consuming and complex (Notess et al., 2021). The task of formalising land tenure globally is complicated by often fragmented and overlapping land rights. Very small landholdings of less than 2 hectares are common in many low-income countries, where multiple stakeholders have different types of rights to the same land parcel. Additionally, there are capacity gaps when it comes to demarcating land, which requires proper training in surveying. A key and recurrent concern with land tenure formalisation is that not all legitimate land rights are recognised, especially in the cases of women and youth (Meinzen-Dick et al., 2019). Furthermore, land formalisation brings land to the market, providing entry points for wealthy investors, which can disadvantage local communities (Deininger, 2003).

Although secure and formal land rights do not always deliver all of the desired outcomes, formalising land tenure should be a matter of how, not if. Efforts should be carefully designed and implemented to be inclusive and sustainable in the long term.

Participatory and integrated land-use planning

In many cases, land-use planning is a prerequisite for the process of land formalisation. It is also a strategic approach that guides the allocation, management and development of land resources. Integrated land-use planning – assessing land capabilities, considering socioeconomic factors and integrating environmental objectives to optimise land use – is crucial for halting land degradation by reducing decision uncertainties linked to LDN and other land restoration initiatives (Verburg et al., 2022). These processes are often conducted top-down by spatial planners and government offices; in contrast, participatory land-use planning involves local communities and integrated planning which considers land uses at multiple scales. These approaches can help avoid conflicts over land and strengthen equitable access and (perceived) security of land tenure (Sawathvong, 2004). Land-use planning interventions tend to improve environmental outcomes in the majority of cases, although some evidence points to zero or negative impacts (Tseng et al., 2021).

Implementing participatory or integrated land-use planning is often challenged by time and resource constraints, or a lack of sustained policy and administrative support. Although appropriate land-use planning can promote land restoration, poorly implemented planning processes can also lead to displacement of communities, bureaucratic inefficiencies and unintended environmental impacts (Shen et al., 2019), exacerbating social inequities and disproportionately affecting lower-income and marginalised groups (Kaswamila and Songorwa, 2009; Anguelovski et al., 2016). These challenges make truly participatory, bottom-up approaches all the more relevant. A key group that is often excluded from land-use planning is (agro-)pastoralists (Devereux, 2010). Better inclusion can ensure that their land needs and rights are adequately considered when allocating land uses (Lengoiboni, Bregt and van der Molen, 2010; McPeak and Little, 2018).

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Conflict resolution mechanisms

Improved conflict resolution mechanisms can contribute to clarifying land rights and support the fair attribution of land-based responsibilities and benefits, while decreasing violence (Blattman, Hartman and Blair, 2014) and increasing overall economic activity (Aberra and Chemin, 2021). But land conflict resolution mechanisms in low- and middle-income countries vary significantly in their effectiveness and scope, reflecting broader socio-political and economic challenges. In many regions, land tenure insecurity exacerbates conflicts, with informal settlements and agricultural lands being particularly vulnerable. Traditional mechanisms, such as community-based mediation, can coexist with formal legal systems, but nevertheless face limitations in effectiveness and accessibility. Efforts to strengthen these mechanisms are ongoing, with initiatives focusing on legal reforms, capacity building, and the integration of customary and statutory systems, with the aim of creating robust, accessible, inclusive and transparent conflict resolution frameworks.

The provision of legal support can increase investment in land (Aberra and Chemin, 2021), however formal court systems are often overburdened, leaving land disputes unattended for long periods of time. In such cases, strengthening informal mechanisms can be an alternative for the rapid and low-cost treatment of disputes. At the same time, local courts or administrative bodies often lack enforcement powers, and can be prone to biases in favour of powerful elites (Mattsson and Mobarak, 2024). A combination of both approaches might be needed, with a more decentralised model (i.e. setting up more local, formal courts) while also increasing human resource capacities. There is a risk that conflict resolution mechanisms could be co-opted, allowing elite capture of the process. But if they are implemented well, dispute resolution mechanisms could more effectively reach and empower those traditionally excluded from the formal system, such as women and other marginalised groups (Deininger and Castagnini, 2006).


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Strengthening land governance in Benin

A study in northern Benin analysed access to land, tenure security and land rights using a survey of approximately 300 farming households across 10 villages (Vodounhessi et al., 2024). These households hold customary land titles called Attestations de Détention Coutumière (ADCs), and the study found that farmers perceived ADCs as boosting agricultural productivity and food security by encouraging them to invest in their land. Additionally, farmers reported that it can support infrastructure improvements and empower women to invest in small businesses and other economic activities. Secure access to land also helps mitigate land-related disputes, promoting peace and stability. Considering these findings, policymakers should improve land title acquisition by making it more transparent and accessible, encouraging more people to secure their land, especially women and marginalised groups.

4.2 An enabling environment for transformative action

Transformative actions to combat land degradation and stay within the land-based planetary boundaries require an enabling environment. Technical solutions already exist and are being further refined, but progress on large-scale implementation is lagging behind. This implementation gap can be partly explained by the lack of an enabling environment in many countries, regions, and at the global level. Creating such an enabling environment is crucial for achieving long-term environmental and socioeconomic sustainability. Figure 7 illustrates the various elements of an enabling environment.

A key point is cooperation among actors to meet global targets. This will require global coordination to help with their translation into national agendas, encourage public–private partnerships and enhance uptake at the local level (Verburg et al., 2019). Shared goal-setting, coordination and monitoring are needed to address challenges that are inherently transboundary in nature, and often interconnected through global supply chains. For example, zero-deforestation commitments have been made by both companies and countries, and are included to a certain extent in sustainability certification schemes (Lambin and Furumo, 2023). Commitments are only the first step on the path to transformative action, but they point to a shared goal and vision of the future we want.

Policies are now beginning to address the global interconnectedness that results in land and forest degradation. One example is the EU's Deforestation Regulation (EUDR), which aims to address demand-driven pressures on forests through agricultural expansion (European Commission, n.d.). But the EU is only a fraction of the market that is driving forest conversion (Lambin and Furumo, 2023), and a coordinated approach with other large markets will be needed for transformative action to take effect.

Traditional top-down institutional mechanisms often overlook diverse perspectives, especially local and Indigenous knowledge, leading to ineffective outcomes. Engaging stakeholders – such as land users, local communities, NGOs, scientists, policymakers and international bodies – is crucial for advancing sustainable land management (UNCCD, 2017). No single actor can achieve global land-based goals alone, and a two-pronged strategy is recommended, where global objectives guide local goals while insights from local projects are integrated into international frameworks (Akhtar-Schuster et al., 2011; Chasek et al., 2015).

In particular, the inclusion of neglected voices is essential. Women, youth, Indigenous peoples and local communities face unique impacts from land degradation, but can also offer unique perspectives, which have often been overlooked in the past (Meinzen-Dick, Kovarik and Quisumbing, 2014; Doss et al., 2018). Indigenous and traditional knowledge provides valuable insights for sustainable practices; including women in decision-making can enhance land management, while engaging youth has the potential to foster sustainability and innovation. However, effective inclusion requires more than legal action; acknowledging and overcoming social norms and gender biases are also important (Bayisenge, 2018) as are enhanced social protection and livelihood support policies (FAO, 2021). Inclusive policies and practices that address these diverse needs and contributions can foster resilience, equitable resource access and community ownership, leading to the uptake of more effective sustainable land management. For example, restoration practices can be enhanced by relying on traditional weed prevention methods, and only planting locally sourced species to preserve cultural connections (Hall et al., 2021).

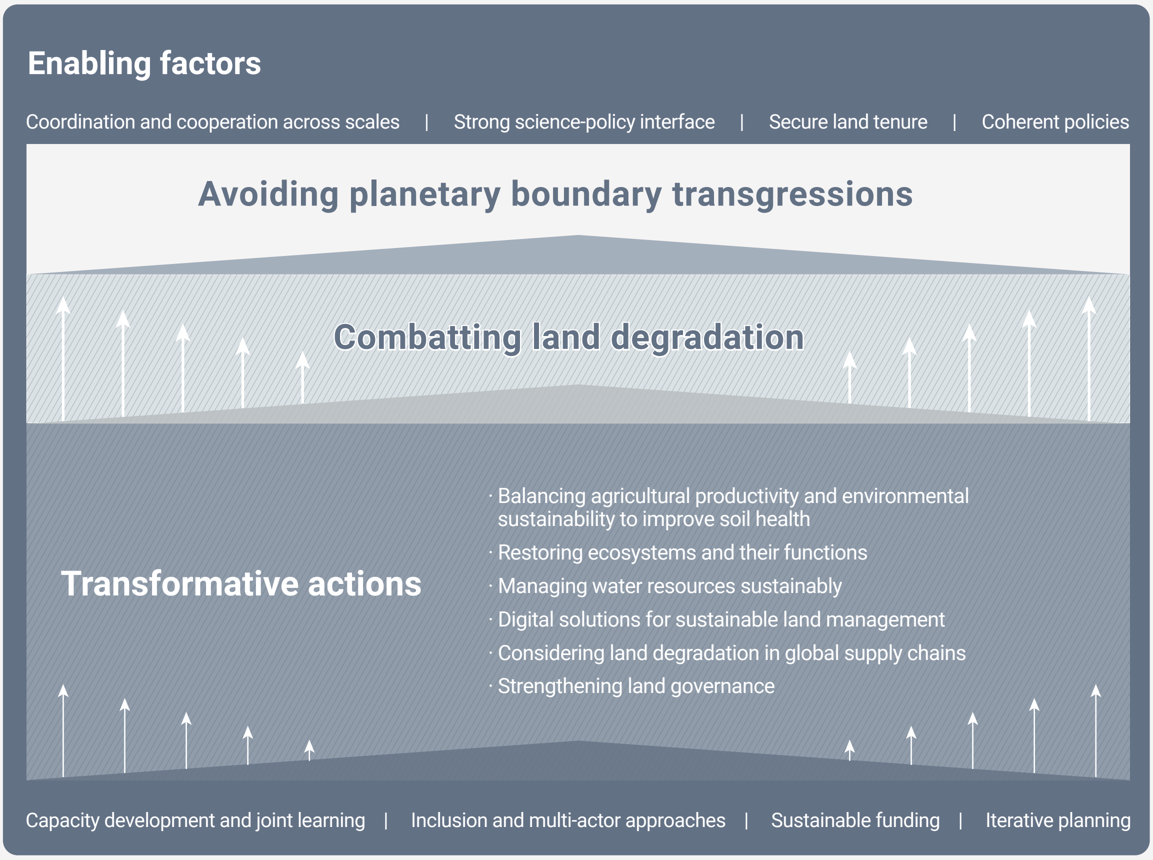
Another key element of the enabling environment is a functioning science–policy interface. Without this interaction, scientific efforts lack the channels through which to reach policymakers with the evidence on which to base their decisions (Akhtar-Schuster et al., 2011). In the context of the land-based planetary boundaries, it is particularly important to set local and global targets for transformative action and monitor progress to avoid planetary boundary transgressions. Several tools and technologies are available to facilitate tracking.

For monitoring global targets, satellite remote sensing is useful for large-scale spatial and temporal coverage (Giuliani et al., 2020; O'Connor et al., 2015), while UAVs allow for more local, fine-grained tracking (Gómez-Sapiens et al., 2021; Opedes et al., 2023).

Indicators also need to be aligned with desired outcomes in a way that enhances our understanding of the issue at stake. For example, the control variable for the planetary boundary for land-system change focuses on forest cover – but this is only one land cover type (Richardson et al., 2023) – whereas indicators for land [degradation] are far richer, often covering land use and land cover, land productivity or carbon stocks (Liniger et al., 2019). The extent of forest cover or loss does not necessarily provide information on the quality of the forest, its function, structure or the ecosystem services provided (Betts et al., 2024). To move away from binary indicators on forest cover or ecosystem conversion, policymakers need support from science to develop the appropriate methods and data products. Other key elements of an enabling environment for achieving LDN include capacity development and joint learning, as well as secure land tenure (see Chapter 4.1.6).

Figure 7

Enabling factors that facilitate the adoption and long-term implementation of transformative actions for combatting land degradation and avoiding planetary boundary transgressions (own elaboration).



4.3 Multilateral agreements guiding transformative action

Dedicated policies at various scales are needed to create an enabling environment and ensure that transformative actions are implemented. This section synthesises policies aimed at combating land degradation and other challenges related to the land-based planetary boundaries – in some cases through specific transformative actions – with a focus on multilateral agreements and synergies between them. Embracing these synergies and coordinating targets has the potential to accelerate action aimed at halting land degradation and staying within the planetary boundaries. This need for coordination and policy alignment is not new, nor is it unique to land degradation and the land-based planetary boundaries. Yet, it remains insufficiently addressed and is critical given the strong interconnection and complexity of processes driving Earth system (in)stability, as highlighted through the land-based planetary boundaries and their interactions.

Land-system change

There are numerous high-level, multilateral agreements on land-system change, including clauses in Nationally Determined Contributions (NDCs) under the UNFCCC. These include commitments to reduce deforestation and scale up forest conservation measures. Another international framework is the REDD+ (Reducing emissions from deforestation and forest degradation, plus other forest-related activities), aimed at incentivising developing countries to reduce emissions from forested lands and invest in sustainable low-carbon development. During COP26 in Glasgow, 145 countries pledged to halt and reverse deforestation by 2030. These countries represent 90% of the world's forest cover (Messetchkova, 2021).

Parties to the UNCCD recognise the concept of LDN as a strong vehicle for driving the implementation of the Convention. By promoting integrated land-use planning, Parties agreed in 2015 to set voluntary LDN targets to avoid, reduce and reverse land degradation. Countries are encouraged to be land-degradation-neutral by 2030, which is aligned with SDG 15 (life on land). These LDN targets should be developed with the participation of affected populations, integrating strategies for poverty reduction, food security and sustainable development. Article 10(3) of the UNCCD (1994) encourages the incorporation of existing social, economic and environmental conditions to promote a fair share of responsibility among all actors involved.

Forest conservation is integral to the implementation of the CBD. Most recently, the Kunming-Montreal Global Biodiversity Framework set targets for protecting, restoring and increasing the area of natural ecosystems by 2050. Specifically, the countries set targets to better manage land such that the loss of areas of high biodiversity importance is close to zero by 2030. Furthermore, they agreed to conserve 30% of land, water and seas. This is to be accomplished through the proportionate, "just, fair, effective, and equitable" elimination of harmful incentives, by at least USD 500 billion per year, and scaling up positive incentives for biodiversity conservation. Additionally, the Parties to the CBD agreed that developing countries, particularly the least developed and small-island states, will have access to USD 700 billion annually to halt biodiversity loss.

Climate change

The climate change boundary is most closely associated with the UNFCCC, and related agreements and decisions. The Special Report on Climate Change and Land (IPCC, 2019) and contributions to the Sixth Assessment Report (Bezner Kerr et al., 2022; Nabuurs et al., 2022; Parmesan et al., 2022) specifically address the interactions between land, land use and climate change. These reports highlight the potential benefits of mitigation and adaptation measures in the land-use sector, as well as the pitfalls of misguided design and implementation of these measures. Successful implementation of adaptation and mitigation measures will have to consider the highly variable social and environmental context of land-use practices.

Change in biosphere integrity

Efforts to integrate biosphere integrity into policymaking have yielded mixed results. Europe has been comparatively successful due to its history of forest protection and a relatively well functioning science–policy interface (Hurley and Tittensor, 2020), but global adoption remains limited, highlighting the need for a more unified approach to effectively secure biosphere integrity (Leclère et al., 2020). The CBD, with its Global Biodiversity Framework, is the primary convention associated with biosphere integrity. The framework marks a significant step forward in global biodiversity commitments, emphasising that "biodiversity is fundamental to human wellbeing, a healthy planet, and economic prosperity for all people", contributing to "food, medicine, energy, clean air and water, security from natural disasters as well as recreation and cultural inspiration" (CBD, 2022).

As part of its ambitions, the framework aims to halt species extinction, protect genetic diversity and manage human-wildlife conflicts. It also seeks to reduce pollution to non-harmful levels for biodiversity and minimise climate impacts on biodiversity. The framework aims to halt human-induced extinction of threatened species, reduce extinction rates and risks ten-fold by 2050, and increase the abundance of native wild species to healthy levels. Additionally, it focuses on maintaining genetic diversity within wild and domesticated species to safeguard their adaptive potential.

Ultimately, conserving biodiversity and maintaining ecosystem functions requires a balanced approach that integrates conservation and restoration with sustainable development. This involves protecting and restoring critical habitats, optimising land use and fostering policies that support biodiversity alongside agricultural productivity (Gerten et al., 2020; Mohamed et al., 2022; Von Jeetze et al., 2023). Addressing the interconnected challenges of climate change, land degradation and biodiversity loss is essential for ensuring a resilient and sustainable future for our planet.

Freshwater change

To date, there is no global governance framework for preventing the transgression of the freshwater change boundary, although several UN conventions deal with aspects of the global water cycle (Ahlström et al., 2021). Instead, relevant policies are found at the level of watersheds, river basins or sub-global political entities, which calls for a downscaling of the freshwater boundary to inform relevant political processes (Häyhä et al., 2016). This can be achieved either by assigning a fair share of the global safe operating space to the specific context, or by deriving a local safe operating space based on local conditions (Zipper et al., 2020). In both cases, the planetary boundaries perspective can inform and complement existing approaches at the local level by focusing on long-term resilience (Wang-Erlandsson et al., 2022).

Another important contribution of the planetary boundaries framework is the consideration of both blue and green water. Most current water policies focus exclusively on blue water, ignoring the importance of land management practices for moisture recycling within and between regions (te Wierik et al., 2020). Consideration of green water requires a more holistic approach to water governance, including land and soil management and conservation planning. To incentivise sustainable land and water management in areas of particular importance to the global water cycle, financial resources could be provided to compensate regions for foregone local benefits (Zipper et al., 2020). A broader view on water governance could also inform and complement attempts to address the food–energy–water nexus in sustainable development policies (Cai et al., 2018).

Biogeochemical flows

The biogeochemical flow boundaries for both N and P have the same drivers (high input use and low nutrient use efficiency in agriculture) and common impacts (e.g. eutrophication of water bodies). Policies should aim for an integrated and regionally adjusted approach to both nutrient types (Kanter and Brownlie, 2019). The "Global Partnership on Nutrient Management", hosted by the United Nations Environment Programme (UNEP), brings together relevant stakeholders on this issue. It has promoted a joint scientific assessment of both N and P (Sutton et al., 2013), as well as for P individually (Brownlie et al., 2022), with an assessment of N currently in preparation.

Existing international environmental policies could help to coordinate or incentivise national legislation on N and P pollution. In 2022, the CBD's Global Biodiversity Framework adopted the global target of halving the release of excess nutrients into the environment by 2030, which now needs to be translated into action at the national level (Möhring et al., 2023). Similarly, actions aligned with the LDN targets, NDCs and SDGs can be designed in a way that reduces N and P pollution (Kanter and Brownlie, 2019). There are over 2,700 national policies on N worldwide (Kanter et al., 2020), while policies on P pollution are largely absent (Brownlie et al., 2021). However, most N policies incentivise N use in agriculture and focus on waste management to mitigate the impacts of N losses (Kanter et al., 2020); existing mitigation policies in the United States, Europe and China have so far failed to reduce nutrient pollution (Malone and Newton, 2020). Innovative policies that incentivise sustainable agricultural practices and overcome existing barriers to implementation are needed (Gu et al., 2023).

Novel entities

The main challenge with novel entities is the lack of assessment capacity considering the range of novel entities being released into the environment (Persson et al., 2022). The multilateral environmental agreements that address this topic at the global level have been criticised for being too narrow in scope to deal with the breadth of the issue (Wang et al., 2021). More recently, the Global Framework on Chemicals established a set of goals to guide the chemical pollution policies of participating governments (Diamond et al., 2024). In 2022, the United Nations Environmental Assembly mandated a new science-policy panel – the Intergovernmental Panel on Chemicals, Waste and Pollution Prevention – to support national-level action. This new panel is charged with identifying current knowledge gaps, anticipating future challenges and informing existing policy bodies. These activities are also intended to improve information on chemical pollution in low- and middle-income countries, and to guide transformative action to return to a safe operating space for novel entities at regional and global levels (Brack et al., 2022).

Scientific assessments of the problem need to be followed with immediate responses. Inspired by discussions on greenhouse gas emissions, it has been suggested that the global emission of novel entities be capped at a rate consistent with the capacity of the Earth system (Persson et al., 2022). Synergistic actions that simultaneously address climate change, biodiversity loss and novel entities are needed (Baste and Watson, 2022), including the sustainable intensification of agriculture with a focus on the resilience of agroecosystems (Rockström et al., 2017).

Atmospheric aerosol loading

Tackling atmospheric aerosol pollution requires a multifaceted approach, prioritising robust scientific data collection to better understand aerosol impacts and define safe limits. International cooperation and informal agreements are needed to address the transboundary nature of aerosol pollution and leverage synergies with other environmental initiatives (Duvic Paoli and Webster, 2020). Policymakers should strengthen existing environmental regulations and promote cleaner production processes in key sectors, including agriculture, energy and transport. For example, banning the open burning of agricultural residues and improving fertiliser management can significantly reduce aerosol emissions (Campbell et al., 2017). Regulating livestock production to reduce ammonia emissions is another cost-effective measure (Wyer et al., 2022; Gu et al., 2023). Promoting land management practices, such as reforestation, afforestation and agroforestry can mitigate the feedback loop between soil degradation and aerosol emissions, contributing to climate resilience and food security (Casazza et al., 2018).

Policy synergies for avoiding the transgression of the land-based planetary boundaries

While it is important to understand how each boundary can be addressed individually, there is considerable scope for synergies between policies and actions. To capitalise on these synergies, policymakers will require scientific assessments of the interactions between planetary boundaries (Fanzo et al., 2021) based on complex model simulations that evaluate future land-use scenarios. So far, only a limited number of studies have explored possible land-use trajectories, while also accounting for interactions between planetary boundaries (Heck, Donges and Lucht, 2016; Gerten et al., 2020; Drüke et al., 2024).

Specific policies and programmes can be evaluated in terms of their relationships to multiple planetary boundaries. Such assessments can range from large-scale modelling to local-level empirical assessments of existing policies and programmes. For instance, global modelling studies suggest that an improved spatial distribution of land use can contribute to increased terrestrial carbon storage, biodiversity gains and reduced freshwater and fertiliser use (Heck et al., 2018; Gerten et al., 2020). This spatial distribution would also improve productivity in low-yield regions through improved fertiliser use and shifts in crop production to more suitable areas. If this includes transboundary shifts, there must be additional consideration of fair distribution and international trade. A redistribution of fertilisers would not only help to increase nitrogen use efficiencies, but would also increase food sovereignty in food insecure countries (Kahiluoto et al., 2024).

Addressing land degradation holds significant potential for implementation synergies, which deserves more explicit acknowledgement in the global policy architecture. For example, restoring habitats (land) and protecting natural areas (land) are also critical strategies for climate change mitigation and biodiversity conservation (Thonicke et al., 2024). Model simulations suggest that comprehensive strategies to expand conservation efforts, restore degraded lands and implement landscape-level conservation planning could reverse biodiversity trends by mid-century, though results vary across scenarios (Leclère et al., 2020). Most importantly, sustainable agricultural practices and land-use optimisation are crucial for mitigating these impacts and restoring ecosystem integrity (Heck et al., 2018; Von Jeetze et al., 2023).

No single measure or intervention can keep land use and food production within a safe operating space. Even far-sighted land use and agricultural practices need to be complemented by a reduction in food waste/losses and lower levels of industrial meat consumption are needed (Springmann et al., 2018; Gerten et al., 2020). The simultaneous implementation of complementary strategies also yields mutually reinforcing benefits. For example, it has been shown that respecting the land-system boundary is an important measure for combating climate change, and vice versa (Richardson et al., 2023).

The interactions between planetary boundaries pose a challenge to their governance, as knowledge of and responsibility for specific boundaries is scattered across different institutions and levels (Galaz et al., 2012). Additionally, some interactions unfold over decades or centuries, and require institutions that can deal with these timescales (Hanusch and Biermann, 2020). Coordination to stay within planetary boundaries should include a polycentric approach, where actors are connected through global and regional partnerships on specific topics, governed by overarching principles for managing interactions and norm conflicts (Kim & Kotzé, 2021). The SDGs and other sustainability frameworks, like the planetary commons (Rockström et al., 2024), can provide a shared vision and help foster coordination between various actors and governance levels.

4.4 Investment in land-based action

Tackling land degradation requires significant and sustained investment. It also demands a holistic approach that considers both the spatial and temporal dimensions of investment, while prioritising fairness and equity. Incentive structures must align actors at all levels, from global corporations and national policymakers to local communities, with sustainable development priorities that promote sustainable land management. This could involve revisiting established models, such as payments for ecosystem services (PES), tax incentives or conservation grants, while embracing innovative approaches and building fit-for-purpose incentives into land-related policies and programmes. In addition to policy ambition and action, community-driven initiatives, private-sector engagement and philanthropic support play pivotal roles. By fostering cross-sectoral collaboration and prioritising equitable outcomes, resilience and prosperity for all can be achieved within planetary boundaries.

Incentive structures for land-based investment

Financial flows have considerable impact on how land is used and managed (UNEP, 2023). This concerns investments within countries, but also international financial flows. Governments can set regulations that influence land-based investments, for example by introducing tax incentives, subsidies and grants for sustainable land management practices coupled with penalties for non-compliance. Regulatory frameworks that mandate environmental impact assessments for land development projects can also drive investments towards more sustainable practices. The EUDR is one example of this approach, whereby deforestation-free supply chain legislation requires companies to ensure that their products do not contribute to deforestation, thus holding businesses accountable for their sourcing practices (European Commission, 2023).

Governments can also facilitate access to financing by partnering with financial institutions to provide low-interest loans or guarantees for land restoration and conservation projects. Bilateral financial aid, particularly from high-income donors to low and middle-income countries, often includes a condition that funds be used for effective land-based interventions such as sustainable land management, ecosystem restoration, climate adaptation and biodiversity conservation (Persson, 2009; Temple, 2010). The same is true for multilateral funding channels, such as the World Bank and the International Monetary Fund (IMF), which increasingly incentivise investments in similar domains. Other institutions, such as the Adaptation Fund and the Green Climate Fund (GCF), specifically target climate adaptation and mitigation projects, often emphasising co-benefits derived from sustainable land management and biodiversity enhancement, as is the case with the Global Environment Facility (GEF). These funds explicitly focus on outcomes that contribute to both climate goals and broader environmental sustainability (GCF, 2023).

Funding sources for land-based investment

Funding for land-based investments in sustainable management and restoration comes from many different sources. National governments are still the primary funder of land-based interventions, either directly or through multilateral funds and international organisations. Public and private finance for NbS is estimated at USD 200 billion per year, 82% of which is provided by governments (UNEP, 2023). To put this in context, nature-negative global financial flows – those that harm the environment – are estimated to be almost USD 7 trillion per year. Private finance accounts for USD 5 trillion of this nature-negative finance – over 140 times larger than private investment in NbS (UNEP, 2023).

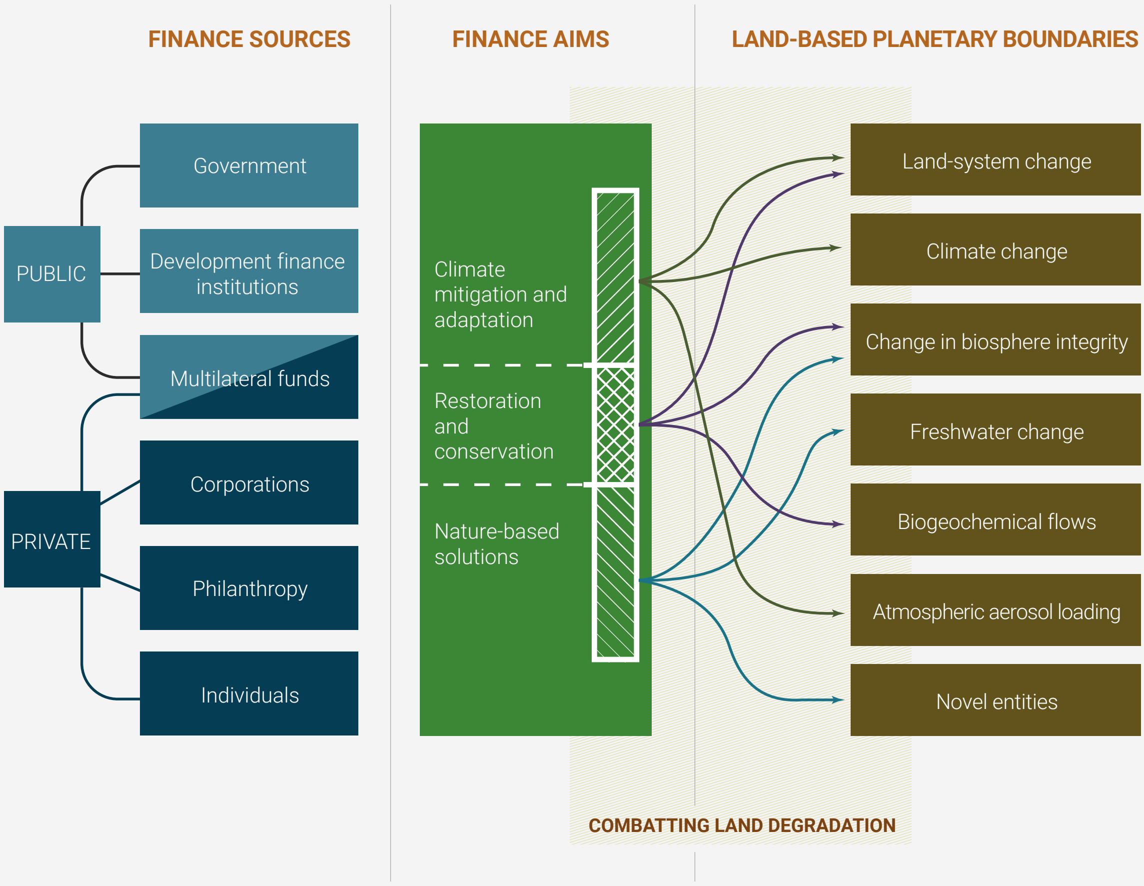
Figure 8 illustrates the flow of finance from different sources, their specific aims and their corresponding land-based planetary boundaries. These often overlap, such that land restoration and conservation can be considered nature-based finance, which also contributes to climate action. Current finance labels classify flows based on specific goals, like climate change mitigation. Expanding these to include their impact on land-based planetary boundaries could help clarify the benefits and trade-offs of financial investments.

A key challenge for effective restoration investments relates to scale and impact. Funds are often only available to organisations that can handle large financial volumes, which neglects the communities and local actors who are often most effective in implementing restoration projects (World Bank, 2020). The GCF, for example, is a major channel for sustainable land management and NbS funding under the climate finance label, but they only grant funding to selected partners (National Designated Authorities and Accredited Entities) who meet high standards for the handling of large-volume GCF projects, thus limiting access for community organisations.

There is a push for more private investment and voluntary contributions aimed at land restoration. There is increasing investment from philanthropic actors, but given the size of the investment needed

Figure 8

Finance sources and aims for staying within the land-based planetary boundaries (own elaboration). Arrows are examples of flows, many more exist.



to achieve LDN, as well as other Rio convention targets, private-sector contributions are crucial but currently fall far short of what is needed (UNEP, 2023). This can partly be explained by the high-risk profile and limited returns inherent in land restoration investments. Furthermore, private sector finance for restoration is biased towards low-risk geographies, neglecting natural regeneration projects. Private investment in restoration programmes is mainly driven by emission reduction commitments, corporate social responsibility and branding considerations, as well as a growing interest in sustainable supply chains (Löfqvist, Garrett and Ghazoul, 2023). ESG criteria are gaining traction in the finance sector, exhibiting correlations with corporate financial performance (Friede, Busch and Bassen, 2015).

Payments for ecosystem services (PES)

Once funding has been secured, it needs to reach the intended beneficiaries and agents of change through specific investment in land, soil, water and biodiversity management models. The most well-known, explicit investment models for sustainable land management and ecosystem services are loosely grouped under the term "payments for ecosystem services" (PES). These are market-based instruments for financing nature conservation (IPBES, 2017), and they have been extensively advocated and put into practice (Shapiro-Garza et al., 2020). While ecosystems provide their services for free, PES programmes assign them a monetary value to create incentives for local actors to manage and steward these natural resources (IPBES, 2017). PES range in scope from large-scale, state-run and state-funded programmes to small-scale sub-national and local projects, often with diverse focus areas including carbon sequestration, watershed protection and biodiversity conservation (Shapiro-Garza et al., 2020).

Specific examples include the REDD+ mechanism, which aims to enhance carbon storage in forests (UNFCCC, n.d.). Developing countries participating in REDD+ framework activities – such as reforestation – can obtain results-based payments for emission reductions. Biodiversity credits are emerging as a financial mechanism for promoting their conservation and restoration, functioning in a similar way to carbon credits but focused on habitats (land) and species diversity (Biodiversity Credit Alliance, 2024). Landowners and organisations can earn biodiversity credits by implementing conservation activities, such as habitat restoration, species protection and sustainable land management practices. Soil carbon credits and carbon farming are similarly gaining traction. Carbon farming involves agricultural land practices that enhance the rate of CO_2 removal from the atmosphere, and its storage in plants and soils. Since such practices incur a cost for the farmer but provide benefits to the public, farmers are given soil carbon certificates that can be traded on the voluntary carbon market.

With these global mechanisms in place, and many national and local actors moving towards PES approaches, a key question is whether such models are effective in ensuring long-term sustainable land and water management. Evidence from rigorous impact evaluations of PES (especially REDD+ programmes) suggest that they are effective in reducing deforestation, but do not necessarily deliver on other co-benefits, such as poverty reduction (Duchelle et al., 2018). A study from Sierra Leone found that a large-scale, voluntary REDD+ project was able to slow deforestation by 30% in treatment versus control communities over 5 years, but it did not reverse deforestation, nor did it influence economic wellbeing or conservation attitudes (Malan et al., 2024). Quasi-experimental evidence from Brazil shows that REDD+ was able to delay forest loss, but not permanently stop it (Carrilho et al., 2022) – a finding echoed by a PES scheme evaluation in Uganda (Jayachandran et al., 2017). More research is needed on the effects of PES and similar programmes, ideally through rigorous impact evaluations that operate with high scientific standards and measure long-term outcomes (Malan et al., 2024).

4.5 Fairness and justice in land-based action

Planetary boundaries operate at the global level, and therefore need to be scaled down to local contexts to guide effective environmental policymaking. This process must not only consider biophysical factors, but also ensure fairness and justice by including socioeconomic and ethical dimensions, such as responsibility, capacity and the right to sustainable development (Häyhä et al., 2016; Sala et al., 2020), as well as cost effectiveness. Principles like actor or national fair shares, and approaches that include environmental footprints, can help to quantify the impacts of human activities and link them to global sustainability targets. Key principles from the 1992 Rio Declaration, such as harm prevention, precaution, sustainable development, equity (inter- and intra-generational), and common but differentiated responsibility, are also relevant in this context (Rajamani et al., 2021).

Strategies for allocating fair shares

The planetary boundaries reflect absolute environmental limits (Ryberg et al., 2020), which means the distribution of resources to one party will impact the resources available to all the others. These must be distributed fairly to prevent overconsumption by some actors that diminishes the shares of others (Ryberg et al., 2020; Kahiluoto et al., 2024). The fair share concept refers to the equitable distribution of responsibilities and actions among different actors to address global challenges, based on their respective capacities, historical contributions and current capabilities (Holz, Kartha and Athanasiou, 2018).

The planetary boundaries framework was not designed for disaggregation, complicating its application to real-world decision-making (Lucas et al., 2020). Applying the fair share principle to planetary boundaries means translating global environmental limits into actionable targets at relevant decision-making scales, using science-based targets to quantify the gap between current impacts and biophysical limits (Sala et al., 2020). To allocate a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fair share of the safe operating space to individual actors, such as countries, regions, cities, communities or companies, these boundaries must be downscaled in a consistent way (Li, Wiedmann and Hadjikakou, 2019).

The allocation landscape is complex, reflecting different ethical perspectives and leading to different outcomes (Ryberg et al., 2020). For instance, wealthier nations may bear more responsibility for mitigation, due to their historical contributions and larger current capacities, while poorer nations might need to increase consumption to improve living standards. Some allocation methods emphasise historical responsibility for environmental degradation, while others prioritise the ability to act (Häyhä et al., 2016), which is determined by spatial heterogeneity and varying capacities to address environmental issues (Lucas et al., 2020).

Fair share discussions are most advanced in the context of the climate change boundary, particularly regarding the distribution of responsibility for emission reductions. The principle of common but differentiated responsibilities, as outlined in the Paris Agreement, acknowledges the varied capacities of nations (Häyhä et al., 2016), fuelling debates on burden-sharing and equity in climate negotiations (Meinshausen et al., 2015). Various approaches have been proposed: the grandfathering approach allocates responsibilities based on historical environmental pressure (Lucas et al., 2020), the equal-per-capita approach distributes responsibility according to population size, and the ability-to-pay approach uses per-capita GDP as a basis for allocation. Cost effectiveness aims for the most impactful mitigation actions at the lowest cost, but it is occasionally included in the list of principles. With the Paris Agreement's emphasis on voluntary targets through NDCs, the challenge of ensuring fair shares and accountability remains unresolved. There is no international mechanism to enforce compliance, address overshooting of national carbon budgets or censure failures to meet NDC targets (Fanning and Hickel, 2023).

Effectively responding to land degradation requires the downscaling of fair share allocations to national or local levels, and addressing the socioeconomic drivers of degradation in that specific context. In terms of downscaling planetary boundaries, the principle of equal shares per capita is common (Ryberg et al., 2020; Li et al., 2021), but has limitations when applied to geographically or temporally constrained resources like freshwater use (O'Neill et al., 2018). The application of equity-per-capita-based approaches is challenging when targets are difficult to quantify. Unlike climate change, which has a clear, global metric (CO_2 equivalent) alongside robust data sources, land-system change is highly localised and context-specific, with multiple contributing factors, making it difficult to assign responsibility (Lucas et al., 2020; Ferretto et al., 2022).

Currently, no globally accepted principle exists for sharing responsibility to stay within the safe operating space, making the selection of an allocation method a political decision (Dao, Peduzzi and Friot, 2018; Lucas et al., 2020). Nations have differing preferences, and the choice – whether based on equality, responsibility or capacity – affects global fairness and environmental justice (Ryberg et al., 2020). This highlights ethical dilemmas in downscaling planetary boundaries, particularly concerning national environmental footprints that transcend borders, and the varying capacities of countries to tackle environmental issues (Häyhä et al., 2016). Successful responses that keep humanity within planetary boundaries relies on integrating environmental, economic and social systems while addressing ethical challenges related to resource distribution.

A concrete proposal for distributing responsibility is the per-capita convergence approach, which accounts for current unequal contributions to planetary boundary transgressions while aiming for equal-per-capita distribution over time (Williges et al., 2022). For practical applications, this approach would have to be operationalised across different governance levels, from national to local. Moreover, feedback loops between planetary boundaries must be taken into account, as they are interconnected. A holistic, global approach is essential for considering the supply chain and consumption teleconnections across national borders (Li et al., 2021).

National downscaling of planetary boundaries

To date, national downscaling of planetary boundaries has been undertaken in relation to several countries and regions, including detailed studies on the European Union, India, the Netherlands, New Zealand, South Africa, Sweden and Switzerland (Ferretto et al., 2022).

Countries may choose different approaches when downscaling planetary control variables to their national administrative areas. Apart from theoretical considerations regarding the different biophysical, socioeconomic and ethical downscaling mechanisms, the choice also depends on the information available at the national level (Häyhä et al., 2016). Here, we briefly present four studies conducted in different contexts, using different methodologies.

European Union: Sala et al. (2020) evaluated how production and consumption in the European Union impacts on planetary boundaries using life cycle assessment-based indicators. Consumption-based indicators showed that the European Union was close to transgressing several global boundaries, despite representing only 10% of the world's population. However, they also found a high variability between different indicators used to represent planetary boundaries through life cycle assessment.

India: Priyadarshini and Abhilash (2020) assessed the safe operating space for India using production-based indicators, with a focus on national policy implications. They also evaluated social boundaries, and in some cases replaced planetary boundary control variables with variables that were more relevant to the national context. The findings indicate major transgressions of the boundaries for aerosol loading, biogeochemical flows and freshwater change, and the importance of addressing gender inequality in sustainable development policies.

South Africa: Cole et al. (2014) examined safe and just boundaries for South Africa based on national environmental concerns identified through a stakeholder dialogue. They used production-based indicators, with all boundary control variables being adjusted to national circumstances and data. The results showed an improvement in social indicators since 1994, but increasing pressure on environmental boundaries, with four already having been transgressed.

Switzerland: Dao et al. (2018) analysed Switzerland's environmental performance by comparing its ecological footprint to limits within five planetary boundaries. Using an equal per-capita allocation principle, and considering both historical and future resource use, they linked these boundaries to socioeconomic activities. The findings revealed that Switzerland exceeds four of the five boundaries – climate change, biogeochemical flows, ocean acidification and biosphere integrity – highlighting significant environmental pressures driven by the country's consumption patterns.

Multiple countries: O'Neill et al. (2018) calculated national boundaries and social thresholds for more than 150 countries, using consumption-based footprints and social indicators. The majority of countries used resources above their per-capita environmental boundaries. There was a clear relationship between reaching social thresholds and crossing biophysical boundaries, although the results also suggested that resource use could be significantly reduced in wealthy countries without compromising social outcomes.

Environmental footprints as a tool for downscaling

Frameworks like the Doughnut Economics model (Raworth, 2017) and Safe and Just Earth System Boundaries (Gupta et al., 2024) integrate planetary boundaries with social justice considerations, but need clear metrics for action. Environmental footprints, such as those proposed by Vanham et al. (2019), provide a way to translate these frameworks into measurable impacts, quantifying the extent to which human activities exceed planetary boundaries (Fang, Heijungs and De Snoo, 2015; Ferretto et al., 2022). Footprints assess impacts across spatial scales and value chains, identifying opportunities to reduce distant environmental pressures, such as through dietary changes (Vanham et al., 2019). While widely used footprints – like carbon, water, and ecological – are common, others such as energy, land, and nitrogen footprints are less standardised but equally critical for identifying key sources of emissions and degradation (Laurent and Owsianiak, 2017). By connecting abstract environmental goals with concrete policy action, footprints can help countries adopt multi-criteria assessments for more targeted sustainability policies (Dao, Peduzzi and Friot, 2018; Ferretto et al., 2022). A key advantage of using environmental footprints is their ability to assign responsibility to final consumers, linking consumption patterns to their environmental impacts across international supply chains (O'Neill et al., 2018).

Although high-income countries represent a small fraction of the global population, they are responsible for a disproportionately large share of resource use, with a significantly greater material footprint than lower-income nations, driving global environmental degradation (O'Neill et al., 2018; Li et al., 2021; Hickel et al., 2022). This can also manifest through "leakage", where impact is effectively exported to other geographical locations. For example, wealthier countries have reduced their domestic phosphorus use but rely on imports of agricultural products grown with phosphorous-intensive farming methods, resulting in environmental degradation in food-exporting countries like China and Brazil (Li, Wiedmann and Hadjikakou, 2019).

The EU Environmental Footprint tool assesses environmental performance in 16 impact categories aligned with the planetary boundaries and SDGs (Sala et al., 2020), including land use, water use and resource use from fossil sources. The tool includes key quantitative metrics for each category – land use, for example is evaluated through soil erosion, quantified in kilograms of soil loss – and reveals that EU consumption currently exceeds several planetary boundaries, including climate change and land-system change boundaries, despite comprising less than 10% of the global population. Similarly, Switzerland has already transgressed four planetary boundaries, underscoring the urgent need for national action (Dao, Peduzzi and Friot, 2018).

An analysis of the impact of food production and consumption on five land-based planetary boundaries, including cropland use (Springmann et al., 2018) informed the EAT–Lancet Commission's development of the Planetary Health Diet, aimed at staying within planetary boundaries while safeguarding human health (Willet et al., 2019). Building on this example, a combined consumption-based and production-based approach to allocating national-scale cropland environmental limits would be determined by population and the biophysical availability of arable land (Shaikh, Hadjikakou and Bryan, 2021; Ferretto et al., 2022; Gupta et al., 2024).

In a consumption-based approach, agri-food impacts are distributed across the entire product life cycle, tracing effects along the value chain to the country of final consumption. In contrast, a production-based approach assigns these impacts to the country of origin. This dual framework is crucial for ensuring equitable access to global land resources and aligning national targets with global sustainability goals (Shaikh, Hadjikakou and Bryan, 2021). Integrating both perspectives allows for a more accurate assessment of the environmental pressures associated with domestic production and international trade, providing a more comprehensive understanding of direct and indirect drivers of land degradation.

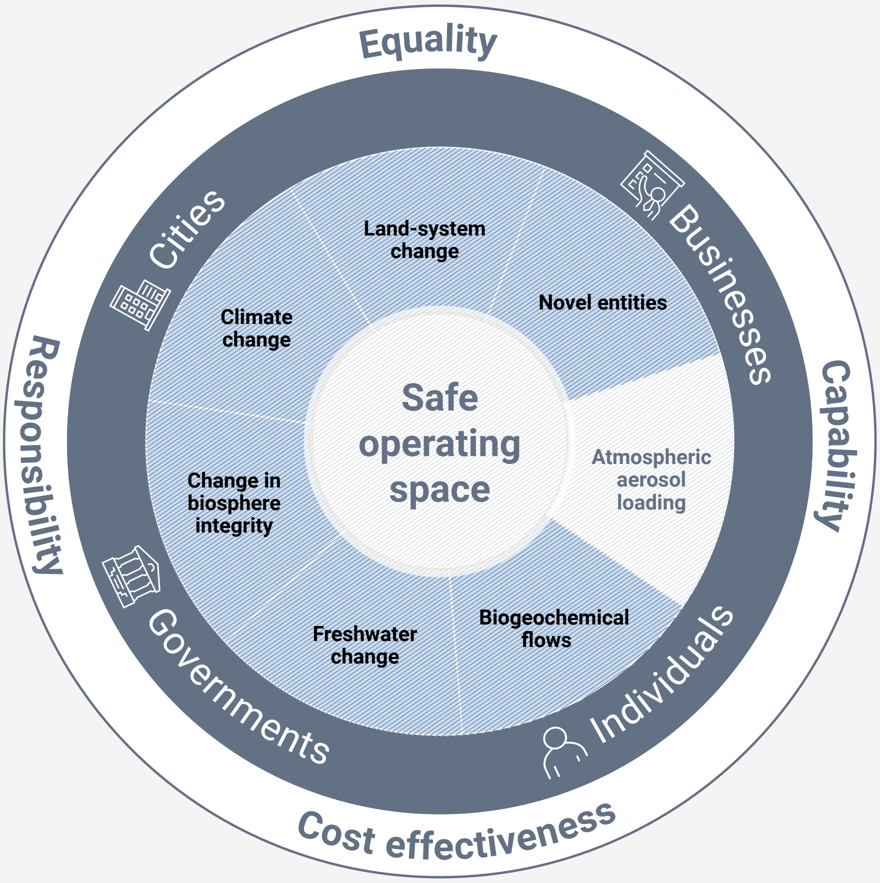
No single footprint captures the full complexity of environmental impacts. Footprints are interconnected, and addressing one without considering others can create trade-offs (Fang, Heijungs and De Snoo, 2015). For instance, focusing solely on the carbon footprint may overlook impacts on land use. This narrow approach risks creating imbalances in resource management and undermining the overall sustainability of ecosystems. A “footprint family” based on the nine planetary boundaries has been proposed, incorporating indicators such as pollutant emissions and resource consumption (Wu et al., 2021). This integrated method aligns with the planetary boundaries framework by addressing all boundaries collectively, enhancing decision-making, increasing transparency about those responsible for environmental degradation, and promoting strategies to mitigate boundary transgressions.

Integrating environmental footprints into policymaking

Figure 9 provides a conceptual overview of the key actors relevant to staying within land-based planetary boundaries, as well as various options for allocating fair shares. Nations, cities, businesses, individuals (including farmers) and other stakeholders are called upon to help prevent or reverse trans-

Figure 9

Principles and actors in allocating fair shares in the context of the land-based planetary boundaries (based on Höhne et al., 2014). All land-based boundaries are transgressed, except for atmospheric aerosol loading. Governing principles are depicted in the outer circle, while actors are shown in the circle between the planetary boundaries (centre) and the governing principles.



gressions of the planetary boundaries. Cities and businesses are key actors in this regard, as they are more agile and can quickly implement changes to reduce their environmental footprint and contribute to equitable and transformative land-based actions (Gupta et al., 2024).

Reconciling human activities with ecological limits and promoting social justice requires a fundamental shift in current consumption patterns and resource allocations. Recent studies emphasise the land-based impacts of individual food consumption and dietary habits (Willet et al., 2019; Gerten et al., 2020; Gupta et al., 2024; Humpenöder et al., 2024; Ruggeri Laderchi et al., 2024). For instance, animal-based foods contribute the most to dietary impacts on land-use boundaries (Hallström et al., 2022), and food consumption significantly influences the EU's carbon footprint, highlighting the urgent need for a 90% reduction in food-related emissions (Sala et al., 2020).

Although national and local governments often bear the responsibility for finding solutions to environmental problems, individual consumers can help to reduce environmental impacts, e.g. by adopting sustainable dietary habits. Environmental footprint tools contribute to these changes by raising awareness of the critical role individuals play in driving change. Utilising environmental footprints to assess consumption effects can inform the allocation of responsibility throughout the entire value chain, and contribute to policy interventions and transformative action in areas with significant environmental impacts.

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CHAPTER 5

Future directions

Land degradation poses a severe threat to the environment and human life on Earth, leading to the loss of biodiversity and increasing vulnerability to the impacts of climate change, which in turn threatens agricultural productivity, food security and livelihoods. If we do not recognise the central role of land and act accordingly, the repercussions will be felt across all domains of life and far into the future, increasing challenges for generations to come. Transformative action is therefore needed for a future based on planetary sustainability and prosperity for all.

5.1 Key findings

This special report on land set out to review the current state of scientific research on global land degradation, and opportunities for transformative action towards sustainable land management, through the lens of the planetary boundaries framework. Current trends in land use, management and governance are pushing the seven land-based planetary boundaries into an increasingly dangerous zone, raising serious concerns about future human wellbeing. Except for atmospheric aerosol loading, all of the land-based planetary boundaries have been transgressed.

Land-system change, driven primarily by the expansion of cropland and livestock grazing, is threatening terrestrial ecosystems and their regulatory functions for the planet. Climate change impacts continue to intensify and worsen, marked by rising temperatures, changing precipitation patterns and an increased frequency and severity of extreme weather events. Biosphere integrity is under threat from species extinction and the degradation of habitats and diminishment of ecosystem functions and services. Freshwater change is marked by over-abstraction and intensified dry and wet periods, leading to water scarcity and increased environmental hazards. Biogeochemical flows, in particular those of N and P, are destabilised by the excessive agricultural use of fertilisers, resulting in nutrient imbalances and eutrophication. Novel entities continue to emerge and pose unknown risks to the environment and humanity. Only aerosol loading, which affects regional and global climate patterns, is still within the safe operating space. Overall, the current trajectory of the land-based planetary boundaries indicates a need for immediate, coordinated and synergistic efforts at all policy and decision-making levels to ensure consistent and mutually reinforcing transformative action.

The land-based planetary boundaries cannot be considered in isolation as they are embedded in complex socioeconomic systems, where human activities on land profoundly impact and are impacted by other environmental changes. This report highlights various socioeconomic challenges and their linkages to the land-based planetary boundaries. Women, youth, Indigenous peoples and local communities are often disproportionately affected, having limited access and control over natural resources, putting them at a disadvantage in terms of economic opportunities, decision-making power and resilience to environmental change. Governance issues play a key role, as ineffective or corrupt land governance tends to exacerbate inequalities and hinder the uptake of sustainable land management practices. To ensure a just transition, these and other socioeconomic challenges need to be fully considered when designing transformative actions for staying within the Earth's safe operating space.

Finally, this report examined transformative actions related to agricultural production, ecosystem restoration and water resource management, which contribute to combating land degradation and avoiding further transgressions of the land-based planetary boundaries. The ecological restoration of grasslands and peatlands is key to mitigating climate change and enhancing biodiversity, while integrated water resource management can increase efficiency and enhance drought resilience. These transformative actions hold great potential for addressing land degradation, but their implementation will require an enabling environment, conducive policies, significant investments and an integration of principles of fairness and justice across multiple sectors and scales.

5.2 Recommendations for action

This special report on land illustrates examples of transformative action and promising pathways to more sustainable land use, management and governance. At the same time, it has revealed critical gaps in implementation that must be addressed with great urgency.

Policy as a critical enabler

At the forefront of these efforts, international bodies and governments at all levels should lead the way by formulating, implementing and enforcing policies that support responsible governance, strategic investment and accessible finance for sustainable land use. This includes preventing future land degradation and restoring land that has already been degraded, as well as recognising that all biomes play a critical role in maintaining planetary resilience. Nature-based solutions and ecosystem-based approaches offer the promise of multiple benefits, but will require greater political and financial attention to meet the growing demand for land-based commodities and services.

Evidence for effective policies

Science can play a key role by providing the evidence needed for informed decision-making, and to guide the design and implementation of effective policies. Although land plays an important role in achieving nearly all of the SDGs and preventing further planetary boundary transgressions, it remains insufficiently represented in current scientific models and assessments. These are essential for a more comprehensive understanding of land degradation and land-system change, for example by using control variables that consider a wider range of terrestrial biomes, the dynamics of human-dominated landscapes and the importance of soil processes. These aspects would better capture land degradation and its pivotal role in many environmental challenges. Equally important are knowledge gaps regarding the enablers for effectively addressing land degradation. Rigorous research can support the prioritisation and optimal combination of enabling factors to create a conducive environment and coherent policy bundles for combating land degradation and preventing boundary transgressions.

Investments for sustainable land use

The financial resources available for addressing land degradation and related challenges lag far behind the scale of funding required. Investing in sustainable land use is not just a moral imperative, it is a rational economic decision that ensures long-term viability, socioeconomic stability, and greater resilience for people and nature. While some funds and donors do emphasise multiple sustainability goals, in particular those linked to the three Rio conventions, there is significant scope to restructure incentives and to mainstream land use, management and governance into prevailing investment models, including funding for climate, biodiversity and food security.

Scientific frameworks in practice

The planetary boundaries framework illustrates the central role of land and its linkages to other environmental challenges. To operationalise this global framework, boundaries must be reoriented to local, national and regional scales to inform and guide transformative land-based actions. Sub-global dynamics are highly relevant for land-system change and biosphere integrity, which largely operate on a regional level. While the initial proposal for the planetary boundaries relied primarily on coarse global values for boundary thresholds, the framework is increasingly supported by detailed, high-resolution datasets on processes such as biogeochemical flows and freshwater change. These datasets can provide a basis for applying a planetary boundary to a local context via the actor fair shares approach, or as a local safe operating space. New indicators, improved modelling tools and other advanced methodologies are needed to quantify the contribution of transformative land-based actions to halt land degradation at different scales.

Endnotes

1 The Earth system includes all flows of energy and matter at the Earth's surface. It therefore encompasses the interactions between the geosphere, biosphere and anthroposphere. Major components include the atmosphere, the large ice shields, marine and terrestrial ecosystems, and human populations, including their energy systems and production/consumption patterns (Lenton, 2016; Steffen et al., 2020).

2 In this report, we define sustainability based on the five FAO principles as the ability to increase productivity and economic growth, protect natural resources, enhance resilience, improve livelihoods and adapt governance to new challenges (FAO, 2024b). Conversely, any practice that undermines this ability is considered unsustainable.

3 There is an ongoing scientific debate about whether human impact on Earth warrants the designation of a new geological epoch. In March 2024, the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS) rejected the proposal for such an epoch. However, the concept of the Anthropocene remains a significant framework for understanding the profound and unprecedented impacts humans have had on various Earth system processes.

4 See: https://greencitykigali.org/.

5 Forest degradation can be defined as "[c]hanges within the forest which negatively affect the structure or function of the stand or site, and thereby lower the capacity to supply products and/or services" (FAO, 2005).

6 See: https://casestudies.naturebasedsolutionsinitiative.org/case-search/.

7 See: https://plantix.net/.

8 See: https://www.kakaoforum.de/en/about-us/german-initiative-on-sustainable-cocoa/.

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List of abbreviations

ACLED	Armed Conflict Location and Event Data
ADC	Attestation de Détention Coutumière
AOD	Aerosol optical depth
BECCS	Bioenergy crop production combined with carbon capture and storage
BMEL	German Federal Ministry of Food and Agriculture
BMZ	German Federal Ministry of Economic Cooperation and Development
BRG	Indonesian Peatland Restoration Agency
CBD	Convention on Biological Diversity
COP	Conference of the Parties
ELD	Economics of Land Degradation
E/MSY	Extinctions per million species per year
ESG	Environmental, social and governance
EU	European Union
EUDR	European Union Deforestation Regulation
FAO	Food and Agriculture Organization of the United Nations
GCF	Green Climate Fund
GDP	Gross domestic product
GEF	Global Environment Facility
GISCO	German Initiative on Sustainable Cocoa
GPS	Global positioning system
HANPP	Human appropriation of net primary production
ICS	International Commission on Stratigraphy
IMF	International Monetary Fund
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISFM	Integrated Soil Fertility Management
IUGS	International Union of Geological Sciences
LDN	Land degradation neutrality
LSLA	Large-scale land investment
NbS	Nature-based solutions
NCP	Nature's contributions to people
NDCs	Nationally Determined Contributions
NGO	Non-governmental organisation
PES	Payments for ecosystem services
R&D	Research and development
REDD+	Reducing emissions from deforestation and forest degradation, plus conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks
RSPO	Roundtable on Sustainable Palm Oil
SDGs	Sustainable Development Goals
SLM	Sustainable land management
UCDP	Uppsala Conflict Data Program
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
UAV	Unmanned aerial vehicle
WFD	Water Framework Directive
WWF	World Wide Fund for Nature

List of figures

Glossary

This glossary defines key terms as the authors interpret them in this report. Where definitions from other sources are used, this is indicated.

Actor fair shares: The equitable distribution of responsibilities and actions among different actors to address global challenges like land degradation, based on their respective capacities, historical contributions and current capabilities (Holz et al., 2018).

Amplifying interactions: Interactions between planetary boundaries, where impacts on one boundary can cause changes in the state of another boundary, often leading to the easier transgression of the affected boundary.

Atmospheric aerosol loading: The concentration of airborne solid or liquid particles that influence climate by affecting temperature and precipitation patterns. Aerosols can be released from human activities or natural sources.

Biogeochemical flows: The flow of chemical elements that are essential for life, and which circulate throughout the Earth system. The planetary boundaries framework focuses specifically on nitrogen and phosphorus.

Biosphere integrity: The maintenance of the overall dynamic and adaptive character of the biosphere, which encompasses all ecosystems and living organisms on Earth and co-regulates the state of the planet by influencing energy balance and biogeochemical flows.

Climate change: Changes in the Earth's radiative balance – for example, through the emission of greenhouse gases – which can alter the long-term state of the atmosphere, leading to increases in global temperatures and changes in precipitation patterns.

Climate change adaptation: The process of adjusting to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities (IPCC, 2023).

Climate change mitigation: The process of taking action to reduce emissions or enhance the sinks of greenhouse gases (IPCC, 2023).

Earth system: All flows of energy and matter at the Earth's surface. Major components include the atmosphere, the large ice shields, marine and terrestrial ecosystems, and human populations, including their energy systems and production/consumption patterns.

Enabling environment: A set of factors that facilitate the adoption and long-term implementation of specific actions. These factors can include favourable policies, financing, institutional learning and inclusive modes of collaboration, among others.

Environmental footprint: The impact of human activities on the environment, including the allocation of key contributors. It is typically based on resource use and waste emissions.

Freshwater change: The alteration of the global hydrological cycle on land, including surface and groundwater flows, terrestrial precipitation, evaporation and soil moisture.

Governance: The structures, processes and practices through which various stakeholders – including governments, international bodies, businesses, civil society and local communities – make decisions, and establish and reinforce policies and actions to achieve common goals. It can be measured through the ability to make and enforce rules, as well as to deliver services (Fukuyama, 2013).

High-risk zone: The zone entered when a planetary boundary is severely transgressed. Conditions in a high-risk zone have deviated significantly from safe levels, making non-linear, potentially irreversible environmental changes more likely.

Land-based planetary boundaries: Intimately linked to land and land-use processes, these are boundaries for land-system change, climate change, change in biosphere integrity, freshwater change, biogeochemical flows, novel entities and atmospheric aerosol loading.

Land degradation: The "reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices" (UNCCD, 1994).

Land restoration: A continuum of activities that avoid, reduce and reverse land degradation with the explicit objective of meeting human needs and improving biosphere stewardship (UNCCD, 2022).

Land-system change: This comprises both the conversion of natural ecosystems to human-dominated landscapes, and the transformation of terrestrial ecosystems through changing environmental conditions.

Multilateral agreement: A legally binding agreement between two or more parties.

Novel entities: Novel anthropogenic introductions to the Earth system, including synthetic chemicals, plastics and genetically modified organisms.

Planetary boundaries: Scientifically determined thresholds within which humanity can operate safely. Crossing these thresholds can lead to catastrophic environmental change and destabilise the Earth system with serious consequences for economic development and equity.

Safe operating space: A state of the Earth system that enables humanity to develop and is capable of sustaining contemporary human societies over the long term. It encompasses environmental conditions similar to, but not identical with, those of the Holocene epoch, which began about 11,700 years ago.

Sustainability: The ability to simultaneously increase productivity and economic growth, protect natural resources, enhance resilience, improve livelihoods and adapt governance to new challenges (FAO, 2024). Conversely, any practice that undermines this ability is considered unsustainable.

Sustainable land management: A broad term encompassing local practices related to agricultural production or ecosystem restoration, and land-based policies and investments. It enables various societal needs, including food, health and shelter, to be met within the safe operating space of the Earth system.

Transformative action: Any action leading to positive systemic change, improving both environmental and human wellbeing. Such actions include the implementation of concrete practices, enhancing governance frameworks, channelling investments into land-based action, and considering aspects of fairness and justice.

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