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Reviews and syntheses: Current perspectives on biosphere research 2025: from poly-crisis to poly-solutions

Friedrich J. Bohn [1,2], Giles B. Sioen[3,4], Ana Bastos[5], Yolandi Ernst[6], Marcin P. Jarzebski[3,4], Niak Sian Koh[7], Romina Martin[8], Anja Rammig[9], Alex Godoy-Faúndez[10], Alexandros Gasparatos[11], Alvaro G. Gutiérrez[12], Amanda J Aceituno[8,13], Andra-Ioana Horcea-Milcu[14,15], Andrea Marais-Potgieter[6], Ayyoob Sharifi[16], Caroline Howe[17], Cornelia B. Krug[18], Eduardo E. Acosta[19], Emmanuel F. Nzunda[20], Erik Andersson[21], Hans-Otto Pörtner[22], Helen Sooväli-Sepping[23], Ishihara Hiroe[4], Ivan Palmegiani[24], Kaera Coetzer[25], Kirsten Thonike[26], Krizler Tanalgo[27], Lisa Biber-Freudenberger[28], Nicholas O. Oguge[29], Mi S. Park[30], Milena Gross[31], Pablo De La Cruz[32], Paula R. Prist[33], Peng Bi[34], Rivera Diego[35], Roman Isaac[31], Ro McFarlane[36], Sinikka J. Paulus[37,38,39], Stefanie Burkhart[40,41,42], Sung-Ching Lee[37], Susanne Müller[43], Uchi D. Terhile[44], Wan-Yu Shih[45], William K. Smith[46], Viola Hakkarainen[47], Virginia Murray[48], Yuki Yoshida[49], Yohannes T. Damtew[34,50], Zeenat Niazi[51,52]

1. BAM Nachhaltigkeit Beratung Medien, Berlin, Germany
2. Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany
3. Sustainable Society Design Center, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan;
4. Future Earth Global Secretariat, Tokyo, Japan
5. Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany
6. Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa
7. Department of Biology, University of Oxford, Oxford, UK
8. Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
9. TUM School of Life Sciences Weihenstephan, Technische Universität München, Freising, Germany
10. Sustainability Research Center, Facultad de Ingenieria, Universidad del Desarrollo
11. Institute for Future Initiatives, The University of Tokyo, Tokyo, Japan
12. Departamento de Ciencias Ambientales y Recursos Naturales Renovables, Facultad de Ciencias Agronómicas, Universidad de Chile. Instituto de Ecología y Biodiversidad (IEB)
13. Leuphana University Lüneburg, Germany
14. Kassel Institute for Sustainability, University of Kassel
15. Faculty for Humanities and Cultural Studies, University of Kassel
16. The IDEC Institute, Hiroshima University, Japan
17. Imperial College London, UK
18. University of Zurich, Switzerland
19. Independent researcher in indigenous epistemologies and climate change. Colombia
20. Sokoine University of Agriculture, Tanzania
21. University of Helsinki, Sweden
22. Alfred-Wegener-Institute, Germany
23. Tallinn University of Technology, Estonia
24. Leibniz-Institute for Zoo- and Wildlife Research (IZW), Berlin, Germany
25. Department of Geography, Geoinformatics and Meteorology, University of Pretoria, South Africa
26. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
27. Eco/Con Lab, University of Southern Mindanao, Philippines
28. Center for Development Research, Bonn University
29. University of Nairobi, Kenya

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30. Graduate School of International Agricultural Technology, Seoul National University, Republic of Korea
31. Social-Ecological Systems Institute, Leuphana University Lüneburg, Germany
32. Ministerio de Ambiente y Desarrollo Sostenible-Colombia, Colombia
33. IUCN, Forests and Grasslands Programme, United States
34. School of Public health, University of Adelaide, Adelaide, Australia
35. Centro de Recursos Hídricos para la Agricultura y la Minería, Facultad de Ingeniería, Universidad del Desarrollo, Chile
36. Faculty of Health, University of Canberra. Canberra, Australia
37. Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Jena, Germany;
38. Institute of Geoscience, University of Jena, Jena, Germany;
39. Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany
40. Institute for Social-Ecological Research (ISOE), Frankfurt/Germany
41. Institute of Ecology, Diversity and Evolution, Goethe University Frankfurt/Germany
42. Senckenberg Biodiversity and Climate Research Centre SBiK-F, Frankfurt/Germany
43. TU Dresden, Germany
44. Federal University Dutse, Nigeria
45. National Taiwan University, Taiwan
46. School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, 85721, USA
47. Sustainability Education and Transdisciplianry Research Institute, School of Sustainability, Leuphana University Lüneburg
48. UK Health Security Agency, London, UK
49. National Institute for Environmental Studies, Japan
50. Haramaya University, School of Environmental Health, Harar, Ethiopia
51. TERI School of Advanced Studies, New Delhi, India
52. Society for Development Alternatives, New Delhi, India

Correspondence to: Friedrich J. Bohn (friedrich@bock.am)

Abstract. Accelerating changes across various Earth system compartments, coupled with intensifying geopolitical and socio-economic turbulences, have increased the interdependence of global crises, resulting in a complex polycrisis.

This review summarises recent advances in biosphere research, focusing on ten topics selected for their thematic relevance to biodiversity, ecosystem functioning, socio-economic interactions and anthropogenic threats to the biosphere.

An interdisciplinary expert panel identified these themes from a public survey, based on scientific relevance and evidence.

The aim is to inspire future research and provide decision-makers with actionable solutions. The themes highlight innovative opportunities to enhance resilience, advance the understanding of dryland dynamics, promote a sustainable bioeconomy, foster greener urban planning, regulate disease dynamics, support nature-based solutions, mitigate the impact of conflict on the biosphere, address demographic challenges to ecosystem stewardship, integrate indigenous knowledge and embed biosphere valuation in decision-making processes.

Finally, we emphasise the importance of polysolutions that address the target issue, while simultaneously generating positive outcomes in neighbouring economic, social and ecological domains. To ensure planetary stability, this review highlights the urgent need for policies and investments that prioritise the protection, restoration and sustainable management of the biosphere.

https://doi.org/10.5194/egusphere-2025-3619
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1 Introduction

The accelerating changes in the various compartments of the Earth system, and the intensifying geopolitical and socio-economic turbulence are leading to greater interdependence of the various crises and rising uncertainty about future trends, taking us into an unprecedented phase in human history (Friedlingstein et al., 2025; IPBES, 2019; IPCC, 2023b; Ripple et al., 2024) . For years, scientific studies have shown that the threats to the Earth system endanger a habitable planet and human well-being (Jaureguiberry et al., 2022; Matthews et al., 2022; Pfenning-Butterworth et al., 2024; Richardson et al., 2023; Romanello et al., 2022). The future of humanity depends on our creativity, ethical resolve, and perseverance in addressing ecological overshoot and implementing just and sustainable solutions (Dickson et al., 2021; O'Brien et al., 2025). Although the biosphere and societies are under threat from various crises, it remains an essential component of efforts to address these issues and offers a variety of appealing solutions (Balvanera et al., 2022; Bohn, et al., 2025).

There is growing recognition from governments and businesses, but also NGOs, CBOs and other initiatives, that our societies need to fully account for human impacts on nature and balance our demands for renewing and non-renewing resources (P. Dasgupta & Treasury, 2022; TNFD, 2023). A whole-of-society perspective is needed, as scholars also highlight that fair and just transformations are crucial to reach the global sustainability goals for climate and biodiversity in the areas of food supply, energy, and material systems, thus ensuring human well-being in the long term (Folke et al., 2021; Griggs et al., 2013; Jiménez-Aceituno et al., 2025; Leach et al., 2018; A. Martin et al., 2020; McDermott et al., 2023; Obura et al., 2023; Pickering et al., 2022; Schlesier et al., 2024). Despite the increasing calls to 'live in harmony with nature', we still need improved assessments and concrete solutions in relation to this goal. This becomes even more challenging when considering not only one, but several of the Earth System crises, which have their nexus in the biosphere (e.g. Mahecha et al., 2024; McElwee et al., 2024). Furthermore, there is an emerging critique that the concept of "sustainability"—in the sense of maintaining the status quo and/or minimizing harm—may no longer be sufficient to address the scale, depth, and interconnected nature of current global challenges (Buckton et al., 2023; Fischer et al., 2024).

Here, we define the biosphere as the global ecological system that includes all living organisms and their interactions. We aim for a plural representation of perspectives on the biosphere in this summary, and combine in particular the socio-economic, political, and justice views. This interdisciplinary approach is expected to bridge between the longer established and recently evolving strands of biosphere related sciences. Here we aim to build on and move beyond well-established findings such as the need to drastically reduce fossil fuel emissions, the biggest lever in the fight against climate change (Friedlingstein et al., 2025; IPCC, 2021) — and provide recent scientific insights that go beyond annual reports from the WMO, FAO and others (e.g. FAO, 2024a, 2024b; WMO, 2025). Alongside these special reports, numerous scientists have published summaries on a variety of subjects - sometimes under the heading 'Scientists' Warning' (e.g. Fernández-Llamazares et al., 2021; Harvey et al., 2023; C. C. Pereira et al., 2024; Sachs et al., 2025) or within the annual '10 New Insights in Climate Science' series (e.g. Bustamante et al., 2023; M. A. Martin et al., 2022; Schaeffer et al., 2025).

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

The second synthesis in the Current Perspectives on Biosphere Research series reviews the latest policy-relevant, peer-reviewed, biosphere-related research findings, with the aim to inform political and economic decision-making in the years ahead (see also Bohn et al., 2025). This international, interdisciplinary effort complements existing assessments and bridge the gap until the next major assessment reports are published. We hope it will inspire scientists to pursue interdisciplinary questions and holistic solutions to address the polycrisis of the Earth system.

We present this year ten themes that are gaining traction in the scientific community with recent and significant findings from biosphere research, based predominantly on peer-reviewed literature published since January 2023. Each theme summarizes background information and the latest scientific advances, identifies challenges and offers strategies for maintaining thriving ecosystems or enhancing degraded ecosystems and their diverse contributions to human society. For each theme, we emphasize the synergies, trade-offs, and implications for other related themes in this synthesis. This contributes to a more comprehensive understanding of processes in the biosphere, their mutual dependencies with more strategic human decisions, and to stimulate future research questions.

Section 3.1 emphasizes the relevance of the resilience concept for decision-making, while Section 3.2 summarizes recent findings on drylands. Strategies to promote a sustainable bioeconomy are presented in Section 3.3. Section 3.4 analysis the multiple benefits of compact, green cities, while cautioning that careful planning is essential to prevent social and ecological harm. Section 3.5 outlines the role of ecosystems in regulating diseases, and Section 3.6 discusses why and how to support nature-based solutions. Section 3.7 examines the impacts of conflict on the biosphere and biosphere research. Section 3.8 addresses demographic challenges that differ between the Global North and South. Section 3.9 highlights the value of Indigenous knowledge and proposes ways to integrate it more effectively into decision-making. Finally, Section 3.10 offers an overview of diversity of values and their incorporation into decision-making and sustainability transformations.

With this study, we hope to raise awareness of the various challenges within the biosphere – emphasizing links across environmental and socio-economic domains – and their interlinkages with recognized crises within the Earth system, to provide synergistic strategies for addressing complex challenges and to stimulate future research questions.

2. Method

We adopted the methodology outlined in Bohn et al. (2025), with further refinements in several areas.

First, we established an editorial board comprising experts from ecology, sociology, and economics. In addition to disciplinary expertise last year, considerations of geographic representation and gender balance were integral to the selection process.

Concurrently, we issued an open call for thematic proposals, inviting the scientific community to suggest review topics based on peer-reviewed literature published since January 2023. The call (see Annex A) was disseminated via social media, mailing lists, and targeted invitations. A total of 38 proposals were received from a broad geographic spectrum—

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

approximately double the number from the previous year. Nevertheless, this second selection remains provisional and subject to several limitations in topics and global representation of knowledge.

Due to thematic overlaps and some proposals lacking a robust literature base, the core team consolidated the submissions into a final list of 23 topics. The editorial board selected these topics based on the following criteria: (i) availability of sufficient peer-reviewed evidence from the past two years; (ii) lack of active scientific controversy; and (iii) relevance to international policy and negotiation processes.

Each topic was written by a team of two to five experts selected on the basis of their expertise and scientific reputation, as evidenced by their recent scientific publications. In some cases, AI tools were used to improve the grammar and wording of the texts. Diversity in terms of gender, geography and scientific discipline was also considered (Fig. 1, Table 1).

Although we have tried to ensure a balanced presentation by highlighting ongoing scientific debates, the limited number of expert authors per topic may have resulted in only a subset of relevant topics being covered.

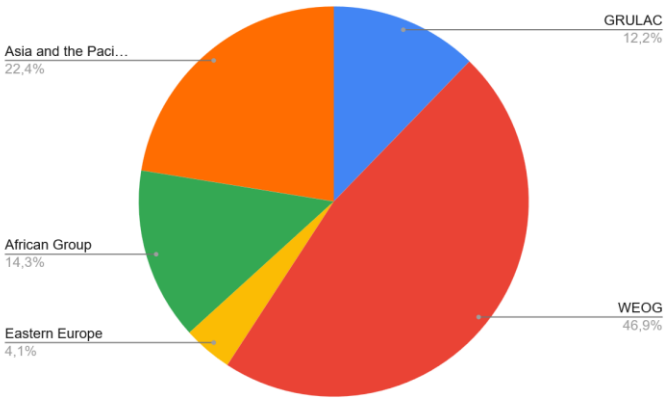


Figure 1: Origin of the authors from the geopolitical regional groups of member states of the United Nations: African Group; Asia and the Pacific Group, Eastern Europe, Latin American and Caribbean Group (GRULAC), and Western European and Others Group (WEOG)

Table 1: Web of Science research areas represented by the authors

research area	Nr. of authors	research area	Nr. of authors
Environmental Sciences & Ecology	30	Water Resources	3
Social Science	16	Mathematical & Computational Biology	3

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

Biodiversity & Conservation	11	Agriculture	2
Meteorology & Atmospheric Sciences	9	Government & Law	1
Urban Studies	6	Fisheries	1
Public, Environmental & Occupational Health	6	Engineering	1
Remote Sensing	5	Education & Educational Research	1
Infectious Diseases	3	Development Studies	1
Geography	3	Demography	1
Business & Economics	3	Construction & Building Technology	1
Forestry	3	Architecture	1

3 Themes

3.1 ecosystem resilience

3.1.1. Key take-aways

- Acknowledge agroecosystems' multi-scalar nature—from field to landscape—requiring integrated management frameworks that bridge ecological processes, social dynamics, and policy design.
- To bridge scales and ensure that restoration strategies are both inclusive and adaptive, restoration and regeneration planning should be guided by three core questions: *Resilience to what?* (identifying specific ecological or socio-economic disturbances), *Resilience of what?* (focusing on critical functions and structures to preserve), and *Resilience for what?* (clarifying management goals and desired future outcomes)
- Call for resilience indicators grounded in place-based knowledge and co-produced with stakeholders.
- Need for integrative governance to handle resilience trade-offs and synergies in a fair way over time.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

3.1.2. Background

Ecosystem resilience is defined by the "capacity of a [...] system to absorb disturbance, reorganize, maintain essentially the same functions and feedbacks over time and continue to develop along a particular trajectory" (Elmqvist et al., 2019) which goes beyond engineering resilience entailing only the capacity to shock resistance and recovery. That is why ecosystem resilience remains difficult to measure in quantitative terms and is deeply context-dependent. This chapter illustrates how the operationalization of resilience in ecosystems is widened in the face of complex, multi-scalar environmental and socio-political realities.

In ecosystems, different species operate at various spatial and temporal scales, which helps maintain balance and resilience. For example, in coral reefs, both small, territorial fish and larger, wide-ranging fish help control algae. If one group is disrupted, the other can step in, ensuring maintenance of processes. Similarly, migratory birds adjust their territories and timing to cope with changing food availability or weather. This kind of flexibility — in when and how resources are used — supports long-term resilience by smoothing out shortages. However, human activities, especially urbanization and global trade, are increasing connectivity while reducing modularity — the natural separation of systems into semi-independent parts. This makes systems more synchronized and vulnerable to widespread disruption. For instance, the global food system has become less resilient due to its tight interconnections. To rebuild resilience, systems may need to return to a more balanced state with moderate connectivity and stronger modularity.

Diversity is held to be key to resilience, but to offer any guidance for how to build resilience it needs to be more specific. Diversity, through redundant options for how a function is realised, may open up for differential (and on average less detrimental) impacts of disturbance. The baseline is that species and ecosystems vary in their vulnerability to different disturbances but overlap in terms of functional roles. Suitable scales to investigate and interact with the type of critical response diversity are the community and landscape level, whereas biodiversity loss is currently observed on the habitat and global level.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

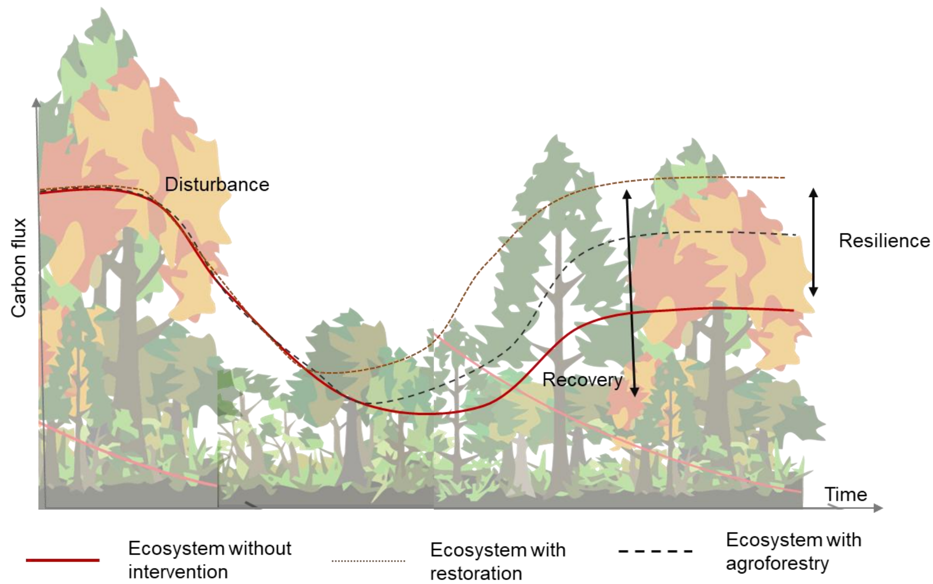


Figure 2: Schematic illustration of the resilience and recovery following a disturbance for three different ecosystems regarding carbon flux over time.

3.1.3 Challenge

Ecosystem degradation and biodiversity loss are clear signs from global environmental change impacts on agriculture and in turn affect the food production systems heavily (Popescu et al., 2023a; Rockström et al., 2017; Willett et al., 2019). For example, it is estimated that 5-8 per cent of global crop production, which has an annual market value of $235-577 billion USD, is directly attributable to animal pollination (IPBES, 2016). Food production, shaped by global demand and dominated by powerful actors, increasingly disrupts local ecological processes through land conversion, water overuse, and nutrient pollution. While global frameworks propose technological and system innovations to enhance sustainability—including improved input efficiency and biodiversity integration (Willett et al., 2019) - implementation at the local level faces severe social-ecological challenges (Jiménez-Aceituno et al., 2025; see also Secgion 3.5 - health). For example, irrigation efficiency investments may paradoxically lead to increased water use (Grafton et al., 2018; Pérez-Blanco et al., 2021).

Soil health is critical for agricultural productivity and ecosystem services, yet it faces threats from climate change, including erosion, compaction, and nutrient depletion (Blanco & Lal, 2023; Davis et al., 2023). Human activities, such as pollution and habitat degradation, exacerbate soil degradation, leading to diminished biodiversity and agricultural output. A study in China showed that crop yield would be up to 25% higher if soil degradation had not occurred (Bindraban et al., 2012), while in India an increase of 1% in soil degradation, lead to USD 1.21 loss in agricultural productivity per hectare (Gorain et al., 2024).

EU policies, though designed for cohesion, often fail to adapt to the realities of fruit and vegetable production sites, which produce all year round with an immigrant labour force. These cross-scale governance mismatches undermine resilience and

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

sustainability, as climate extremes and soil degradation compound existing vulnerabilities in agricultural systems (Carpenter et al., 2005; Corrado, et al., 2016).

Also forest ecosystems are increasingly threatened by both direct and indirect drivers, with land-use change and unsustainable resource extraction being key contributors to global biodiversity loss (IPBES, 2019; McElwee et al., 2024a). This loss undermines the resilience of critical ecological services such as carbon storage, climate regulation, soil stabilization, water purification, and the provision of livelihoods for local and Indigenous communities (Lecina-Diaz et al., 2024; McElwee et al., 2024a). As ecological pressures rise, forests lose resilience to climate change, disease, and other disturbances, potentially crossing critical thresholds that lead to irreversible ecosystem changes (Shackleton et al., 2018; Viñals et al., 2023).

However, operationalizing ecosystem resilience is complex due to conceptual ambiguity, challenges in measuring resilience across scales and timeframes (Folke, 2006; Viñals et al., 2023), lack of standardized metrics (Nikinmaa et al., 2020, 2023) , and potential trade-offs between different subsystems (Nikinmaa et al., 2023). Building resilience thus requires a deeper understanding of socio-ecological dynamics and tailored strategies to cope with extreme climate events and other interconnected threats (Jacobs et al., 2016; Lecina-Diaz et al., 2024).

3.1.4 Offering solutions

Agricultural practices and policies can lead to improved resilience and sustainability, suggesting a potential for positive transformation in agricultural systems despite the adversities faced. Effective policies and community engagement are essential for fostering resilience in agricultural systems, ensuring that both ecological and social dimensions are considered. Here, we focus on solutions addressing particular complexities intricate to ecosystems in general, which are cross-scale dynamics and the required shift in management from reactive to proactive approaches.

Popescu et al., 2023b emphasize sustainable intensification, advocating for increased yields without additional land conversion or environmental harm, through strategies like resource efficiency, landscape-scale resilience, and advanced technologies (e.g., smart sensors, rhizosphere microbiomes). However, this global-oriented, techno-centric view contrasts with agroecology as promoted by Dagunga et al., 2023, which emphasizes restoring extensive pasture-based systems and enhancing resilience via ecological principles—diversity, synergy, and nutrient cycling (Bernués et al., 2011; Wezel et al., 2020). Agroecology, rooted in local knowledge and social organization, is shown to boost household resilience and ecosystem services (Dagunga et al., 2023). Davis et al., 2023 present a middle ground with conservation agriculture, integrating resilience attributes into soil health assessments. In the Palouse River case, resilience is framed in terms of soil resistance, recovery, and thresholds (Davis et al., 2023). Practices like no-till farming, species diversification, and SOM enhancement increase adaptive capacity and regenerative resistance. All three approaches increase resilience and stability of agricultural yield.

A key recommendation across approaches is recognizing agroecosystems' multi-scalar nature—from field to landscape—requiring integration frameworks that bridge ecological processes, social dynamics, and policy design (Dagunga et al., 2023;

Nikinmaa et al., 2023). This aligns with the Kunming-Montreal Global Biodiversity Framework's emphasis on integrated spatial planning and sustainable use of biodiversity across all land uses, as reflected in Targets 1, 2, and 10, as well as the EU's Nature Restoration Law, which mandates large-scale, landscape-level restoration—particularly in agricultural areas—through coordinated, cross-sectoral strategies.

Regenerative agriculture and ecosystem restoration are two established approaches that explicitly address multi-scale resilience and the respective proactive management needs. Broadly, regenerative dynamics refers to the interacting processes of change that lead to ongoing improvements in the state of any given system, without negative spill-over effects in other systems and their dynamics (Fischer et al., 2024). Buckton et al., (2023) identify five qualities for regenerative social-ecological ecosystems, namely: an ecological worldview embodied in human action; mutualism; diversity; agency for humans and non-humans; and reflexivity. Specifically, regenerative agriculture practices, such as no-till farming, agroforestry, crop rotation, and cover cropping, contribute to the restoration of soil health, enhancement of biodiversity, and long-term carbon sequestration - for example, regenerative agriculture sequester up to 23 gigatons of carbon dioxide by 2050—representing a significant share of the mitigation needed to keep global warming below 1.5°C.

Regeneration refers to a primarily endogenously driven process, suggesting that humans co-evolve with the system and participate in this process as nature (Fisher et al 2024). On the other hand, ecological restoration refers to a conscious exogenous process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed, in which humans do things to nature (Fisher et al 2024). However, it can also be seen as a continuous process, with restoration being a prerequisite for unfolding regenerative dynamics. For example, a tree planting restoration activity that leads to the natural regeneration of the forest in the long term (Fisher et al 2024).

With significant interests of decision makers in regeneration and restoration, it is key to define how it entails a broader paradigm shift. Regeneration and restoration efforts that aim to strengthen resilience in social-ecological systems must explicitly consider cross-scale dynamics in both time and space. The ecological and social starting conditions of a given system fundamentally shape its capacity to withstand and adapt to disturbances (Aslan et al., 2021). Therefore, it is essential to integrate a temporal dimension, particularly to address the often-overlooked relationship between short-term and long-term resilience (Lecina-Diaz et al., 2024). Spatially explicit approaches are equally important, requiring scale-appropriate assessments based on ecosystem processes and structures (Lecina-Diaz et al., 2024).

On the social side, humans possess the unique ability to plan ahead and reshape landscapes. Effective regeneration and restoration efforts must therefore embrace an interdisciplinary perspective that integrates scientific knowledge with local perceptions and Indigenous knowledge systems (Chettri et al., 2021; Viñals et al., 2023). Strengthening cooperation and collective action within communities enhances their ability to self-organize, a cornerstone of building social-ecological resilience (Hellin et al., 2018).

Identifying the ecological or socio-economic disturbances challenging the system and defining which attributes need to be resilient for facing them is key. In addition, other factors can also be important to improving resilience: (1) identifying buffers and redundancies, i.e., the extra capacity, or storage, that a system holds, and which can help to minimize the severity

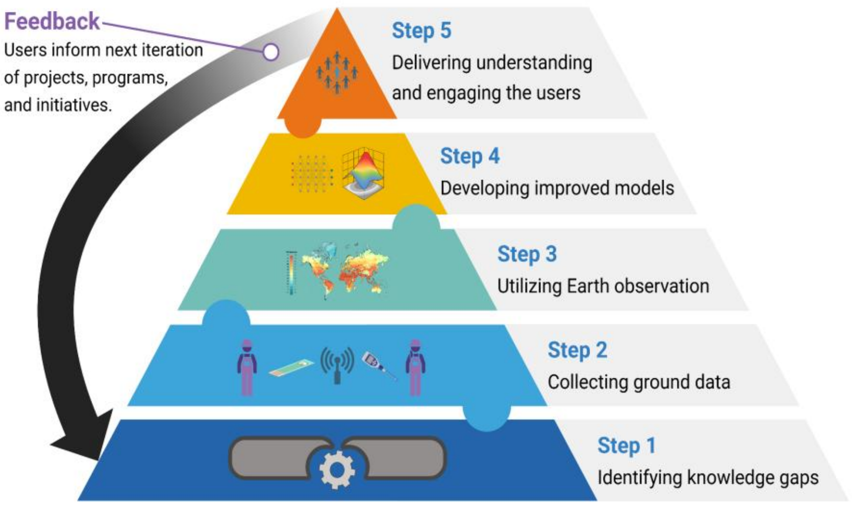
https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

of a disturbance or can enable a faster recovery; (2) monitoring and shared information, with an open and systematic data collection system; (3) scales – identifying the balance between connectedness (connections to neighbouring systems and higher system levels so there can be exchange and support between them) and modularity (autonomous units in which self-organization is enhanced at the local level and threats can be isolated to stop them spreading); (4) heterogeneity, including economic diversity, cultural diversity, biological diversity and response diversity; (5) social capital, or the level of social cohesion within the social system; (6) observing and analysing the ability of a system to produce feedbacks that pushes against disturbance; (7) using a multi-functional landscape approach, landscapes with a high diversity of practices (Vinals et al. 2013; Nikinmaa et al. 2023).

3.2 dry lands

3.2.1. Key take-aways

- Drylands are crucial ecosystems that, because of their global significance, sensitivity to disturbances, and poor representation in models, create large uncertainties in estimating their feedback effects on the Earth's system.
- In addition, due to human-induced changes, drylands are responding dramatically to that and many dryland ecosystems have passed tipping points, consequently leading to abrupt system transitions and persistent degraded states.
- Advanced remote sensing tools, sensors, and data analysis enable scientists from multiple disciplines to scale observations and processes from leaf to orbit in drylands, addressing the complexity, dynamics, and diversity of these critical ecosystems.
- To improve adaptive decision making that can support science-based land management at an effective scale, it is essential to have a framework designed to allow substantial input from both the scientific and data end-user communities.
- Effective community engagement is key for long-term sustainability of restoration initiatives



https://doi.org/10.5194/egusphere-2025-3619
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Figure 3: Adapted from the concept of "Earth Science to Action Virtuous Cycle" from NASA. This diagram shows how to bring together scientists with end-user communities including public and private end-users, tribal nations, industries, and government agencies to tackle the challenges, develop potential solutions, and implement management strategies for global drylands.

3.2.2. Background

Dryland ecosystems, defined as an annual potential evaporation rate that is at least 1.5 times higher than the annual precipitation (Barrow, 1992), include a wide variety of ecosystem types, all featured by limited water availability. They are the largest terrestrial biome on Earth, covering over 40% of the global land area, and home to about 35% of the world's population (Wang et al., 2022), exhibiting the highest population growth rate among ecological zones (Gaur & Squires, 2018). Drylands account for 40% ± 2% of terrestrial net primary productivity (Wang et al., 2022) and store a third of the planet's soil organic carbon and 79% of its soil inorganic carbon (Plaza et al., 2018). It is estimated that drylands contribute to an annual carbon-dioxide (CO_2) drawdown comparable to that of tropics through plant photosynthesis (Yao et al., 2020), along with additional drawdown via their extensive photosynthetic soil communities (e.g., biological soil crusts) (Maestre et al., 2013; Shi et al., 2025). Furthermore, drylands have the most substantial impact (38% ± 7%) of any biome on the year-to-year variability of the global terrestrial carbon sink (Poulter et al., 2014; Sitch et al., 2024). Due to their sensitivity to water availability, significant annual moisture variations can greatly influence surface carbon fluxes and, consequently, atmospheric CO_2 levels (Metz et al., 2023, 2025). Drylands also largely contribute to the overall carbon uptake trend (Ahlström et al., 2015; Wang et al., 2022) and possess much greater tree carbon storage than previously thought (Brandt et al., 2020; Tucker et al., 2023).

Beyond carbon, the long evolutionary history of dryland ecosystems and their role as the origin of many unique plant lineages have made them biodiversity hotspots, maintaining 35% of global biodiversity and 20% of global plant diversity (Gross et al., 2024; Maestre et al., 2021) as well as unique fauna communities (Lewin et al., 2024). In addition, drylands are economically important as they have been found to contribute over 30% to the global Gross Domestic Product (GDP) in the Americas from 1990 to 2015 using global gridded GDP maps (Kummu et al., 2018). However, drylands have been significantly affected by global change such as exceptional drought (Williams et al., 2022), altered precipitation regimes (Feldman, Konings, et al., 2024), high temperature, and great wildfire risk (Jones et al., 2022). These stressors have caused substantial carbon emissions (about 20 to 30 Pg of soil organic carbon) and will very likely result in unforeseen carbon losses (e.g., soil inorganic carbon) across global drylands (Díaz-Martínez et al., 2024; Li et al., 2024; Sun et al., 2024). In addition, drylands are also increasingly vulnerable to it, given the compounded impacts added by anthropogenic stressors (e.g., grazing and wildfire management), causing rapid species decline (Cartereau et al., 2023). Furthermore, dryland area is projected to greatly increase, partly due to drying conditions advecting into downwind wetter transitional regions (Koppa et al., 2024). Besides this, the distinct dryland mechanisms are expected to present in other ecosystem types under a warmer, drier world (Grünzweig et al., 2022). Therefore, drylands are of great economic, cultural, and ecological global importance (Krishnamurthy et al., 2022).

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

3.2.3. Challenge

While the importance of drylands in many aspects are greatly recognized, substantial uncertainties remain regarding the drivers, magnitude, and vulnerability of these features. This has hindered past estimates of their role in the Earth system properly, inducing large uncertainties in our global understanding of anthropogenic change and feedback on Earth system processes.

Functional diversity in drylands is unexpectedly high, a phenomenon known as the "functional paradox". This may be due to the unpredictable environmental conditions, especially high spatiotemporal variability in water availability, which have led to diverse plant strategies and unprecedented vascular plant functional diversity. This includes dynamic mixtures of shallow-rooted crassulacean acid metabolism plants, C3 and C4 grasses, and deep-rooted C3 shrubs and trees, each with specialized water acquisition strategies (Gross et al., 2024). Drylands' functional diversity is further enhanced by photosynthetic soil communities (i.e., biocrusts) composed of cyanobacteria, lichens, and mosses, which fill interspaces and understory, stabilizing soil and aiding in nutrient availability, water retention, and carbon uptake (Elbert et al., 2012; Wang et al., 2025; Weber et al., 2022). Climate change and land use are driving dryland degradation (e.g., Li et al., 2018; Phillips et al., 2022) with serious yet poorly understood implications for structural and functional biodiversity (Berdugo et al., 2020).

Drylands have extended dry periods with rapid biogeochemical responses to brief moisture pulses, making accurate water input quantification crucial. However, in arid regions, globaldatasets (e.g. precipitation, Markonis et al., 2024), land surface models (MacBean et al., 2021), and machine learning products (e.g., FLUXCOM, Markonis et al., 2024; Nelson et al., 2024). Non-rainfall water inputs like dew, fog, and soil vapor adsorption significantly contribute to annual water balance but are underrepresented (Kidron & Starinsky, 2019). Bare soil evaporation in dry conditions is often underestimated (Balugani et al., 2023; MacBean et al., 2020), likely because widely-used models (e.g., Van Genuchten) fail to predict significant water movement in dry soils (Saaltink et al., 2020). Vegetation is a smaller reservoir as drylands store most carbon as soil inorganic carbon (Lal, 2019). Mechanisms like nighttime CO_2 absorption due to cooling and carbonate precipitation, as well as CO_2 transport from fast soil air replacement, are important (Kim et al., 2024; Moya et al., 2019). The scarcity of soil flux data in arid regions remains a major barrier to representing these processes in models (Stell et al., 2021).

The management and mitigation of anthropogenic influences on dryland ecosystems must account for the potential creation of more problems than solutions, spanning from local initiatives to global agreements. Many dryland ecology programs lack knowledge of local communities and Indigenous peoples, from resources rights to current socio-economic relationships, to co-create and share knowledge, as well as to support diverse capacity. For example, the Bedouins in the Wadi Allaqi of the Eastern Desert of Egypt once lived as nomads and were self-sufficient in food. However, following the formation of Lake Nasser in the 1960-1970, they now reside in permanent settlements, putting their ancestral knowledge at risk (Kandal et al., 2022). Additionally, in areas rich in natural resources (e.g., lithium, copper, rare earth elements), the balance between local distribution and global benefits is fragile (e.g., Agusdinata et al., 2018). Furthermore, the highly efficient vegetables and fruit production areas are particularly susceptible to climate change impacts as they are operated by vulnerable population groups like small-scale farmers, who contribute over 50% of global vegetables and fruit production (Herrero et al., 2017). These

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

underscore the need to not only address ecological questions but also explore the socio-economic dimensions of dryland management for enhancing resilience and sustainability in these vital regions.

3.2.1. Offering solutions

Combining enhanced resolution and diversity of current and planned ground based, airborne, and spaceborne sensors with advanced process models and new satellite sensors, we can now characterize ecosystem function properties and responses at the appropriate scales. Drylands, as a previously overlooked and understudied ecosystem type for biodiversity-carbon co-benefits, represent a large but now addressable uncertainty in our understanding of terrestrial ecosystems.

Integrated in-situ observations of surface states and fluxes are essential to addressing scientific questions relevant to the mentioned challenges. Future research projects and activities should leverage rich networks of available ground measurements of soil moisture, water fluxes, carbon fluxes, and vegetation states (e.g., FLUXNET, SRDB, and PSInet; (Baldocchi et al., 2024; Jian et al., 2021; Restrepo-Acevedo et al., 2024). For example, NASA's ARID scoping study has proposed three Distributed International Domains (i.e., Australia, Southern Africa, Northern Mexico) besides the targeted areas in the US (Reed et al., 2025). This cooperation will allow existing research sites to be designated as super sites that can strategically provide multi-year, data-intensive time series across environmental gradients. In addition, observational and manipulative experimental data offer direct means to address long-standing knowledge gaps for dryland ecosystems at representative sites, and for improving interpretation and use of remote sensing data. Therefore, new ground measurements are critical and communities should facilitate effective coordination of them with remote sensing and modeling efforts (e.g., aligned with airborne campaigns and satellite observations; Pierrat et al., 2025).

Drylands significantly influenced remote sensing development due to favorable conditions, enabling major developments like the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979), despite ongoing measurement deficiencies (Smith et al., 2019). An expanding array of Earth-observing missions is enabling detailed and frequent observations of dryland structure (Brandt et al., 2020; Schneider et al., 2020; Zeng et al., 2023) and function (Smith et al., 2018; Wang et al., 2022; Wen et al., 2025). Measurements of diurnal dynamics, such as solar-induced fluorescence (e.g., OCO-3) and canopy surface temperature (e.g., ECOSTRESS), reveal high frequency dryland ecophysiological responses to temperature and precipitation changes (Xiao et al., 2021; Zhang, Fang, et al., 2023). Integrating techniques like space-borne lidar (e.g., GEDI), thermal (e.g., ECOSTRESS), microwave (e.g., BIOMASS), and solar-induced fluorescence (e.g., TROPOMI) offers further new opportunities to constrain parameters like dryland light and water use efficiency (Smith et al., 2019). Future community-led remote sensing campaigns should prioritize the development of robust scaling frameworks and insights from leaf to orbit (Feldman, Reed, et al., 2024; Reed et al., 2025).

Data, both ground and remote sensing, on ecosystem function properties and responses will allow us to improve the representation of dryland mechanisms in models of different scales, enabling more accurate predictions of short-term carbon and water flux variability due to events like rain pulse and extreme weather and long-term vegetation shifts (Feldman, Feng, et al., 2024). These efforts will greatly improve our capacity to simulate how dryland ecosystems respond to global changes and what are the feedbacks of these responses to the climate system (Simpson et al., 2024). Additionally, models offer valuable guidance for hypothesis testing, data collection efforts, and development of remote sensing instruments. Therefore, comprehensive and extensive data-model synthesis are very important to systematically link ground observations of important ecosystem process responses, involving remote sensing observations across different spatial, spectral, and temporal scales, to process-based and machine learning models (MacBean et al., 2021).

The integrated dataset and improved models will help deliver more effective land management and policy-making decisions as restoration, protection, and regeneration requires large investment. For example, observations in US drylands indicated significant vegetation changes over the past 30 years (Kleinhesselink et al., 2023), supporting the application of Sagebrush Conservation Design that aims to conserve drylands by prioritizing the protection and expansion of intact areas (Doherty et al., 2022). Nevertheless, it is critical to note that community engagement is necessary for local success (Moreno-Casasola, 2022) and initiatives' long-term sustainability (Fox & Cundill, 2018). As Aronson et al., (1993) already highlighted, restoration depends on defining the "ecosystem of reference" and engaging with the socioeconomic, technical, cultural, and historical factors that caused the degradation. In addition, power dynamics, potential negative livelihood impacts, and poor knowledge about local communities must be addressed from inception (Fox & Cundill, 2018). Several engagement approaches and actions promote effective knowledge exchange and active project participation (Favretto et al., 2022), such as interviews, workshops, field campaigns, citizen science, and others. Even though there is not a single récipe to a successful community engagement, there are some promising practices to follow such as building trust and respect among stakeholders, communicate and collect sound evidence, and provide long-term support, beyond individual projects (Derak et al., 2024; Favretto et al., 2022).

3.3 Sustainable bioeconomy

3.3.1. Key take-aways

- Complexities arise when contextualising the impacts of bioeconomy within the overarching objective of sustainability.
- One barrier to implementation consists of metrics for measuring the impact of outcomes of the Sustainable Bioeconomy.
- Cultural, economic, and structural barriers are faced during the implementation of a Sustainable Bioeconomy, which requires transformative change.
- Understanding what is needed and implementing transformative change requires a systems thinking approach to avoid trade-offs and risks.

3.3.2. Background

The global community increasingly regards the bioeconomy as a suite of technological solutions to resource-based challenges confronting the world today. According to the Food and Agriculture Organization (FAO, 2021a), the bioeconomy is defined as "the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes, and services) within and across all economic sectors and enable a transformation to a sustainable economy." The core principle of bioeconomy proposes a transition from non-renewable resources as the basis of our economic activity to biological

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

(renewable) feedstocks (European Commission, 2018). This principle has been applied across several sectors, including energy, food, and health. Biotechnology could contribute up to 2.7% of the GDP of OECD countries by 2030, with the largest economic impact in industrial and primary production sectors, followed by health-related applications (OECD, 2009). The bioeconomy has the potential to play a vital role in supporting biodiversity across several sectors of agrifood systems and the bio-based industry. Bioeconomy products and practices—such as biofertilizers, biopesticides, bio-based plastics, bioremediation, and microbiome-based innovations—can contribute to reducing soil and water pollution, as well as associated health risks, by decreasing the reliance on chemical fertilizers and pesticides, which are recognized as major drivers of biodiversity loss (San Juan et al., 2022).

The Circular or Sustainable Bioeconomy (henceforth Sustainable Bioeconomy) represents an emerging paradigm that integrates the biotechnological and bioprocessing principles of the bioeconomy with the political objective of using biological resources in a sustainable way (Aguilar et al., 2019). It promotes the incorporation of further novel bio-based innovations in both products and methods (European Commission, 2018). The "circular" or "sustainable" element refers to the utilization of the waste from one process as an input - whether material or energy - for another, extending the economic lifecycle and enhancing the material flow of biomass within the system (Kershaw et al., 2021).

The Sustainable Bioeconomy offers significant potential for contributing to Net Zero targets, because biological organisms naturally sequester carbon during growth, and the replacement of fossil fuels with biofuels can support the development of carbon-neutral or even carbon-negative supply chains (González-Garay et al., 2021). The Sustainable Bioeconomy remains a contested process within society and holds significant potential to generate social tensions and conflicts between the pro-growth/fossil-based and growth-critical/post-fossil systems (Eversberg & Fritz, 2022). Therefore, the Sustainable Bioeconomy requires us to take a more holistic approach to sustainability, considering the bioeconomy from the three pillars of sustainability – economic, social, and ecological, which is rarely done in practice. This approach aligns with key international programmes such as the UN Agenda 2030 and the Sustainable Development Goals (Aguilar et al., 2019; Gawel et al., 2019), as well as more recent policies such as the Kunming-Montréal Global Biodiversity Framework. Many countries in Europe, the US, and several Global South countries have adopted policies grounded in bioeconomy principles (Birner, 2018), whilst Europe has launched dedicated industrial plans for a Sustainable Bioeconomy (Araújo et al., 2021; Fritsche et al., 2020).

3.3.3. Challenge

A key challenge in realizing a Sustainable Bioeconomy lies in ensuring that the impacts of bio-economic development are contextualised within the overarching goals of sustainability. This requires moving away from a reductionist perspective on natural resource management, to one which embraces the interlinked social, economic and environmental domains (Sterner et al., 2019; Virapongse et al., 2016). Unfortunately, the broader environmental and social context is often ignored (Székács, 2017) and thus, natural resource management of biomaterials or technical processing pathways for the bioeconomy may inadvertently exacerbate, rather than mitigate socio-ecological degradation (Biber-Freudenberger et al., 2018, 2020; Egenolf & Bringezu, 2019; Stark et al., 2022; Wohlfahrt et al., 2019). For example, when examining the bioeconomic supply chain for biodiesel production, it is crucial to account for potential trade-offs in land use between cultivating biofuel crops and

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

preserving natural ecological habitats. Such trade-offs may heighten tensions within and between local communities due to competing demands for land access (Gawel et al., 2019; Jeswani et al., 2020).

A second challenge is the tendency to assess the success of sustainable bioeconomy initiatives primarily through economic measures. Rather than considerations of broader ecological dynamics, the assessments often focus on carbon metrics, leading to over-emphasized claims of sustainability (Gawel et al., 2019; Urmetzer et al., 2020). It is essential that bioeconomy programmes are evaluated using a holistic framework that includes not only broader ecological metrics but also measures of social and technical sustainability (Székács, 2017; Wohlfahrt et al., 2019). This lack of data on environmental impacts and ecological feedback loops remains a significant barrier to the development of sustainable bio-economies (Dace et al., 2024).

A third challenge to the successful implementation of a Sustainable Bioeconomy lies in the presence of cultural, economic, and structural barriers. This challenge interacts with the technical development of bio-economic products and the environmental issues (Dace et al., 2024). For example, a full-scale transition to a bioeconomy is not feasible under current levels of consumption which exceeds the renewal capacity of ecosystems (Giampietro, 2019). This issue is coupled with a lack of effective incentives aimed at encouraging changes of consumer behaviour (Dace et al., 2024). Cultural barriers include limited collaboration and engagement between communities either affected by, or invested in emerging bio-economic markets, whilst economic barriers include complexities of market structures, business models, investment dynamics, and profitability concerns (Dace et al., 2024). In addition, governance gaps, including lack of policy coordination and market assess, further constrain the development and scaling of a Sustainable Bioeconomy (Dietz et al., 2023).

3.3.4. Offering solutions

A Sustainable Bioeconomy is an opportunity to contribute to achieving multiple Sustainable Development Goals, as well as several goals outlined in the Kunming-Montréal Global Biodiversity Framework (Dace et al., 2024; Dietz et al., 2023). It also holds the potential to foster innovative business models that can revolutionise the bioeconomy, promoting sustainability for both businesses, society, and the environment (Papamichael et al., 2024). Realizing the potential requires the development and implementation of transformative policies and financial systems, the creation of new markets and business models, and the provision of incentives for encouraging behaviour change of consumers and education programs for increasing awareness (Dace et al., 2024). Effective governance mechanisms are essential to support bioeconomy entrepreneurs and businesses at scale, driving the transformation of bio-based innovations into long-term economic success. National bioeconomy policies must align with broader social, economic, and ecological objectives. Consequently, global and cross-sectoral policy coordination is imperative to guide bioeconomic transformation more effectively and minimize risks to social and environmental sustainability (Dietz et al., 2023). This ties with guidance from the IPBES Transformative Change Assessment (O'Brien et al., 2024), which outlines the determinants of transformative change required to achieve the 2050 Vision for Biodiversity.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

A recent systematic review of sustainable food practices has shown that incorporating Circular Bioeconomy principles into food systems can increase agricultural productivity and optimise resource use, whilst also boosting profitability and generating new revenue streams from waste (See also Section 3.1 - resilience). From a social perspective, the integration can improve community well-being by generating new employment opportunities. From an ecological perspective, it can also support natural capital regeneration and promote the sustainable use of natural resources (T. H. Nguyen et al., 2025). However, the study also found that there were still significant research gaps relating to cross-sectoral relations and the multi-level impacts of Circular Bioeconomy practices.

Undertaking this transformative change requires that we undertake "systems thinking" (Arnold & Wade, 2015). In human-nature systems, systems thinking emphasises the embeddedness of society within ecological systems and the critical interdependence (Reyers & Selomane, 2018). Incorporating the principles of sustainability into decision-making for the Sustainable or Circular Bioeconomy is therefore essential (O'Shea et al., 2024). A study assessing the feasibility and potential impacts of developing seaweed aquaculture alongside wind farms in a Multi-Use Setting (MUS) demonstrated that whilst an offshore MUS reduced spatial competition within the marine economy there were significant negative impacts which suggested that potential alternative strategies could avoid significant trade-offs and risks (O'Shea et al., 2022, 2024). The study applied cognitive maps and Integrated Assessment Models (IAMs) to formalise a holistic sustainability assessment of an emerging bio-economic innovation through a comprehensive evaluation of associated risks and trade-offs, helping to mitigate the potential for expensive investments (O'Shea et al., 2022, 2024). The study illustrated how current tools and a systems thinking approach are essential for studies of the emerging bioeconomy to ensure sustainability (O'Shea et al., 2022, 2024). Evidence-based decision-making systems support the Sustainable Bioeconomy using the results of assessment of trade-offs and value chain of bio-economic products.

3.4 Urban centers

3.4.1. Key take-aways

- Rapid, unplanned urban growth harms ecosystems and deepens inequality, especially in Asia and Africa.
- Cities drive environmental damage but are sites for effective implementation of nature-based solutions.
- Urban strategies must be locally tailored and equity-focused to reflect diverse contexts and needs.
- Compact, green cities offer benefits but need careful planning to avoid social and ecological harm.
- Transformative change needs strong institutions, public engagement, and systemic, cross-scale urban planning.

3.4.2. Background

Urbanization is accelerating globally, with projections indicating that 68% of the world's population will reside in urban areas by 2050, up from 55% in 2018 (UNPD, 2012). This anticipated increase of approximately 2.5 billion urban residents will be heavily concentrated in Asia and Africa. India, China, and Nigeria alone are expected to contribute 35% of this

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

growth (Ritchie & Rodés-Guirao, 2024). It is estimated that globally, urban land cover will increase by a factor of 1.8-5.9 during this century (Gao & O'Neill, 2020). The speed, scale, and spatial forms of urbanization in these regions diverge significantly from historical patterns observed in Europe and North America, where urban expansion occurred more gradually and was typically accompanied by planning and infrastructure development (Henderson & Turner, 2020).

Urban growth in much of Asia and Africa is frequently characterized by informality and limited spatial regulation (Sharifi et al., 2014, 2025). This growth is driven by a combination of population increase and rural-urban migration, often resulting in the expansion of urban settlements into ecologically sensitive areas, and the displacement of agricultural or conservation land (UNCCD and UN-Habitat, 2024a). Urban replacement of agricultural land will be most pronounced in Asia and Africa accompanied by a 6 and 9% reduction in food production (Fao, 2023). Consequently, these regions are witnessing uncoordinated development patterns, heightened socio-spatial inequalities, disproportionate climate risk, pollution, and the fragmentation of habitats and degrading ecosystem services (Elmqvist et al., 2013; Haque & Sharifi, 2024a).

Resource extraction for urbanization, currently estimated at 30.6 billion tonnes annually, is dominated by non-metallic minerals (76%), used mainly in construction of buildings and infrastructure, and is projected to nearly triple by 2050 (UNEP & IRP, 2024). This increasing material intensity places disproportionate environmental burdens on both rapidly urbanizing regions, especially in Asia and Africa (Sharifi et al., 2025), and those beyond, influencing natural ecosystems and societies (Shih et al., 2024). The high density urban centers created by these cities are changing urban climate and causing droughts, heat, flood, and air pollution in their surrounding rural areas (Yang et al., 2024).

In established cities, urbanization has been gradual and regulated, producing diverse urban forms. These are compact in Europe and Japan, low-density in North America and Australia. Future development in these areas have to deal with climate risk inequality, brownfields, existing and aged infrastructure, political fragmentation, risk of gentrification, shrinking and aging population (Section 3.8 - demographics), and immigration.

Recent IPCC-IPBES joint assessments, including the 2024 Nexus Assessment, emphasize the central role of urban areas for city-region wide interventions with nature-based solutions that can generate synergistic benefits for climate adaptation, public health, food security, and biodiversity (McElwee et al., 2025; Puppim de Oliveira et al., 2022). Recognizing the importance of the holistic and systematic manner of green infrastructure in spatial planning; its interconnection between (water, energy) resources and functions; and the need to address heterogeneity and context-specific dynamics of different urbanization is thus critical to designing policy frameworks that mitigate ecological risks while harnessing urbanization as a transformative force for sustainability (Puppim de Oliveira et al., 2022).

3.4.3. Challenge

Urban sustainability efforts face context-specific challenges shaped by divergent historical, institutional, socio-economic trajectories, and climate change impacts in each city. While each context offers opportunities to integrate nature-based solutions (NbS), circularity, and equity into urban planning, their strategies and starting points differ (Simkin et al., 2022) and are usually detached from existing planning mechanisms, failing to maximize co-benefits (Puppim de Oliveira et al., 2022).

Rapidly growing cities expand often beyond the reach of formal planning systems (Elmqvist et al., 2013), resulting in low-density urban development. They often face pressure to meet basic needs for socio-economic uplift whilst having limited resources (Shih & Mabon, 2018). Urban housing and infrastructure in some of these cities are dependent on material resources within proximity. Combined with development imperatives, limited available data, inadequate institutional mechanisms, lack of planning tools and policy, proliferating informal settlements, and fragmented governance hinder the enforcement of growth boundaries and the protection of natural areas (Shih & Mabon, 2018). E.g. degrading natural flood protections increase 25-40% faster than global averages (Rentschler et al., 2023), putting over 200 million urban residents at risk (Muis et al., 2023; Hauer et al., 2024). Such cities often do not prioritize green infrastructure and NbS due to a combination of the issues described above. This could have significant economic and social consequences, including increased healthcare costs, reduced property values, higher energy costs from urban heat island effects, decreased productivity, and increased vulnerability to climate change. Additionally, this can exacerbate social inequities, reduce tourism potential, create water management issues, lead to biodiversity loss, and decrease social cohesion.

Although increasing material circularity during the process of urbanisation reduces global environmental impacts, it may disproportionately benefit wealthier regions with the institutional capacity for recycling, raising justice concerns (Elliot et al., 2024).

Even with circular practices, material consumption is projected to exceed planetary boundaries, necessitating additional strategies such as extending building life, promoting multifunctional infrastructure, and reducing material footprints (Dasgupta & Dasgupta, 2025).

Lastly, co-benefits deriving from well-planned increases in green space, such as reduced heat, improved air quality, and enhanced wellbeing, are argued to be inequitably distributed within cities, whilst it still need to be leveraged between ecosystem functions, such as wildlife habitat, and carbon storage, which are likely to be configuration-dependent spatially (Puppim de Oliveira et al., 2022; Shih et al., 2024). In both Global North and South contexts, inequality has been widely found in cities due to planning decisions (Haque & Sharifi, 2024a).

3.4.4. Offering solutions

Reducing the impact of cities is critical for achieving a just and sustainable future. The challenges outlined above demand science-informed, context-sensitive, and justice-oriented responses ensuring that future urban development stays within the safe and just space of the earth's system. Addressing climate resilience development and biodiversity loss requires transformative change, which entails not only modifying physical infrastructure and planning systems but also reshaping values, institutions, and relationships between people and nature (O'Brien et al., 2025). In both established and rapidly growing city contexts, solutions must be grounded in a systems understanding of urban metabolism (material use), ecosystem process of cities, land-use dynamics, and socio-ecological interactions (Huang and Chiu, 2020).

Table 2. Indication of how similar challenges require different approaches based on the context and growth phase of the city. Further differentiation is needed depending on various other variables. In some cases, the suggestive interventions may be similar but require tailoring to local context.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

	Global North (Established Cities)		**Global South (Rapidly Growing Cities)**	
Characteristic/Need	**Context**	**Suggestive intervention**	**Context**	**Suggestive intervention**
Growth Patterns	Gradual, planned, stabilized growth or shrinkage	Strategic densification, infill-brownfield development, rehabilitating green infrastructure or NbS	Rapid, unplanned, informal, sprawl	Boundary control, compact development, integrated planning with green infrastructure or NbS at city-region
Material Use	Established infrastructure	Reuse, refurbishment, circular economy	Increasing demand for materials and infrastructure	Vernacular design, use of locally-sourced materials inlcuding secondary resources from industrial and agricultural processes
Institutional Capacity	Strong, regulatory frameworks	Participatory development and enhanced awareness	Weak, evolving from informal to formal	Training and capacity building needed
Equity / Gentrification	Inequitable distribution of ecosystem services	Prevent loss of access due to gentrification	Unbalanced growth that leaves some groups out	Equitable access to NbS, prevent exclusion

Environmental upgrades must be balanced with affordability and inclusion to avoid displacing vulnerable populations. Selective demolition, modular design, and the use of "material passports" show promise, but current trends risk downcycling and unsustainable resource demand (Keena et al., 2025). Circular economy practices such as reuse and refurbishment are being explored in a number of different cities around the world such as Glasgow (United Kingdom), Granada (Spain), Groningen (Netherlands), Umeå (Sweden) and Valladolid (Spain) (OECD, 2020).

A key strategy involves promoting well-designed, compact urban forms that reduce land consumption, energy use, and facilitate the integration of green and blue infrastructure (Intergovernmental Panel on Climate Change (IPCC), 2023; UN-Habitat, 2022). Compact development enables multifunctional land use, reducing infrastructure burdens and preserving surrounding ecosystems. For instance, evidence from the United States shows that urban sprawl incurs significant costs across various dimensions, including personal travel time, vehicle expenses, parking subsidies, public infrastructure, environmental damages, and externalities such as congestion and accidents, with total costs ranging from $0.79 to $1.20 per vehicle mile. Compact cities also offer measurable benefits such as reduced vehicle miles traveled (VMT), lower infrastructure costs, and decreased energy consumption and greenhouse gas emissions. For example, compact development can reduce fuel consumption and CO_2 emissions by 20–40% compared to sprawl, and aggregate metropolitan VMT could decrease by 12–18% by 2050. Additionally, compact cities are associated with improved public health outcomes, such as lower obesity rates and reduced traffic fatalities, and can lead to savings of up to 12% in road infrastructure costs and 7% in water and sewer infrastructure costs (Ewing & Hamidi, 2015). It also provides an effective platform for implementing distributed NbS such as green roofs, facades, and vertical greening systems (Elmqvist et al., 2013; Simkin et al., 2022). While such solutions may be suitable in cities undergoing regeneration, rapidly urbanizing regions require different priorities and proactive actions, such as the enforcement of green infrastructure to safeguard ecosystem health and resilience while establishing gray infrastructure. However, realizing these benefits depends on effective planning, intersectoral coordination, and the availability of local evidence and knowledge that facilitate climate-resilient that support biodiversity and ecological connectivity, that mitigate negative trade-offs that compact cities present (Yang et al., 2024).

NbS must be embedded within wider urban systems rather than treated as isolated interventions. A systems-based approach aligns ecological performance with other urban goals such as climate adaptation and resilience, social equity, and public health. This requires assessing trade-offs and synergies across sectors and spatial scales. For example, strategic greening can enhance mental health, limit the spread of diseases (see also Section 3.5 - Health) and mitigate urban heat islands and associated heat-related mortality, but if not properly governed, may lead to gentrification and the displacement of vulnerable populations (Haque & Sharifi, 2024b). Equity considerations should therefore be central to the design, implementation, and monitoring of NbS.

Emerging evidence also highlights the role of cities as refugia for biodiversity, particularly for species displaced by regional habitat degradation (Tzoulas et al., 2007; S. Wang et al., 2021). Enhancing ecological function within urban areas, through habitat restoration, green corridors, and landscape connectivity, can support urban biodiversity while delivering co-benefits to human populations (O'Brien et al., 2025; Puppim de Oliveira et al., 2022).

Circular economy approaches, such as reuse, refurbishment, and adaptive reuse of buildings, can reduce both upstream environmental impacts and downstream waste generation (Keena et al., 2025; Simkin et al., 2022). Key enablers include the development and implementation of material passports, which document the provenance, composition, and recyclability of building materials, enabling future disassembly and reuse (Markou et al., 2025; Oliveira et al., 2024).

Modelling studies show that selective demolition and modular construction can reduce lifecycle emissions and resource use, with gains of up to 70% in GHG emissions and 67% in water consumption (Keena et al., 2025). Some construction materials have a negative carbon balance and cause less harm to the environment during their initial production (Bohn, et al., 2025; Churkina et al., 2020). However, the effectiveness of such strategies is influenced by local building typologies, energy sources, and institutional capacity.

The ability to implement the above solutions is contingent on institutional capacity and governance frameworks. For cities in the Global South, strengthening planning institutions, improving land tenure systems, and investing in the formalization and upgrading of informal settlements are urgent priorities (IPCC 2023; UN-Habitat, 2022). Capacity-building must focus on multi-scalar planning and inclusive decision-making processes.

Ultimately, urban transformation requires societal engagement. The IPBES 2024 assessment emphasizes that transformative change hinges on reconnecting people with nature through education, participatory governance, and community stewardship.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

Embedding nature in daily urban experience not only enhances ecological outcomes but also cultivates public support for long-term sustainability transitions.

3.5 Public health

3.5.1. Key take-aways

- Implement the One Health approach by integrating human, animal, and ecosystem health, emphasizing specific host and vector ecologies rather than broad biodiversity concepts.
- Enhance disease surveillance and facilitate data sharing through open-access platforms and interdisciplinary collaboration to unify information on pathogens, hosts, and vectors.
- Preserve biodiversity and systematically evaluate its role by monitoring disease trends in conjunction with ecosystem changes and assessing the impacts of biodiversity loss or restoration on disease risks.
- Implement international agreements and treaties including the Quadripartite Memorandum of Understanding (MoU) signed for a new era of One Health collaboration, Kunming-Montreal Global Biodiversity Framework and Pandemic prevention, preparedness and response accord.

3.5.2. Background

Climate change and biodiversity loss are driving a public health crisis by disrupting disease dynamics and raising the risk of infectious diseases (Pfenning-Butterworth et al., 2024). Habitat degradation and global warming weaken natural controls on disease carriers, e.g. like mosquitoes (Madzokere et al., 2022; Ogden, 2017; X. Wu et al., 2016). Human-driven ecosystem changes and force pathogens to find new hosts, and declining biodiversity disrupts disease regulation, increasing transmission (Schlaepfer & Lawler, 2023). These effects are intensified by extensive degradation of terrestrial, marine, and wetland environments, which further destabilize ecological balance.

A warming climate intensifies these threats by driving species to shift their ranges, altering population sizes, and changing human behaviour and exposure patterns (Ebi et al., 2021; Rocklöv & Dubrow, 2020). Many vector-borne and enteric pathogens, including those causing dengue, malaria and *Salmonella*, become more active, reproduce faster, and survive longer under warmer conditions. This results in higher environmental pathogen loads and greater transmission risks (Mora et al., 2022).

Enteric infections also rise, as heat accelerates bacterial growth and contaminates food and water (Manchal et al., 2024). For example, a 1°C increase in temperature raises the risk of dengue by 13% (Damtew et al., 2023), and *Salmonella* and *Campylobacter* infections by 5%(Damtew et al., 2024). A recent World Economic Forum report warns that climate change could cause 14.5 million more deaths and $12.5 trillion in global economic losses by 2050 (World Economic Forum, 2024). Climate change is projected to result in approximately 250,000 additional deaths annually between 2030 and 2050, primarily attributable to undernutrition, malaria, diarrhoea, and heat stress, and is expected to incur an additional healthcare cost of $1.1 trillion.

3.5.3. Challenge

Climate change and biodiversity loss pose significant threats to ecosystems on a global scale. Despite international commitments such as the Paris Agreement and the Aichi Biodiversity Targets, many objectives remain unmet—most notably, the critical goal of limiting global warming to 1.5°C (Matthews et al., 2022; Schlaepfer & Lawler, 2023). None of the 20 Aichi targets were fully achieved, and they have since been replaced by the Kunming-Montreal Global Biodiversity Framework (GBF), adopted in 2022 (https://www.cbd.int/gbf).
Biodiversity loss, rising temperatures, and shifting rainfall patterns directly influence disease dynamics by altering vector breeding sites, accelerating pathogen development, and changing human behaviors that affect exposure risks (Mahon et al., 2024; McKay, 2023; Rocklöv & Dubrow, 2020). The decline in biodiversity reduces the presence of species that regulate pathogens, such as predators, competitors, and decomposers (Kim et al., 2024; Wyckhuys et al., 2024). For instance, amphibians and birds help control insect vectors, while soil microbes suppress harmful bacteria. When these species decline, ecosystems lose their self-regulating functions (White, 2019). A study of 345 wetlands found that increased amphibian diversity was associated with a 78% reduction in pathogen transmission (Johnson et al., 2013). Experimental manipulations across realistic diversity gradients further revealed about a 50% decrease in disease spread.
Biodiversity also affects disease risk through host regulation and transmission mechanisms, which can either amplify or reduce infection (Glidden et al., 2021). A meta-analysis found that biodiversity loss led to an 857% greater increase in disease globally than changes caused by natural gradients like latitude or elevation (Mahon et al., 2024). Climate change exacerbates these risks. A comprehensive analysis showed that 218 of 375 infectious diseases were worsened by climate hazards through more than 1,000 pathways. Of these, 160 diseases were affected by warming and 122 by altered precipitation, making them the most common climate-related drivers (Mora et al., 2022). These pressures interact with biodiversity loss and land-use change, as seen in South Asia where Japanese encephalitis is expanding due to warming, rainfall shifts, and rice irrigation near pig farms (Mulvey et al., 2021).
Recent outbreaks reflect these trends. In 2023, over 6.5 million dengue cases and 7,300 deaths were reported across 80 countries (WHO, 2023). The EU recorded over 300 dengue cases in 2024, surpassing totals from the past 15 years (Farooq et al., 2025)(. West Nile virus spread to 19 European countries, linked to Aedes albopictus expansion (Abbas et al., 2025)(Abbas et al., 2025). Malaria cases rose from 233 million in 2019 to 249 million in 2022, driven by warming and extreme weather (Bagcchi, 2024; WHO, 2023). In southern Italy, Anopheles sacharovi reappeared after five decades, linked to warming and habitat shifts (Raele et al., 2024).
Understanding the interplay between climate, biodiversity, and disease is complex, spanning continents and involving feedback mechanisms. However, data fragmentation—especially for multi-host diseases—limits our capacity to monitor these changes (Pfenning-Butterworth et al., 2024). To prevent future outbreaks, we must integrate ecological and health data and align climate, conservation, and public health strategies around shared goals.

3.5.4. Offering solutions

Although direct research linking changes in biodiversity to zoonotic spillover is limited due to cost and logistical challenges, the available evidence supports concepts that can inform biodiversity conservation strategies aimed at reducing the risk of

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

spillover (Glidden et al., 2021). Nature-based strategies and One health approach which connects human, animal, and ecosystem health could offer practical solutions for mitigating associated risks.

Integrating biodiversity data and open-access repositories into disease surveillance is essential for tracking pathogen sources, monitoring vector populations, and predicting outbreak risks more accurately (Astorga et al., 2023). Standardized data repositories play a crucial role in avoiding data fragmentation by consolidating biodiversity, pathogen, and host information into interoperable platforms (Pfenning-Butterworth et al., 2024). The formal recognition of biodiversity databases as essential infrastructure would enhance both research and decision-making processes and aligns with the requirements of the International Health Regulations (IHR), which call for robust, cross-sectoral surveillance systems capable of early detection and coordinated response to public health threats (WHO, 2023). These resources should encompass a broader range of pathogen data and be accessible across various disciplines (Kim et al., 2024). Such measures would facilitate the development of more accurate predictive models, early warning systems, and coordinated responses (Ogwu & Izah, 2025).

Implementing the One Health approach provides a more comprehensive framework for disease monitoring and control by linking human, animal, and environmental health sectors (Figure 4). It recognizes the interdependence between people, domestic and wild animals, plants, and ecosystems. One Health improves early detection and response to disease threats (Erkyihun & Alemayehu, 2022), while also strengthening surveillance and enabling targeted interventions, particularly in addressing antimicrobial resistance (Das et al., 2024). The importance of this integrated approach is further underscored by the Quadripartite agreement which formalizes global collaboration and commitment to advancing One Health at all levels (WHO, 2022).

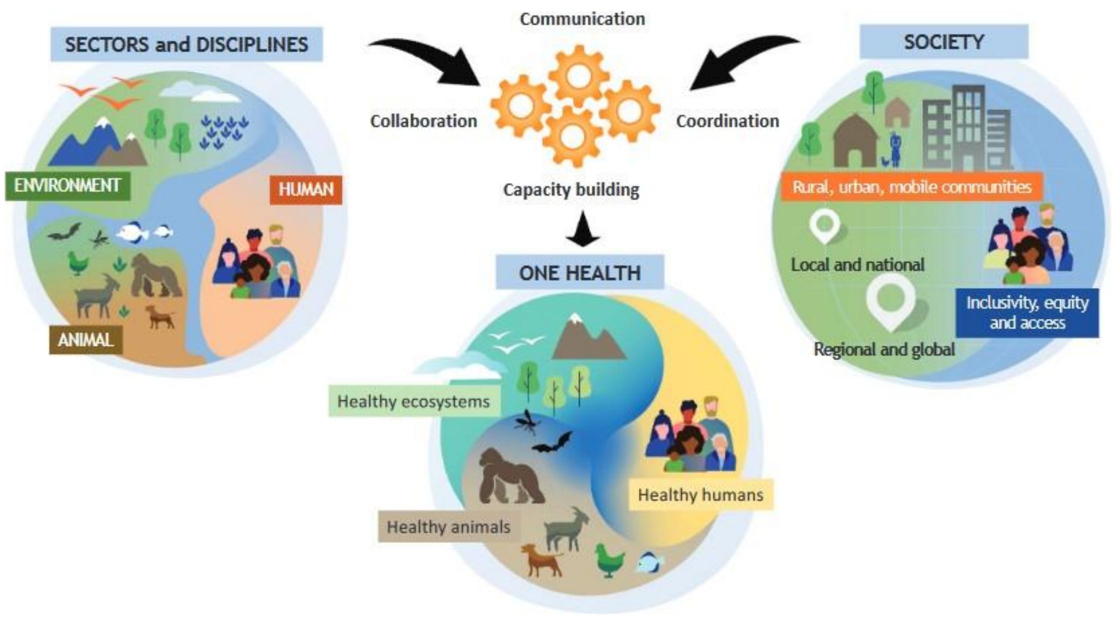

Figure 4: The collaboration, coordination and communicating system of One Health across all sectors; from Erkyihun & Alemayehu, 2022.

Robust disease monitoring must be expanded in vulnerable regions, particularly in areas where climate change is exacerbating the risk of infectious diseases. This expansion necessitates not only the tracking of infection rates but also the monitoring of vector presence, land use changes, biodiversity loss, and climate patterns to comprehend the shifting dynamics of disease. Monitoring a diverse range of risk indicators such as exposure proxies derived from environmental sampling, pathogen traits including resistance genes, and human behaviours such as mobility can yield real-time insights and enhance traditional surveillance methods (Ingelbeen et al., 2025). The World Health Organization (WHO) advocates for the integration of threat, hazard, and vulnerability data to improve early warning and response systems. These indicators facilitate the early identification of outbreaks and support tailored, effective responses that are contingent upon local conditions (WHO, 2023). Site-specific data are crucial for capturing how climate and ecosystem stressors interact in various geographical areas. Site specific data are essential for understanding how climate and ecosystem stressors interact in different regions. In places where data are scarce, using remote sensing and earth observation methods can help gather local information, especially in remote and rural areas. Biodiversity databases should be regarded as core infrastructure for understanding and predicting multi-host diseases, such as West Nile Virus, Salmonellosis, and Campylobacteriosis (Gupta et al., 2024).

Ecosystem conservation plays a key role in reducing disease risk by maintaining natural processes that regulate pathogens and vectors.The conservation of wetlands contributes to the regulation of water flow and supports predator species that effectively reduce mosquito populations in vector-borne transmission. For example, in Sri Lanka, the conservation of urban wetlands has resulted in a reduction of dengue cases by over 50% in high-risk areas, leading to cost savings for public health initiatives (Liyanage et al., 2019; Tissera et al., 2016). In Brazil's Atlantic Forest, where forest restoration has led to a decrease in malaria incidence through the promotion of natural predators of disease vectors (da Silva et al., 2024).

Implementing biological control approaches for vector management is of paramount importance (Figure 5). For example, trials conducted in Indonesia and Brazil have demonstrated that biological interventions, such as the release of Wolbachia-infected mosquitoes can reduce dengue incidence by up to 77% and hospitalizations by 86% (Montenegro et al., 2024). Economic evaluations also indicate that employing the Wolbachia method for dengue control could yield savings of up to USD 1.17 million per 1,000 individuals over two decades (Zimmermann et al., 2024). Biological control plays a significant role in the One Health framework by reducing reliance on chemical pesticides, mitigating the development of antimicrobial and biocide resistance, safeguarding biodiversity, and minimizing habitat loss, thereby supporting the integration of human, animal, and environmental health (Schaffner et al., 2024).

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

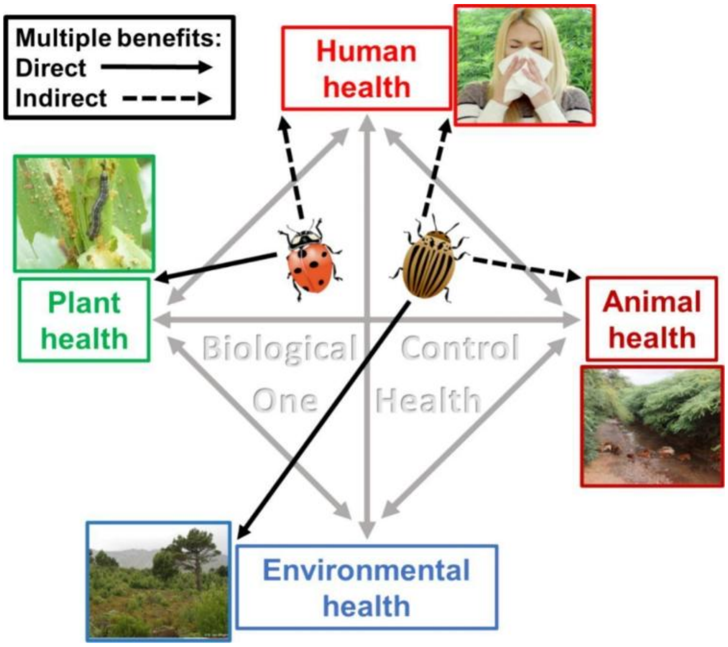

Figure 5: Direct (solid black arrows) and indirect (dashed black arrows) benefits of biological control solutions to different dimensions of the One-Health concept (Schaffner et al., 2024)

Human vulnerability is influenced not only by climatic and ecological factors but also by socio-economic conditions. Urban overcrowding, inadequate infrastructure, and limited access to healthcare create environments conducive to heightened disease transmission. Informal settlements adjacent to degraded ecosystems frequently lack access to clean water and sanitation facilities. Furthermore, poverty and ineffective governance exacerbate the challenges of response efforts. These issues must be addressed through policies that integrate health and environmental objectives, empowering communities with the necessary tools and information to adapt effectively. Strengthening the connections between ecological and epidemiological data, in conjunction with community engagement, will enhance forecasting abilities, resilience, and public health outcomes.

Ecosystem restoration transcends mere environmental protection; it is fundamentally about safeguarding human health (Robinson et al., 2022). By aligning disease prevention efforts with ecological recovery, we can cultivate healthier societies in the face of climate change, necessitating a shift from isolated, reactive responses to collaborative, science-informed strategies that strengthen both ecosystem and human health (McElwee et al., 2024b).

3.6 Nature-based Solutions

3.6.1. Key take-aways

- NbS trade-offs are inevitable but only considering win-win solutions may hinder urgent transformative and transgressive action.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

- Financial challenges can be mitigated through innovative blended funding frameworks and should focus on enhancing economic sustainability.
- Adoption of policy that recognises social equity is key to the successful implementation of NbS

3.6.2. Background

Nature-Based Solutions (NbS) are actions that protect, sustainably manage, and restore natural or modified ecosystems in ways that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Indeed, out of 101 Nationally Determined Contributions (NDCs) from developing countries, 96 include NbS in their strategies, with 92 addressing adaptation and 84 focusing on mitigation (NDC Partnership, 2024). The Paris Agreement, (2015) and the Kunming-Montreal Global Biodiversity Framework (CBD, 2022) have significantly strengthened NBS integration (United Nations Environment Programme, 2021). 89% of developing countries integrate NbS in climate plans (United Nations Environment Programme, 2023), with Latin America and Asia leading implementation (Collins et al., 2025; IPCC, 2023a). Developed nations are increasingly directing climate finance toward NbS in the Global South, with $115.9 billion allocated in 2022, exceeding the $100 billion mark for the first time (OECD, 2024). Innovative financing mechanisms like Belize's $364 million debt-for-nature swap demonstrate growing investment in marine and coastal NbS (Fontana-Raina & Grund, 2024). Private sector engagement is also expanding, with notable commitments, including the Bezos Earth Fund's $3 billion investment since 2020 for nature solutions (Pettinotti & Quevedo, 2023). NbS are proving critical for climate resilience, with mangroves reducing annual tropical cyclone flood damages by $60 billion while protecting 14 million people (Menéndez et al., 2020). Forest conservation in the Amazon and Congo basins mitigates disasters for 50+ million people, enhancing regional resilience indices by 15-30% (FAO, 2020; IPCC, 2023a; United Nations Office for Disaster Risk Reduction, 2022). Despite these benefits, greater than 50% of natural buffers remain degraded, underscoring the urgent need for scaled-up NbS investments to avert $300 billion/year in climate losses by 2030 (OECD, 2021).

Although previously mostly addressed as co-benefits in NbS, societal challenges, including economic and social development, human health, food security, and water security, are also emerging as key focus areas in which NbS can effectively close the gap between climate, biodiversity and socio-economic issues (Dunlop et al., 2024; See also Section 3.4 - Urban centres and 3.5 - Health). NbS in the Global South demonstrate significant social justice gaps, with only 17% incorporating Free, Prior, and Informed Consent (FPIC) protocols and Indigenous communities receiving merely 0.1% of climate finance, despite efforts to improve participatory benefit-sharing and integrate traditional knowledge (L. M. Pereira et al., 2024; Sowińska-Świerkosz et al., 2024).

3.6.3. Challenge

There is a persistent lack of standardized metrics and robust data to assess NbS effectiveness, impacting both policymaker and investor confidence. E.g. in Africa, sustainable housing solutions face challenges like inadequate awareness, policy

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

support, and financial barriers (Asamoah et al., 2024; Longato et al., 2023). The lack of incentives for private property owners, who control a significant portion of urban land, further hinders implementation. Addressing these gaps requires policy adjustments to highlight co-benefits and actively engage private actors (Papari et al., 2024; Thompson et al., 2023). Despite substantial capacity, governance processes often hinder adaptation efforts (Hafferty et al., 2025).

Recognizing trade-offs in NbS requires a nuanced and participatory approach to 'which NbS', for whom, where, and at what scale' (L. M. Pereira et al., 2023, 2024; Wolff et al., 2022). Political instability has disrupted long-term planning and investment in NbS. Fragile states bear a disproportionate burden from climate-related disasters, experiencing higher displacement rates despite contributing minimally to global greenhouse gas emissions (Jaramillo et al., 2023). Key barriers to scaling up NbS include insufficient data, limited funding, and weak governance structures (Enu et al., 2023), all of which hinder effective project implementation and monitoring. The clear geographical bias in the evidence base for the effectiveness of NbS (e.g. the Nature-based Solutions Evidence Platform: https://www.naturebasedsolutionsevidence.info/evidence-tool/; (Chausson et al., 2024; Olago et al., 2024; Sudmeier-Rieux et al., 2021) undermines the potential for the scaling of NbS initiatives more universally. Africa in particular remains underrepresented (~16% in this Platform) relative to the continents' spatial area contribution and the urgency for equitable and socially just action (e.g. Zyoud & Zyoud, 2025), However, globally 'scaling up' may not automatically translate to more universal application in the Global South. Armani et al., (2022), document that locally-scaled initiatives perform better than large-scale counterparts in Africa, due to improved acknowledgement of context-specificity and sensitivities to the cost-effectiveness realities that plague implementation in the Global South. Similarly with respect to social-justice and equity considerations even within Global South communities, women generally invest less in agroforestry, for example, due to limited land-tenure rights, and gendered power relations in forest institutions restrict their access and control over resources like firewood, limiting their decision-making and labor roles (Friman, 2023; Kouassi et al., 2023).

3.6.4. Offering solutions

NbS have considerable potential for supporting pathways towards positive tipping points, provided that the solution-space for designing and implementing NbS is inclusive of a plurality of perspectives and knowledges, prioritises local context and avoids false narratives of positioning NbS as universally ''win-win". The reality of NbS is that there are going to be losers, and existing evidence has shown that NbS can exacerbate existing socio-political inequalities, manifesting new avenues of exclusion (Delbaere et al., 2024). However, engineered solutions like Direct Air Capture (DAC) and Carbon Capture and Storage (CCS) disproportionately burden marginalized communities due to high financial costs, extensive land use, and significant energy demands (McLaren & Corry, 2025; Rojas-Rueda et al., 2024). NbS is consistently more cost-effective, with reforestation initiatives costing $10-50 per ton of CO_2 compared to $50-600 per ton for DAC/CCS systems (Oloyede et al., 2025). However, NbS typically requires more land (FAO, 2021b; Markus & Schaller, 2024), while engineered solutions present risks of ecosystem disruption through infrastructure requirements (Alizadeh et al., 2024; Dooley et al., 2021).

NbS demonstrate strong potential for community integration, with 68% of 85 projects in Africa (focused mainly on the water sector, urban development and agriculture) showing active community participation in NbS implementation and 58% including a gender equity component (Oliver & Marsters, 2022). Despite limitations in data availability on the specific benefits, all of these projects included at least one co-benefit, of which 58% increased job creation and improved livelihoods, 47% mentioned increased biodiversity and habitat protection and 47% included carbon sequestration (Oliver & Marsters, 2022) Nevertheless, it remains essential to improve performance assessment, accounting for synergies and trade-offs (Sowińska-Świerkosz et al., 2024).

It is critically important to identify who will be exposed to the burden of loss (i.e. loss of access) (L. M. Pereira et al., 2024; Seddon et al., 2020). Further, only considering win-win options may effectively paralyse the solution-space as Pereira et al., (2024) argue "to the point of impossibility", which given the urgency for transformative and transgressive solutions (Vogel & O'Brien, 2022), is worryingly short-sighted. Inclusive community engagement must involve diverse voices, particularly in urban regeneration projects in informal settlements and low-income areas, to ensure fair governance and social justice (McEvoy et al., 2024; Tozer et al., 2023) and minimize the risk of displacement due to increased land value from green space development (Anguelovski & Corbera, 2023; Hill et al., 2024; Song et al., 2024).

Payments for Ecosystem Services (PES) programs, like Costa Rica's $65M watershed initiative, demonstrate effective market-based conservation by compensating individuals or communities for sustainability contributions (often linked to land stewardship) (Le et al., 2024). Since 2005, the Conservador das Águas program in Brazil were responsible for the restoration of 60% (3000 hectares) of forest in 10 years, effecting improved watershed management (Richards et al., 2015). Agroforestry systems enhance biodiversity while simultaneously improving livelihoods as smallholder farmers adopt crop diversification (Antonelli et al., 2022; Basantaray et al., 2024; Savilaakso et al., 2024). The assessment on Nature-Based sustainability indicates that diverse rotations can diminish production losses during drought years by about 90% (from a 14% loss to as low as 1–2%), while cover cropping enhances soil water retention by around 20 mm (Altieri et al., 2025; Brempong et al., 2023)(Altieri et al., 2025 & Brempong et al.,2023 see also Section 3.2 - Drylands). While promising, PES success will require the setting of better defined, measurable goals and targeting appropriate ecosystem services from onset (Viguera et al., 2024).

Funding for NbS increased, with new mechanisms supporting implementation, yet it remains insufficient to meet global targets, requiring annual flows to triple to $542 billion by 2030 (Biasin et al., 2024; Den Heijer & Coppens, 2023; United Nations Environment Programme, 2023). While international collaborations enhance capacity and resources, they often perpetuate financial power imbalances, aligning initiatives with funder priorities (Greenwalt et al., 2023). Key enablers, including financial support, land access, economic addition, and long-term monitoring, remain critical, despite disparities in adaptation financing persisting across developing regions (Collier et al., 2023; United Nations Environment Programme, 2023). To mitigate financial power imbalances in international NbS partnerships, three key solutions are involved; direct funding mechanisms to local actors (65% more effective), decentralized decision-making (improves equity by 40%), and co-governance frameworks that redistribute power (GCF, 2024; Malekpour et al., 2021; World Resources Institute, 2024). such

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

as debt-for-climate swaps effectively support adaptation, biodiversity conservation, and socio-economic development, as demonstrated by Ecuador's $1.6 billion Galápagos swap (2023) which allocates $12 million annually to marine conservation, and Belize's $364 million blue bond that funds coastal protection while reducing debt by 10% of GDP (Elmahdi & Jeong, 2024). Voluntary carbon markets have been actively pursuing forest-sector offsetting credits, alongside similar opportunities in other compliance markets (Yin, 2024). Political leaders and experts emphasize the urgent need for international finance to help developing countries mitigate climate change impacts without worsening their unsustainable debt burdens (Tol, 2023). Policy responses aimed at addressing these gaps include gender action plans in 32 nations, strengthened Indigenous rights recognition, and 45% community funding allocations under Africa's Great Green Wall initiative, highlighting the importance of targeted interventions to enhance equity and sustainability (GCF, 2024; ILO, 2024; UNCCD and UN-Habitat, 2024b). Despite these limitations, innovative approaches, such as spatially targeted assessments for NbS show promise in maximizing net returns by prioritizing high-impact areas (Garaffa et al., 2023).

Gender-responsive measures, including quotas, enhance livelihoods by 35%, while secure land tenure has been shown to improve success rates by 60%, yet persistent inequities remain as only 12% of carbon revenues reach local communities and 40% of forest projects experience resource conflicts (Baschieri et al., 2025; Rakotonarivo et al., 2025). Social equity, emphasizing participation, citizen involvement, and distributive justice, is a preferred framework for governance over the broader concept of justice (Anguelovski & Corbera, 2023). Armani et al., (2022) highlight the deafening silence around gender sensitivities and social inclusion linked to climate solutions more generally, with gender equity and social inclusivity similarly noted as critical for ensuring appropriate NbS mainstreaming, (Oliver & Marsters, 2022), particularly if they are not going to exacerbate existing inequalities (Delbaere et al., 2024). The potential gendered impacts of NbS remain a notable gap for successful NbS deployment (Oliver & Marsters, 2022), particularly for Africa (e.g. Awiti, 2022). Gender-focused approaches in NbS (NbS) enhance outcomes as seen in Kenya's Green Belt Movement, where women-led reforestation improved both degraded lands, improved incomes, and strengthened social cohesion (Zhai et al., 2023). Similarly, Ghana's agroforestry projects emphasize land rights, enabling indigenous communities to sustainably manage resources while addressing socio-economic disparities (World Bank, 2024). However, resource diversion intended for vulnerable populations risks undermining social equity and NbS objectives (Shipton & Dauvergne, 2023), and despite targeted efforts by organizations to allocate resources for marginalized groups, challenges such as resource diversion continue to undermine social justice objectives (Bryan et al., 2024; FAO, 2024).

3.7 Geopolitics and conflict

3.7.1. Key take-aways

- Biodiversity and ecosystems are increasingly becoming geopolitical assets, while the global shift in power dynamics exacerbates environmental vulnerability
- Conflict-associated activities restrict biodiversity research and conservation efforts, creating massive biodiversity shortfalls.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

- International governance, diplomatic pressure, continued funding and transboundary environmental governance are essential for biodiversity conservation across national borders
- Inclusive stakeholder engagement, involving governments, local communities, NGOs, and scientific institutions, is critical to the success of transboundary conservation initiatives like Peace Parks and Transboundary Biosphere Reserves.
- International initiatives could include the mandate for environmental governance into international peacebuilding missions and the establishment of "Green Helmets" with legal and diplomatic protection.

3.7.2. Background

The impact of geopolitical conflict, including wars and invasions, on biodiversity and the environment is often overlooked as a threatening process in environmental analyses and discussions. Geopolitical conflict refers to territorial disputes driven by geographical, political, or strategic interests. The effects on biodiversity are complex and reflect different interests and stakeholders (Weir et al., 2024). Sometimes, however, the loss of biodiversity and biosphere integrity is collateral damage.

Geopolitical conflicts can paradoxically provide temporary protection to certain environments, turning them into inaccessible "no-go zones" that protect biodiversity from direct human exploitation. However, the negative impacts of conflict have also been pointed out as they often lead to habitat destruction, overexploitation of natural resources, pollution, and the disruption of conservation efforts (Certini & Scalenghe, 2024; Gaynor et al., 2016; Hanson et al., 2009). Armed groups may exploit natural resources to fund their activities, while displaced communities rely on local biodiversity for survival, often unsustainably (Wirtu & Abdela, 2025) (Wirtu and Abdela, 2025). Moreover, the breakdown of governance in conflict zones can enable illegal logging, mining, and wildlife trafficking, further degrading ecosystems. Notably, between 1950 and 2000, a vast majority of wars (at least 80%) occurred in biodiversity hotspot regions (Hanson et al., 2009).

In the Democratic Republic of Congo (DRC), for example, during the 1990s civil war, protected areas housing endangered great apes were heavily impacted by military activities (Draulans & Krunkelsven, 2002). Forests were destroyed, and local communities became more reliant on bushmeat and forest resources for survival, further threatening biodiversity (Milburn, 2015). Poaching increased, with armed groups exploiting wildlife for trade. Conflict zones that included protected areas became dangerous for conservationists, while the illegal wildlife trade flourished.

Post-conflict, agricultural expansion further degraded these ecosystems, as displaced populations returned and sought livelihoods (Hanson, 2018, p. 201)(Hanson, 2018). In the case of Colombia, studies even found higher deforestation rates after the peace agreement was signed compared to the years before (Clerici et al., 2020; Ganzenmüller et al., 2022; Prem et al., 2020). Other countries and protected areas, such as the Gorongoza National Park in Mozambique have shown rapid biomass recovery (Stalmans et al., 2019). Whether post-conflict periods are characterized by increased or decreased loss of biodiversity is most likely linked to aspects of governance and institutional capacity but there is limited research on this topic.

Southeast Asia also experienced negative impacts during the Vietnam War. The use of Agent Orange by American forces caused severe deforestation, habitat loss, and long-term soil degradation (Frey, 2013; T. L. Nguyen, 2021). Aquatic ecosystems were also contaminated, with toxic chemicals affecting fish populations and other aquatic life (Frey, 2013). In

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

more recent history, the Ukraine-Russia conflict has led to severe air pollution, greenhouse gas emissions, and habitat destruction (P. Pereira et al., 2022; Rawtani et al., 2022)(Pereira et al., 2022; Rawtani et al., 2022). Bombings and tunnelling have disrupted landscapes, while some urban wildlife, such as bats, have been directly affected (Pereira et al., 2022). Additionally, the destruction of industrial sites and chemical storage facilities has caused water and soil contamination (Pereira et al., 2022).

In addition to direct environmental destruction, geopolitical conflicts also hinder our understanding of biodiversity. In Mindanao, southern Philippines, historical conflict has led to significant gaps in biodiversity knowledge, as security concerns have made it difficult for researchers to study these areas (Hilario-Husain et al., 2024; Tanalgo et al., 2025). This lack of data further impedes conservation planning and efforts. Furthermore, disrupted governance during conflicts can weaken protected area management, leaving ecosystems vulnerable. It is therefore essential to understand the complex relationship between conflict and biodiversity for developing strategies to mitigate environmental harm and protect vulnerable ecosystems in conflict zones. Collaborative efforts between conservationists, governments, and international organisations are needed to ensure biodiversity conservation is prioritised even in times of conflict.

3.7.3. Challenge

In recent years, the topic of geopolitics has become more relevant to biodiversity conservation for different reasons. First of all, we have seen an increasing number of armed conflicts in many parts of the world. During the last five years, conflicts worldwide have approximately doubled and increased on every continent (Raleigh & Kishi, 2024)Ra(Raleigh & Kishi 2024). Secondly, we have seen a shift in global geopolitics towards a multipolar world with increasing power of new states (e.g. China, Russia, India and Brazil) as well as non-state actors (e.g. private companies and tech giants). This trend also relates to the growing vacuum left by the United States' withdrawal from key international sustainability and cooperation agreements (e.g., UN frameworks), alongside the rising influence of tech giants and their deepening ties with government. Fourth, we observe a continued rise in global demand for resources—such as rare earth elements, fossil fuels, minerals, and land—intensifying competition and land-use conflicts. Finally, while the Global South's renewed confidence offers a critical opportunity to champion climate and environmental justice and drive equitable transitions, weak governance may instead exacerbate resource exploitation, trigger new conflicts, and undermine political stability.

The current conflict in the DRC and the role of Rwanda within this conflict have been, for example, associated with the increasing demand for Coltan and Cassiterite. The new resource deal of the US with Ukraine and the threats towards Denmark and the EU invading Greenland to get access to its fossil resources and minerals are just some examples, where ecosystems and natural resources are becoming a geopolitical pawn in global geopolitics.

Generally, we assume that the reduction of international engagement and funding in foreign sustainability initiatives (e.g. dismantling US Aid) also has substantial negative backlash impacts on ecosystems and biodiversity. People involved in biodiversity conservation and monitoring, both via international collaboration as well as local staff, might be forced to stop conservation activities either because of security reasons or because of a lack of funding (e.g. due to embargos and international sanctions). As a consequence, not only does biodiversity loss often increase, but also monitoring efforts phase out or stop altogether, leading to a complete lack of knowledge about the actual conditions and trends.

3.7.4. Offering solutions

International collaboration can enable the sustainability of conservation efforts during and after armed conflict. By establishing safeguards to ensure that funding does not inadvertently support war-related activities, the international community can help sustain biodiversity conservation in times of crisis, while also laying the groundwork for ecological recovery and resilience in the post-conflict period. In addition to financial and institutional support, international diplomatic pressure can be essential for safeguarding biodiversity during armed conflicts. Biodiversity conservation may support conflict resolution while protecting biodiversity in the form of transboundary environmental governance (e.g. the Kavango Zambezi Treaty providing the basis for governing the Kavango–Zambezi Transfrontier Conservation Area ratified by 5 countries). This requires the integration of a wide array of actors and institutions engaged in shaping and implementing environmental decisions that span jurisdictions and property boundaries both within and between nation-states (Miller et al., 2022). More specifically, it refers to the cooperative management and regulation of environmental issues that transcend national boundaries, requiring collaboration among multiple countries to address shared challenges, such as biodiversity conservation and the management of transboundary natural resources (Milman et al., 2020).

A notable example of such cooperation is the concept of Transboundary Biosphere Reserves (TBRs), officially endorsed by the International Coordinating Council of the Man and the Biosphere (MAB) Programme in 1992–1993. TBRs exemplify cross-border collaboration for conservation and sustainable development. TBRs include peace parks and national parks. Peace parks are transboundary protected areas that span national borders to promote biodiversity conservation, wildlife movement, and peaceful cooperation between neighboring countries. The designation and effective management of TBRs have yielded several important lessons. First, their successful establishment depends on close cooperation and coordination among participating countries, fostering strong partnerships, a shared vision, effective communication, and, in some cases, contributing to peacebuilding (Köck et al., 2022). Second, inclusive stakeholder engagement—encompassing governments, local communities, non-governmental organisations, and scientific institutions—has proven essential in the design and management of these reserves (Hilty et al., 2023). Finally, the ecosystem approach employed in TBRs offers a holistic and integrated conservation strategy that acknowledges the interdependence of ecosystems and the services they provide. This approach strengthens ecological integrity while promoting socio-economic benefits and cross-border cooperation.

However, geopolitical conflicts have direct environmental impacts on the biosphere and create significant barriers to biodiversity documentation. These barriers limit our understanding of biodiversity status and condition, subsequently hampering the implementation of effective conservation strategies, thereby exacerbating the negative consequences of war and conflict. It is critical to intensify efforts aimed at ensuring the safety of scientists and conservation biologists working in conflict zones. One promising approach to ensure at least constant biodiversity monitoring involves utilising remote sensing technologies, such as drones and camera traps, which have proven effective in monitoring wildlife. These technologies can

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

be deployed effectively in both active and recovering conflict areas, facilitating ongoing biodiversity assessments and management (Drouilly et al., 2025).

Furthermore, adopting these technologies in transboundary initiatives can enhance data sharing and access across borders, promoting international cooperation and coordinated conservation efforts. Furthermore, supporting and connecting field biologists with local communities engaged in environmental monitoring prioritising equitable partnerships and capacity building, empowering local communities to monitor environmental conditions, such as water and soil quality, during and after conflicts, would allow continued monitoring activities (Meaza et al., 2024) .

In order to maintain biodiversity conservation on the ground during conflicts, an innovative approach is to embed ecological sustainability and resource governance in the mandate of UN peacekeeping missions (Böhmelt, 2024) to safeguard ecosystems, endangered species and natural resources while working alongside local rangers and conservationists. This approach could be expanded by establishing "green helmet" missions under a recognised international framework, thereby granting the involved staff legal and diplomatic protection similar to the "Blue Helmets".

3.8 Demographic dynamics

3.8.1. Key take-aways

- Population dynamics—both growth and decline—are critical yet underappreciated drivers of ecological change and must be central to conservation discourse and planning.
- High population growth intensifies land-use pressure and biodiversity loss, especially in regions with expanding cultivation and limited resources.
- Depopulation and aging in rural areas disrupt traditional land stewardship, leading to ecological neglect, land abandonment, and rewilding challenges.
- Conservation and sustainability strategies must integrate demographic foresight across sectors, from biodiversity policy to landscape governance and rural revitalization.
- Empowering women, supporting intergenerational knowledge transfer, and designing labor-efficient land management systems are essential for balancing human development with ecological resilience.

3.8.2. Background

Human population dynamics—comprising fertility, mortality, migration, aging, and spatial distribution—have long influenced the biosphere's structure and function (Jarzebski et al., 2021; Marini et al., 2024). They shape not only the demand for food, water, and energy, but also the spatial extent and intensity of human disturbance across ecosystems (Kopnina & Washington, 2016; Lenzi, 2023; Nzunda & Midtgaard, 2017; Saraswati et al., 2024). In high-growth regions such as Sub-Saharan Africa and parts of South Asia, continued population expansion drives agricultural extensification, urban encroachment, and forest conversion, directly escalating biodiversity loss and ecosystem degradation (Cincotta et al., 2000; Cripps, 2023; Nzunda & Midtgaard, 2019; Saraswati et al., 2024, see also Section 3.5 - urban centres). When coupled with increasing per capita consumption, these patterns result in ecological overshoot—surpassing the regenerative capacity of ecosystems (Boyle, 2025; Steffen et al., 2015; Wiedmann et al., 2020).

On the other end of the spectrum, in much of Europe, East Asia, and parts of Latin America, declining fertility rates and rising life expectancies have initiated demographic contractions, especially in rural areas (Jarzebski et al., 2021; Lloret et al., 2024; Marini et al., 2024). Population aging and youth outmigration leave behind landscapes vulnerable to abandonment, weakening traditional ecological stewardship and contributing to disruptions in ecosystem services (Lloret et al., 2024; Marini et al., 2024; Robson & Klooster, 2019). Land previously managed for agroecological balance is either rewilded in unmanaged forms or becomes a hotspot for invasive species, fire outbreaks, and erosion (Pallotta et al., 2022; H. Wu et al., 2022) . These changes have consequences not only for local biodiversity but also for the cultural and ecological continuity of human-nature relationships (Castillo-Rivero et al., 2023; Marini et al., 2024; Okui et al., 2021).

Importantly, population dynamics are not neutral: they intersect with gender, class, education, and policy frameworks (Cripps, 2023; P. Dasgupta & Treasury, 2022; Fenner & Harcourt, 2023). Fertility decisions are affected by access to healthcare, reproductive rights, and economic opportunities, while aging and migration patterns reflect broader socioeconomic and institutional conditions(Boyle, 2025; P. Dasgupta & Treasury, 2022; Jarzebski et al., 2021). Thus, demographic change is both a driver and an outcome of systemic transformations—affecting not only land and species but also equity, resilience, and sustainability across generations (P. Dasgupta & Treasury, 2022; Harper, 2014).

Recognizing population dynamics as a central axis of global change is essential for any meaningful discussion of sustainable development (Bongaarts & O'Neill, 2018; Cripps, 2023; Jarzebski et al., 2021; Kopnina & Washington, 2016). These dynamics underpin key dimensions of the Sustainable Development Goals (SDGs), including food security (SDG 2), urban sustainability (SDG 11), climate action (SDG 13), and life on land (SDG 15) (P. Dasgupta & Treasury, 2022; Jarzebski et al., 2021; Sheng et al., 2025; United Nations, 2015). Yet, their systemic ecological relevance remains underappreciated in environmental governance discourses (Boyle, 2025; Fenner & Harcourt, 2023; Mehring et al., 2020). A biosphere-informed research and policy agenda must place demographic realities—not just technological or economic factors—at the heart of conservation, land-use planning, and ecosystem restoration (Castillo-Rivero et al., 2023; Lloret et al., 2024; Marini et al., 2024; Saraswati et al., 2024).

3.8.3. Challenge

Despite their centrality, population dynamics remain inadequately addressed in conservation science, policy, and sustainability programming (Jarzebski et al., 2021; Kopnina & Washington, 2016; Lenzi, 2023; Mehring et al., 2020). Most environmental frameworks still rest on outdated or one-dimensional assumptions—treating population either as a constant or a marginal issue—rather than as a core systemic force (Bongaarts & O'Neill, 2018; Boyle, 2025; Cripps, 2023; Saraswati et al., 2024). In regions of rapid population growth, environmental degradation is often attributed to poor land-use practices or governance failure, while the underlying demographic drivers are politically and scientifically downplayed (Cripps, 2023;

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

Fenner & Harcourt, 2023; Kopnina & Washington, 2016; Saraswati et al., 2024). Conservation narratives tend to avoid discussions of fertility, reproductive rights, or youth population bulges due to concerns about equity, political sensitivity, or perceived neo-Malthusianism (Boyle, 2025; Cripps, 2023; Fenner & Harcourt, 2023; Kopnina & Washington, 2016) . This omission neglects the reality that high fertility rates—especially when coupled with rising consumption—amplify pressures on forests, water systems, and marginal lands (Bongaarts & O'Neill, 2018; P. Dasgupta & Treasury, 2022; Saraswati et al., 2024; Steffen et al., 2015). As a result, interventions tend to treat symptoms (e.g., forest loss) without addressing root causes (e.g., land fragmentation driven by population increase) (Boyle, 2025; Jarzebski et al., 2021; Kopnina & Washington, 2016; Saraswati et al., 2024).

Conversely, in shrinking regions, demographic decline is not viewed as an ecological issue at all (Castillo-Rivero et al., 2023; Jarzebski et al., 2021; Lloret et al., 2024; Marini et al., 2024). Environmental governance and rural development programs rarely anticipate the landscape-level effects of aging populations, depopulation, and labor loss (Jarzebski et al., 2021; Lloret et al., 2024; Marini et al., 2024; Pallotta et al., 2022). This blind spot is critical. As communities age and youth migrate to cities, traditional land-use systems—such as satoyama in Japan or dehesa in Spain—break down, threatening biodiversity-dependent agricultural mosaics (Kohsaka & Natuhara, 2022; Marini et al., 2024; Parra-López et al., 2023; Shimpo, 2022). Abandoned terraces, uncultivated fields, and declining livestock grazing leave habitats unmanaged, raising fire risk and disrupting native species assemblages (Lloret et al., 2024; Pallotta et al., 2022; Z. Wang et al., 2024; H. Wu et al., 2022). Furthermore, conservation frameworks rarely integrate spatial demographic foresight. Urban planning models overlook the ecological burden of sprawling megacities absorbing rural migrants (Castillo-Rivero et al., 2023; Jarzebski et al., 2021; Marini et al., 2024; Mehring et al., 2020). Meanwhile, rural revitalization schemes ignore the absence of future generations to manage landscapes (Lloret et al., 2024; Nath et al., 2023; Robson & Klooster, 2019; Uchiyama et al., 2022). Aging populations are often treated as passive recipients of services rather than as holders of ecological memory and stewardship capacity (Jarzebski et al., 2021; Okui et al., 2021; Rollo, 2025; Uchiyama et al., 2022, see also Section 3.2 - Drylands).

Efforts to rewild landscapes in depopulated zones also face blind spots. Without participatory governance, these projects risk exacerbating human-wildlife conflicts or marginalizing local land users (Marini et al., 2024; Tsunoda & Enari, 2020; H. Wu et al., 2022). Conservation organizations often pursue large-scale ecological restoration while ignoring the sociopolitical vacuum left by demographic change (Castillo-Rivero et al., 2023; Marini et al., 2024; Lloret et al., 2024; Tsunoda et al., 2020).

Finally, the disconnection between demographic science and environmental policy-making is institutional (Kopnina & Washington, 2016; Jarzebski et al., 2021; Lenzi, 2023; Mehring et al., 2020). Population issues are siloed under health, migration, or urban planning portfolios, while conservation is relegated to environment ministries or NGOs (Cripps, 2023; Jarzebski et al., 2021; Boyle, 2025; Fenner & Harcourt, 2023). This fragmentation prevents the development of cross-sectoral solutions that reflect real human–nature dynamics (Dasgupta, 2021; Lenzi, 2023; Mehring et al., 2020; Saraswati et al., 2024). The result is a conservation agenda that is ecologically ambitious but demographically naïve—insufficiently

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

prepared for either the growth-related resource squeeze or the decline-induced stewardship void (Jarzebski et al., 2021; Marini et al., 2024; Boyle, 2025; Kopnina & Washington, 2016).

3.8.4. Offering solutions

To correct the underrepresentation of population dynamics in conservation and sustainability strategies, both conceptual realignment and practical integration are required (Dasgupta, 2021; Saraswati et al., 2024; Lenzi, 2023; Cripps, 2023). First, population science must be repositioned from the margins to the center of environmental governance (Dasgupta, 2021; Saraswati et al., 2024; Lenzi, 2023). This begins with embedding demographic indicators—fertility rates, aging indexes, rural labor availability, migration flows—into national biodiversity plans, ecosystem restoration targets, and climate adaptation frameworks (Jarzebski et al., 2021; Jarzebski et al., 2021; Saraswati et al., 2024; Boyle, 2025; Dasgupta, 2021). In high-growth regions, solutions must prioritize reproductive health, education, and gender equity as core environmental strategies (Cripps, 2023; Dasgupta, 2021; Saraswati et al., 2024; Lenzi, 2023). Evidence shows that voluntary family planning programs, coupled with girls' secondary education and women's economic empowerment, lead to reduced fertility and slower population growth—while enhancing household resilience (see also Section 3.1 - Resilience) and ecological sustainability (Bongaarts & O'Neill, 2018; Cleland et al., 2006; Cripps, 2023; P. Dasgupta & Treasury, 2022; Saraswati et al., 2024)(Cleland et al., 2006; Dasgupta, 2021; Saraswati et al., 2024; Cripps, 2023; Bongaarts & O'Neill, 2018). These interventions should be financed not only through health budgets but through conservation funds and climate finance as co-benefits of reduced resource pressure (Dasgupta, 2021; Saraswati et al., 2024; Lenzi, 2023; Boyle, 2025).

In regions of population decline, landscape governance must adapt to shrinking human footprints (Marini et al., 2024; Jarzebski et al., 2021; Lloret et al., 2024; Castillo-Rivero et al., 2023). This includes developing labor-light stewardship models—such as payment for ecosystem services, remote monitoring, and community-based landscape contracts—while incentivizing youth engagement through agricultural apprenticeships, digital farming, or seasonal land stewardship programs (Lloret et al., 2024; Nath et al., 2023; Uchiyama et al., 2022; Wollenberg et al., 2022). In Japan and South Korea, for example, programs that connect city dwellers with abandoned rural plots have helped rejuvenate traditional landscapes while bridging demographic divides (Nath et al., 2024; Wang et al., 2024; Shimpo, 2022; Uchiyama et al., 2022).

Intergenerational learning should be institutionalized in both formal and informal education systems (Okui et al., 2021; Ouma, 2022; Rollo, 2025; Uchiyama et al., 2022)Roll(Rollo, 2025; Uchiyama et al., 2022; Okui et al., 2021; Ouma, 2022). Older populations should be empowered not merely as vulnerable dependents but as knowledge holders in conservation programs, particularly in Indigenous and rural communities (Okui et al., 2021; Uchiyama et al., 2022; Rollo, 2025; Jarzebski et al., 2021). This may include storytelling, agroecological mentorship, and participatory mapping (Rollo, 2025; Uchiyama et al., 2022; Okui et al., 2021; Ouma, 2022).

Lastly, conservation science and policy must become demographically literate (Jarzebski et al., 2021; Lenzi, 2023; Kopnina & Washington, 2016; Saraswati et al., 2024). This involves restructuring governance frameworks to include demographic foresight in all stages of planning—scenarios, risk assessments, funding models, and monitoring systems (Jarzebski et al., 2021; Marini et al., 2024; Lloret et al., 2024; Castillo-Rivero et al., 2023). Cross-sectoral platforms that bring together demographers, ecologists, land planners, and community organizations will be essential to designing sustainable solutions in a rapidly transforming biosphere (Dasgupta, 2021; Jarzebski et al., 2021; Fenner & Harcourt, 2023; Bongaarts & O'Neill, 2018). In short, restoring the relevance of population dynamics in sustainability is not just about numbers—it is about reframing humans not as an external threat to ecosystems, but as integral agents whose demographic realities must shape, and be shaped by, conservation futures (Cripps, 2023; Saraswati et al., 2024; Lenzi, 2023; Marini et al., 2024).

3.9 Indigenous and Local Knowledge

3.9.1. Key take-aways

- ILK is increasingly recognized in biosphere research and supports transformative change providing actionable solutions across different sectors.
- ILK radically challenges currently dominant paradigms in science.
- One important determinant of ILK, especially in Indigenous contexts, is the care and protection of Mother Nature as a spiritual entity.
- Interweaving ILK with scientific knowledge requires inclusive, equitable and accountable approaches.

3.9.2. Background

One of the most significant advancements in biosphere research related to addressing anthropogenic stressors is the increasing recognition of Indigenous and Local Knowledge (ILK) systems in biodiversity conservation and territorial management, including in coastal and marine environments. This shift challenges previous dominant scientific paradigms that are strictly built on evidence-based reductionist natural sciences, avoiding or denying any metaphysical dimension. By means of ILK, flat ontological frameworks enter into science that perceive the biosphere as a living entity with agency. Acknowledging the rights of ILK systems and nature jurisprudence paves the way for a more ethical and holistic science.
Ecuador is an example where the constitutionalization of the rights of nature is strongly linked to Indigenous knowledge systems (Espinosa, 2019). Aiming at defining ILK, researchers stress that there is no unified definition. Nonetheless, there are some basic aspects such as that knowledge derives from an interconnected relationship with nature, is passed down through generations, and often combines practice, culture and spiritual beliefs (Gadgil et al., 1993). Why is such an integrative science relevant for sustainability transformations? Conventional dominant scientific paradigms fail to achieve sustainability due to their reductionism, mechanistic approaches, and control-oriented worldview (Frantzeskaki et al., 2025). On the contrary, Indigenous worldviews, with their emphasis on relationality and ancestral wisdom, offer grounded and mutually beneficial solutions that provide alternative sustainability pathways (Jiménez-Aceituno et al., 2025; Müller et al., 2023). ILK-based perspectives position the biosphere as a relational entity, deeply intertwined with cultural, spiritual, and social life. This reframing not only enriches scientific inquiry but also contributes to more ethical, inclusive, and sustainable

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Preprint. Discussion started: 25 September 2025

ecosystem governance and is increasingly recognized (Bristow et al., 2024). Indigenous knowledge advocates a redefinition of planetary society. It does not speak of the planet or the environment as possessions; rather, it speaks of Mother Nature as the provider of life and recognizing nature's cycles thereby underpinning the legacy of Indigenous grandmothers and grandfathers. Furthermore, it implies a post-development perspective (Erazo Acosta, 2023). Studies consistently show that Indigenous-managed lands exhibit higher biodiversity, lower deforestation rates (17-26% reported for tropics), and more effective carbon sequestration than state-protected areas and/or unprotected areas (Fa et al., 2020; Garnett et al., 2018; Schuster et al., 2019; Sze et al., 2021; see also Section 3.1 - Resilience). These territories, governed by traditional ecological knowledge and customary laws, represent vital refuges against climate change and biodiversity loss. More recently, the IPBES (O'Brien et al., 2025) continues emphasizing the integration of ILK in its assessments and frameworks.

3.9.3. Challenge

Despite growing recognition, the integration of ILK into mainstream biosphere research remains fraught with conceptual, and political challenges. The recent IPBES assessment claimed that ILK currently remains "unrecognized, marginalized, disintegrated and not adequately supported" (O'Brien et al., 2025, p. 28). Conceptually, certain challenges will have to be overcome in order to integrate ILK into mainstream biosphere research. In this regard, Filho et al. (2025) point towards the obstacles of integration on the spectrum of functional operative to philosophical theoretical. So far, ILK has often been reduced to ecological knowledge due to its incompatibility with existing dominant frameworks that were not able to adequately integrate its complexities. Gómez-Baggethun (2022) has also stressed the risk of reducing ILK to its instrumental value without recognizing it having value on its own. Furthermore, the type of knowledge is inherently context-dependent and therefore findings remain limited in terms of generalizations (Zhang, West, et al., 2023).

On a systemic and political scale, power asymmetries and colonial legacies persist in research governance and knowledge production. Therefore, ILK runs the risk of being erased or lost through integration (Kaare, 1994; Yanou et al., 2023). Even when ILK is recognized, communities often lack control over how their knowledge is used, stored, and interpreted (Benyei et al., 2020). These issues are further compounded by ongoing land rights struggles faced by many Indigenous communities, which directly affect their capacity to retain ILK and live in harmony with nature (Kaleb et al., 2020; Rakotonarivo et al., 2025). Fernández-Llamazares et al. (2021) summarize some of the major threats to ILK systems and lifeways of Indigenous Peoples and local communities and the resulting social-ecological consequences such as poverty, cultural erosion, dispossession, drug trafficking, mining and megaprojects. Without frameworks that guarantee data sovereignty, informed consent, and co-ownership, integration efforts risk reproducing again extractive dynamics.

3.9.4. Offering solutions

The recent IPBES assessments (McElwee et al., 2024a; O'Brien et al., 2025) have pointed out how ILK offers philosophies, ethics, values, and practices to facilitate and accelerate transformative change by creating synergies across and weaving together different knowledge systems. The assessments emphasize the need for non-Indigenous researchers to deepen our understanding of Indigenous Peoples and Local Communities (IPLC)-managed systems, particularly their nexus-wide benefits—spanning health, food systems, biodiversity conservation, and climate adaptation and policy (Huambachano et al., 2025). It calls for holistic studies that assess both the monetary and non-monetary value of these systems, address contested property and traditional rights, and explore scalable ILK-based solutions grounded in cultural practices and innovation. Furthermore, the assessments stress the importance of empirical evaluations of response options, examining their impacts across nexus dimensions and identifying synergies and trade-offs over time and scale.

ILK offers a holistic, place-based framework that can meaningfully transform siloed approaches in biosphere research. When interwoven with scientific frameworks, ILK facilitates integrative, equitable, and context-sensitive responses, enabling coordinated action to address the direct and indirect drivers of biodiversity loss in ways that benefit both people and nature (Habekuß, 2024; Kimmerer, 2011; McElwee et al., 2024; Reid et al., 2021). ILK also makes valuable contributions within transformative foresight research, particularly through its holistic perspective on the human–nature relationship, its emphasis on mutual flourishing and practical approaches such as rituals to take care of the mutual relationship (Kimmerer & Artelle, 2024; Preiser et al., 2024). Current approaches to Indigenous food systems exemplify how agrobiodiversity can be effectively addressed through ILK systems (Antonelli et al., 2022; Caviedes et al., 2024). These approaches enable place-based solutions that support seed diversity conservation, integrated landscape management, and community health in culturally relevant ways (see also Section 3.1 - Resilience & 3.5 - Health). In regions such as Mesoamerica, and the Amazon, traditional agricultural practices—including crop rotation, agroforestry, and ritual seed exchange—play a vital role in maintaining biodiversity, strengthening ecosystem resilience, and preserving cultural continuity (Awazi, 2025). In their research on future forest ecosystem services, Hallberg-Sramek et al. (2023) have shown how combining local and scientific knowledge can improve evaluation and model development. Regarding the mechanisms aiming to protect declining ILK, such as intellectual property rights or access and benefit sharing, Nemogá et al. (2022) have suggested a biocultural diversity framework. It can be understood as a framework that recognizes that local knowledge, practices, and values that are integral to understand and sustain both nature and culture and that can provide a more culturally appropriate tool for respecting and acknowledging local realities and complexities, e.g. in terms of intangibility of certain forms of knowledge (Otamendi-Urroz et al., 2025). Furthermore, the concept of epistemic justice can foster an understanding of existing epistemic injustices in order to carry out more just integration of ILK (Baker & Constant, 2020; Cummings et al., 2023). However, these efforts might not yield perfectly just processes on the ground and different contexts might require a more practical ethics focused on reflection and culturally sensitive dialogues (Matuk et al., 2020).

3.10 Sustainable bioeconomy

3.10.1. Key take-aways

- Values are closely linked to both the root causes of the sustainability polycrisis and the transformations needed to reverse the global biodiversity decline and social inequalities, and promote people's quality of life.
- Decision-making tends to disregard so-called sustainability-aligned values ascribed to nature, including the biosphere, by prioritizing a narrow spectrum of policies, motivated by short-term economic gains and reinforced by power asymmetries.

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- To broaden the narrow focus of policy-making and support sustainability transformations, less tangible benefits and relational approaches (relating and reconnecting) need to be accounted for.

3.10.2. Background

Extractivist worldviews and notions of human domination over nature have led to multiple intertwined global crises (IPBES, 2022; IPBES, 2024; Søgaard Jørgensen et al., 2024). Tackling this polycrisis requires transformative changes—"i.e., system-wide reorganizations across technological, economic and social factors, including paradigms, goals and values associated with the ways we relate to nature" (Balvanera et al., 2022, p. 17). These involve fundamental shifts in people's views, including their values, structures, and practices. Simultaneously, transformative changes are driven and guided by often diverse and yet marginalized sustainability-aligned values that foster a just and sustainable world (Gurung et al., 2025; Martin et al., 2024).

To account for the plural values ascribed to nature, including the biosphere, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) proposed a four-layered typology of values (IPBES, 2022; Pascual et al., 2023). First, worldviews (e.g., anthropocentric, biocentric, or pluricentric lenses to interpret the world) connected with knowledge systems (e.g., academic, Indigenous, or local bodies of knowledge, practices, and beliefs) refer to the ways people perceive and interpret the world. Second, broad values are principles that guide people's life goals, encompassing, among others, values attached to societal relationships (e.g., care, equity), spiritual values, values assigned to relationships with other-than-human (e.g., stewardship and empathy) (C. Ives et al., 2024). Third, specific values refer to nature's importance in particular contexts, informed by people's broad values, categorized into intrinsic, instrumental, and relational values (Arias-Arévalo et al., 2018). Fourth, indicators are "quantitative measures or qualitative descriptors of specific values" (Martin et al., 2024, p. 2).

The recent IPBES Values Assessment (IPBES, 2022) revealed that valuation studies are still dominated by a focus on instrumental values and often follow monetary approaches, failing to capture plural, including sustainability-aligned, values (S. Jacobs et al., 2018). Similarly, the polycrisis is often linked to policies that prioritize a narrow set of market-based values (IPBES, 2022; Jax et al., 2018; Pascual et al., 2023; Stålhammar, 2021). Scholars increasingly argue that the polycrisis is fundamentally a value crisis, driven by the failure to recognize diverse ways of relating to nature (Pascual et al., 2023). In light of transformative processes towards a just and sustainable world, the diversity of specific and broad values, both as facilitators for and obstacles to transformation, must not be overlooked (Harmáčková et al., 2023; Lenzi et al., 2023).

3.10.3. Challenge

Integrating plural values and valuation into practical decision-making remains limited where monetary and extractivist approaches persist and reinforce social inequity and cause environmental degradation (see e.g., Harmáčková et al., 2023; Hoelle et al., 2023; Martin et al., 2024; Vatn et al., 2024). These hinder efforts towards transformative change, which require enabling and mobilizing sustainability-aligned values as well as more inclusive and context-sensitive valuation approaches

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(Horcea-Milcu et al., 2023; IPBES, 2022; Merçon, 2025; Pascual et al., 2023). Here, caution is warranted to scrutinize which values actively contribute to just and sustainable transformations. These values may require critical examination, contestation, or reconfiguration (Chapman et al., 2019; Hoelle et al., 2023). An additional challenge for integrating sustainability-aligned values into decision-making, lies in the rich value-related literature and its diverse value definitions (Chan et al., 2025).

The complexity of mobilizing sustainability-aligned values to contribute to transformative changes is further compounded by power issues and political circumstances in multi-level governance contexts (Arias-Arévalo et al., 2023; IPBES, 2022). This involves navigating a web of competing interests, institutional mandates, and power asymmetries among actors, all of which shape whose values are prioritized, whose are dismissed, how they are understood, and researched. Recent research has sought to unpack these dynamics between power and values by emphasizing how the embedding of plural values is inherently political (Arias-Arévalo et al., 2023). For example, discursive power exercised through knowledge production and shaped by socio-cultural processes plays a central role in decision-making by influencing what are deemed legitimate knowledge and values, and determining which become hegemonic (Vatn et al., 2024).

Bridging theory to action and operationalization in decision-making is inherently contextual and institutionally embedded. Understanding the actors involved, including their motivations, constraints, and capacities, is crucial for identifying both barriers and opportunities for change within diverse institutional contexts that articulate values (Vatn et al., 2024). In these settings, individuals might work in misaligned environments, with limiting professional mandates in articulating certain values. Zafra-Calvo et al. (2020) argue that plural valuation holds genuine transformative potential when it relies on shared principles and knowledge co-production that fosters more inclusive and just decisions.

3.10.4. Offering solutions

Only when plural valuation was initiated with the purpose of guiding actions, it led to desired outcomes in terms of equity and sustainability (Zafra-Calvo et al., 2020). Despite the working of methods as value-articulating institutions, this implies first addressing the purpose of valuation, i.e., “the ‘why’ before the ‘how’” (Jacobs et al., 2023, p.6 ; Jacobs et al 2020; Vatn, 2009). Recent literature highlights the importance of co-creating the valuation process, involving researchers, policymakers, and practitioners, to account for different needs, interests, institutional rationales and embeddedness, and power asymmetries. Hence, plural valuation is not a mere documentation of diverse values, but a participatory and iterative process involving co-learning, dialogue, and negotiation among researchers, policymakers, and communities (S. Jacobs et al., 2020, 2023).

Values are often cited in actions and strategies towards sustainability transformation as entry or intervention points (Table 3). Both IPBES assessments emphasize that one of the keys to considering values and transformations in practice lies in the distinction between dominant and marginalized values (Gurung et al., 2025; A. Martin et al., 2022).

https://doi.org/10.5194/egusphere-2025-3619
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Table 3: Broad approaches to acting on or with values proposed by the IPBES experts and other sustainability scientists in a given setting of a valuation process.

		Actions on or with values				
		Recognising plurality and interdependencies	**Intervening**	**Including**	**Enabling and facilitating**	**Changing institutions**
Broad approaches	**A strategy of shifting societal views and values to recognize and prioritize fundamental interconnections between humans and nature** in Gosnell et al. (2025)	Increasing nature connectedness and recognition of human-nature interdependencies in complex webs of life.	Shifting culture through new narratives.	Co-creating knowledge and weaving diverse knowledge systems.cec	Facilitating transformative learning processes and spaces that foster nature-inclusive thinking and acting.	Changing social norms regarding production and consumption.
	Actions of faith-based organisations shaping the 'value landscape' of cities in Ives and Baker (2024)	Understanding the value context Aerating values	Remediating Toxic values	Mixing values Enriching values through collaborative processes	–	–

	Modes of mobilizing values for sustainability transformation in Horcea-Milcu et al., 2023; Ives et al., 2024; Martin et al., 2022	Reflecting on values	Shifting values (also called tempering values)	Including values (also called diversifying values)	Enabling values (also called nurturing values)	–
	A set of values-centred leverage points can help create the necessary conditions for activating transformative change towards more sustainable and just futures in IPBES, 2022	Recognizing the diversity of nature's values through undertaking relevant and robust valuation.	Shifting societal-level norms and goals to support sustainability-aligned values across sectors.	Embedding values in decision-making.	–	Reforming policies and stimulating institutional change.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

	The leverage point of unleashing latent values of responsibility to enable widespread action in (Chan et al., 2020)	–	Intervening at multiple levels to align incentives, impose constraints	Intentional broadening of existing norms	Intervening at multiple levels to remove barriers, Co-evolving values with changes in practice	–

Many governance and policy interventions are rooted in a control-oriented, optimizing, top-down governance paradigm, continuing to do more of the same, i.e., measuring and valuing (Gurung et al., 2025; Merçon, 2025). There is a widespread assumption that the authoritative knowledge necessary for decision-makers to 'solve' sustainability problems relies on a relational turn which emphasizes the intertwinedness of the "social" and the "ecological" and aims to overcome their separation (West et al., 2020). Disempowering dualisms and narrowly-focused solutionisms determine decision-makers and practitioners to evaluate success in terms of outcomes as well as the predictability and concreteness of planning and implementation (Knight et al., 2019). Moreover, a mindframe of disconnection, e.g., between humans and nature, legitimizes the search for short-term solutions that prioritise the securities of the privileged to the detriment of the collective. Shortcomings of this type perpetuate the root causes of the polycrisis and ignore the full spectrum of possible responses, such as the fractal agency of each and everyone, often dismissed because they are not 'plannable' (O'Brien et al., 2023). Disproportionately less attention is given to the quality of inter-relationships during processes of realizing respective outcomes or to processes of becoming aligned with the broad values inherent to desired outcomes. Acknowledging false divides (in dualisms) as suggested by a human-more-than-human relational dynamic, increases the potential for innovative co-existence and adaptation (Ison, 2018). A mindset of mutual learning and experimentation favors inclusive decision-making spaces where the development of alternatives to market-oriented business as usual is possible and where wisdom plays a role alongside technology (Bentz et al., 2022). Although intangible, the inner worlds and broad values of all people, including civil servants and policymakers, can be leverage points for sustainability transformations (Otero et al., 2025).

Sustainability transformations entail i) redefining human well-being, ii) taking action towards a good quality of life, and iii) overcoming the prevailing paradigm of economic growth. Concerning the first recommendation, a more inclusive understanding of human well-being is commonly practiced in some Indigenous and local communities (e.g., (Artaraz et al.,

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

2021; Fleming & Manning, 2019)), and within initiatives holding potential to shape a just and sustainable future (also called Seeds of a Good Anthropocene). Learning from these practices is important for scaling transformations. Regarding the second recommendation and consistent with a broader understanding of human well-being, is the recognition of inner well-being and development. Following the motto "inner growth for outer change", the quality of the connection to oneself can lead to the initiation of sustainability transformation/s (Bennett et al., 2025). Regarding the third recommendation, the mismatches between recent advancements in research, policy, and practice need to be addressed. To do so requires open spaces to identify and reconcile a diversity of value perspectives as well as to mobilize sustainability-aligned values, empower collective agencies, and encourage mutual knowledge co-production at the science-policy-practice interface (Kelemen et al., 2023; A. Martin et al., 2024; Montana, 2021). Learning from Indigenous practices and sustainability initiatives can be complemented with socio-cultural valuation and indicators alternative to the GDP. These include indices/indicators focusing on the quality of human relationships as a core component of well-being, e.g., the OECD Better Life Index, the Genuine Progress Indicator, the City Doughnut Indicator, and the Happy Planet Index, while applying them requires awareness about their limitations.

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

4 Synthesis

The world we live in faces multiple interconnected crises that threaten nature´s and human well-being. In addition to climate change, challenges such as biodiversity loss, the overload of man-made chemical compounds, rapid urbanization, degradation and loss of natural land and disrupted biogeochemical cycles are contributing to a broader 'polycrisis' of the Earth system. In ten Sections, we explore selected aspects of this polycrisis and its interaction with the biosphere, examining its impact on human society.

Here, we discuss scientific, societal, and policy-related issues while offering potential solutions derived from scientific publications. Moreover, we stress the importance of minimizing trade-offs and maximizing co-benefits. For example, technical solutions like Direct Air Carbon Capture and Storage (DACCS) require substantial energy input, and their large-scale deployment could significantly increase demand for renewable energy and resources, degenerating landscapes and the biodiversity they contain (Section 3.6). Similarly, reforestation initiatives aimed at climate mitigation may displace native species when implemented without considering the local ecosystem, potentially leading to land appropriation and biodiversity loss (Bohn et al. 2025, Section 3.2).

Moreover, both technological and nature-based interventions have the potential to adversely affect local communities. Such projects may exclude residents from the benefits they generate while simultaneously limiting access to ecosystem services essential to their livelihoods (see also Section 3.9 - Indigenous Knowledge). Recognizing and addressing these trade-offs is crucial for ensuring just and sustainable transformations. Finally, some solutions are currently not economically viable today (even though they might become so in the future).

We argue that to address the polycrisis, identifying and implementing 'polysolutions', rather than ‘mono-solutions’ is needed. In this series, we compile several potential poly-solutions. We define a poly-solution as one whose net benefits clearly outweigh its drawbacks in all three areas of sustainability: ecology, society and the economy. By contrast, we define 'oligo-solutions' as those that provide net benefits in at least two of these domains (See Figure 6).

https://doi.org/10.5194/egusphere-2025-3619
Preprint. Discussion started: 25 September 2025

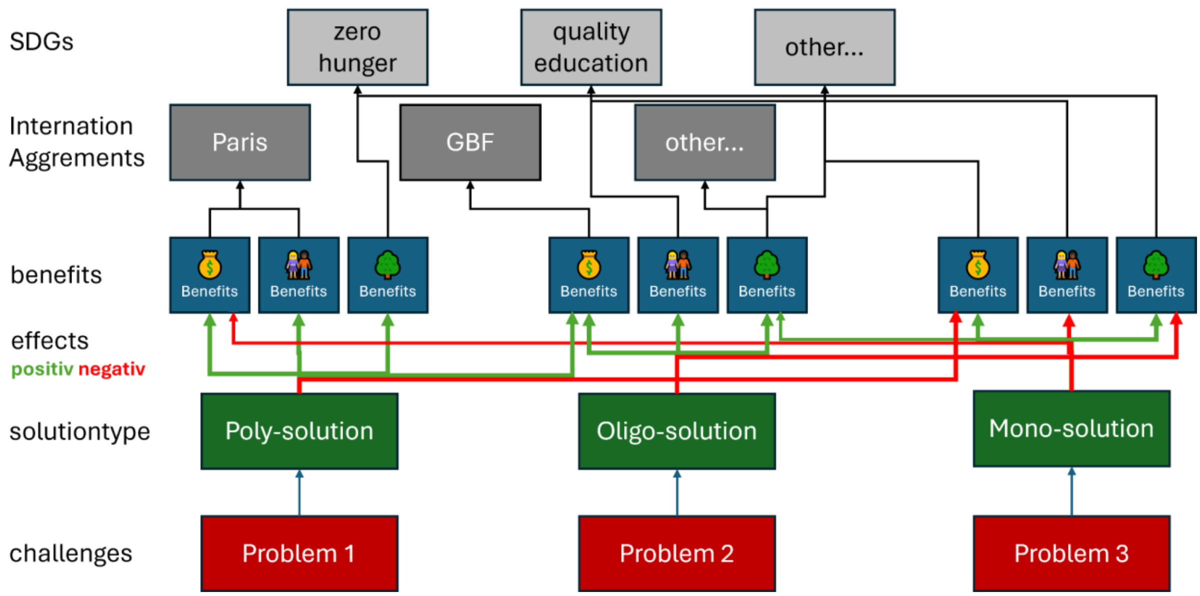

Figure 6: Concept of Poly-, Oligo-, and Mono-solutions: The poly-solution results in positive benefits in all sustainability spheres in the contexts of Problems 1 and economically in 2, while having negative economic effects in the context of Problem 3. Its four benefits support progress toward the Paris Agreement, the Kunming-Montreal Global Biodiversity Framework (KMGBF), and reduce hunger. Furthermore, it has no effect on SDG quality education and a negative impact on one other SDG. The oligo-solution instead delivers benefits across all three sustainability spheres within its problem context but shows negative ecological effects in the context of Problem 3. The mono-solution shows benefits in the ecological and economic spheres but exacerbates social issues in its context; it also creates financial burdens in Problem 1, offering net benefits only in the ecological dimension.

Many nature-based solutions are grounded in robust scientific evidence and can deliver significant climate benefits while helping to halt or reverse biodiversity loss. By contrast, the ecological outcomes of some forms of climate change mitigation remain uncertain (Buma et al., 2024). The ecological (and social and economic) benefits of these solutions can be categorised into several types. Firstly, some Sections emphasise the development of **reliable indicator systems** based on local knowledge and in collaboration with stakeholders, in order to assess ecosystem conditions across multiple dimensions (Section 3.1, 3.2, 3.9 and 3.10). Secondly, expanding data collection via remote sensing, field monitoring and the integration of indigenous knowledge, combined with advanced modelling, enables a deeper and multifaceted **understanding of ecosystems** under transient dynamics (Section 3.1, 3.2, 3.7, 3.8, 3.9 and 3.10). Thirdly, several solutions focus on **usage and/or improvement of ecological functions** and services through habitat restoration, regeneration, sustainable land management and enhanced landscape connectivity (Section 3.1, 3.3, 3.4, 3.5 and 3.9). In addition to climate and biodiversity, polysolutions must address a variety of societal challenges (see also Dunlop et al., 2024). Realising the social potential of polysolutions requires **integrative governance** to ensure meaningful stakeholder participation and facilitate sustainable decision-making processes. Equity must be central to the design, implementation and evaluation of such solutions (Section 3.1, 3.2, 3.3 and 3.4). Strengthening **cooperation and collective action** within communities enhances their capacity for self-organisation, which is a key pillar of social-ecological resilience (Section 3.1

and 3.10). The **collection and** open **distribution of knowledge**, as well as user-oriented access, are essential for supporting informed decision-making at all levels (see Section). Ultimately, solutions should **improve quality of life** while respecting cultural values, rather than imposing additional (e.g. administrative) burdens and social losses (Section 3.6 and 3.7).

A global meta-analysis demonstrates the economic and hazard mitigation advantages of nature-based solutions (NbS): 71% of studies found NbS to be consistently cost-effective, while 24% identified them as cost-effective under specific conditions (Vicarelli et al., 2024). Lehmann et al. (2025) further emphasize that NbS are often less costly than conventional technical alternatives, while also underscoring the importance of context and timing in their application. However, NbS are not a universal remedy. In urban environments or severely degraded landscapes, hybrid or technical solutions may be necessary. Therefore, **funding of transdisciplinary research** that integrates NbS with technical, infrastructural and social approaches is required to achieve resilient, cost-effective outcomes that are adapted to local circumstances (Section 3.3 and 3.4). **Effective governance mechanisms** (including laws and administration) are essential to support entrepreneurs and businesses at scale, driving the transformation of innovations into long-term economic success (Section 3.3). To move beyond the pioneering phase, it is essential to address the chronic underfunding of NbS by **reorganizing financial flows** through a mix of instruments—including targeted funding programs, subsidies, taxes, and tariffs (Section 3.6) **Comprehensive valuation** methods should extend beyond narrow economic metrics to capture broader societal and ecological benefits. Such assessments should include business-as-usual comparisons to justify initial investment costs (Section 3.1 and 3.10). Finally, to ensure long-term success, it is crucial that local communities directly affected by the implementation of the NbS have a **stake in the generated wealth,** to increase their living standard (Section 3.6 and 3.7)

As demonstrated in these sections and in the preceding publication in this series (Bohn et al., 2025), the Earth system crisis represents a complex system with several linkages between its subcrises. Recognizing the ecological–social–economic system (including cultural dimensions) as a complex, adaptive system—neither fully predictable nor entirely chaotic—is a necessary step for decision makers. We must be prepared to make decisions under limited process understanding, uncertainty, and incomplete data to transition away from the current destructive pathway and toward a sustainable pathway. On top of that, science and evidence-based thinking are increasingly being pushed back, threatened or prevented at a time when greater efforts to understand a changing world are crucial for making wise, long-lasting decisions.

We argued that adopting a more holistic perspective is essential to deepening our understanding of interdependencies, particularly within the biosphere and, more broadly, across the entire Earth system. Such a perspective enables us to identify more effective interventions with multiple co-benefits, avoiding the pitfalls of narrowly focused, single-issue solutions that sometimes present themselves as wicked problems. Therefore, domain-specific expertise must be complemented by systems thinking in order to account for nonlinear interactions, positive and negative feedback loops, and potential tipping points across sectors. Such systemic insights can reveal opportunities where small interventions could catalyse large-scale positive change (see Lenton et al., 2023).

In addition, it is important to recognise who has access to which types of information and what information different societal groups need. It is also important to consider how this information is presented to them. Advertising, for example, is a powerful driver of societal desires and rarely relies on statistical data or formal reports spanning hundreds of pages. This raises the question: how can we ensure that decision-makers at all levels (from citizens to the presidents of states, companies and institutions) receive information at an appropriate level of aggregation? This paper series, in combination with its homepage [www.c-pob.com], attempts to aggregate the necessary information at different levels to help consumers easily navigate relevant information. The most aggregated information can be found on the website, with the second level comprising the series of papers and the third level comprising the references.

Moreover, attention must be paid to the rules that govern the ecological, social and economic systems, and to those responsible for setting them (Meadows, 2008). While natural laws are fixed and unchangeable, the system also encompasses governmental laws and social norms, which are human-made and can be altered when a critical mass of people reach consensus. The latter can be changed if a critical mass of people agree. Transition pathways should provide opportunities for those who benefit from the current system while minimising the number of 'losers' to secure broad support for change.

Lastly, we must learn to trust in society's ability to organise itself, provided clear and shared goals are established (Meadows, 2008). Not everything can - or should - be centrally planned. Local actors must be empowered to adapt and implement internationally agreed goals in ways that suit their specific contexts.

5. Conclusion:

In conclusion, the literature strongly supports the argument that polysolutions, especially those rooted in nature, are necessary and superior for addressing the Earth systems crisis. Nature-based poly-solutions offer ecological services, cost-effectiveness and a range of social co-benefits that are not always delivered by purely designed mono-solutions when evaluated across environmental, social and economic dimensions. In order to achieve planetary stability, policy and investment must prioritise the protection, restoration and sustainable management of the biosphere, alongside targeted technological interventions where appropriate.

Author contributions

Conceiving and designing the study and providing editorial oversight: FJB, GBS, YE, MJ, NSK, AB, AR, RM,. Constituted the editorial board to select the themes: AB, AR, AGa, AGo, Agu, YY, IH, HP, NO, MP, KT, CK, HS. Led and coordinated the overall writing: FJB. Performed literature review: all. Contributed to the writing: all.

Competing interests

At least one of the Co-authors (Anja Rammig) is a member of the editorial board of *Biogeosciences*.

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