European Commission

Towards Sustainable Transformation

Research Priorities in Climate Change and Biodiversity

Independent Expert Report

Research and Innovation

Prepared by

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Towards Sustainable Transformation – Research Priorities in Climate Change and Biodiversity

European Commission
Directorate-General for Research and Innovation
Directorate B — Healthy Planet
Unit B.3 — Climate and Planetary Boundaries

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Towards Sustainable Transformation

Research Priorities in Climate Change and Biodiversity

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INTRODUCTION

Purpose: an international assessment for forward-looking research

Future Earth is a global network-of-networks that brings together scientists, researchers, and innovators to advance transformations to sustainability. The Future Earth community includes 9 Secretariat Hubs, 19 National and Regional Committees, and 27 Global Research Networks. These networks convene several thousand experts from around the world, across natural, social and earth sciences, to identify and conduct new research in support of societal transformations, and to bridge knowledge-to-action so that decisions are informed by openly accessible and shared knowledge. Future Earth's international scope, and extensive, participatory process to gather input for this report (methods described in detail in the Appendix), ensures that the insights collated reach beyond Europe to a much wider contingent of global stakeholders focusing on global challenges. For this report, Future Earth received valuable support from the International Institute for Applied Systems Analysis and Sustainability in the Digital Age.

International cooperation is a driver of world-class research and innovation. However, in today's evolving global environment, marked by escalating geopolitical tensions and the questioning of societal norms, cross-national research collaborations face heightened challenges. This underscores the value of this report's collaborative approach, which also defines sustainability science - a transdisciplinary field uniquely suited for addressing global challenges. By recognising the importance of different types of knowledge and expertise and advocating for concerted action, sustainability science advances a holistic and solutions-forward understanding of global change. Fundamentally, sustainability science seeks to facilitate a sustainability transition or transformation (Clark, 2007), thereby including a normative element: the field not only studies and describes the world as it is, but also examines what the world should be like (Soini et al. 2024).

In this context, Horizon Europe – the European Union's flagship research funding program with a budget of €95.5 billion – continues to offer opportunities to internationally collaborating researchers and innovators to advance science for addressing the most pressing global concerns. The European Commission DG RTD invited Future Earth to issue an independent expert report identifying knowledge gaps and research priorities on climate change and biodiversity science to inform the development of future Horizon Europe's work programmes, building on state-of-art scientific evidence and expertise.

The objective of this report is to provide recommendations to the European Commission and other relevant research and innovation funding entities on what climate change and biodiversity research should prioritise to maximise the societal relevance and impact of public funds. Future Earth is confident that the findings presented in this report reflect the views from our scientific networks regarding the critical gaps in climate change and biodiversity research, where evidence is most urgently needed to advance a global sustainability transformation.

Context: building from established frameworks

The Paris Agreement on climate change, the Kunming-Montreal Biodiversity Framework, and UN Sustainable Development Goals (SDGs) are among the key sources setting the foundational guidance for the report, by defining the societal transformations ahead. Each of these frameworks highlights a systems approach and sets high aspirations for 2030 and beyond, respectively aspiring to holding the increase in the global average temperature to well below 2°C, and preferably to 1.5°C, above pre-industrial levels (Paris Agreement to the UNFCCC, 2015), protecting 30 percent of the planet's land and water, and eradicating

poverty. Despite this ambition, progress to reach targets has been incremental. To accelerate, priority areas exist where rigorous science can support decision-making and institutional change, namely: removing roadblocks to progress; identifying transformation pathways; and improving governance (Malekpour et al. 2023).

This report also recalls that the intertwined crises of climate change and biodiversity loss must be addressed together, as identified by assessments of both the IPCC (Intergovernmental Panel on Climate Change) and IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). A "nexus approach" to governance, involving mainstreaming of biodiversity into climate policy and vice versa, has been suggested to help guide policy interventions that have the potential to generate synergistic wins and avoid unintended consequences while facilitating deep and rapid transformative change (Pörtner et al. 2023).

This report was also inspired by Kate Raworth's internationally recognised Doughnut model, first published in 2012. "The Doughnut consists of two concentric rings: a social foundation, to ensure that no one is left falling short on life's essentials, and an ecological ceiling, to ensure that humanity does not overshoot the planetary boundaries that protect Earth's life-supporting systems. Between these two sets of boundaries lies a doughnut-shaped space that is both ecologically safe and socially just: a space in which humanity can thrive" (Doughnut Economics Action Lab). This concept continues to be a compass and checkpoint for many nations and cities around the world seeking to implement their vision for humanity in the 21st century. This report also builds on the experience over the last 7 years of producing the 10 New Insights in Climate Science (10 New Insights), a collective effort to gather leading scholars from around the world to highlight the most essential findings in climate research each year. The 10 New Insights report is jointly produced by Future Earth, the Earth League and the World Climate Research Programme.

The most recent assessment of Planetary Boundaries finds that six of the nine boundaries are crossed (Richardson et al. 2023). Groups like the Future Earth-hosted Earth Commission continue work to define a safe and just corridor for people and the planet (Rockström et al., 2023; Rockström et al. 2024). The background structure and approach for this report build off the work of the Earth Commission and draws on the comprehensive Global Sustainable Development Report (GDSR) 2023, an independent, peer-reviewed scientific assessment, involving global consultations to synthesise scientific evidence from across disciplines and regions. The GDSR assessment puts forward an organising framework (six entry points for transformation across five levers of change) that also informed the current report.

Framing the research questions: A transdisciplinary exercise

The research recommendations presented in this report emerged from an extensive consultative and participatory process. A preliminary scanning of the over 120 inputs received from respondents[1] revealed a remarkable degree of consensus regarding the overall scope and mode of research that will be needed to address the challenges of climate change and biodiversity loss (see Appendix, Methods, Section 3 "Survey" for details). This consensus, which also reflects the diverse expertise of the report's international and interdisciplinary Editorial Board, can be summarised in terms of four key insights:

[1] Responses were received through a survey shared through Future Earth's networks and with participants of the Sustainability Research and Innovation Congress 2023.

1. Human health and wellbeing, and the health of the biosphere are inextricably linked. It follows that it is imperative to take a systems approach to investigating the health of the planet, including all living and non-living, human and non-human (Özdemir 2020; Pongsiri et al. 2017; Ebi et al. 2020). This report relies on a simple definition of planetary health as, “the health of human civilisation and the state of the natural systems on which it depends” (Whitmee et. al. 2015). Furthermore, the report embraces the idea of the one-ness of the planet - and the "one nature" approach (Özdemir 2019, 2020).
2. An integrated research approach is needed to tackle the challenges posed by climate change and biodiversity loss. This echoes the conclusion of Pörtner et al. (2021), who point out that the research community investigating the climate system is significantly distinct from that investigating biodiversity. They argue that “this functional separation creates a risk of incompletely identifying, understanding and dealing with the connections between the two. In the worst case it may lead to taking actions that inadvertently prevent the solution of one or the other, or both issues” (Pörtner et al. 2021).
3. Research must focus upon finding effective societal, governance, and policy solutions to the linked challenges of climate change and biodiversity loss. Much research in recent years has been directed towards a better scientific understanding of Earth and social systems, and developing new technologies and methods to enhance that understanding. The new research agenda should focus increasingly upon societal, governance and policy issues. In particular, research must be aimed at developing governance and policy frameworks to tackle the challenges of climate change and biodiversity.
4. Transdisciplinary approaches must be a prominent feature of the new research agenda. Many comments and suggestions were received concerning the type of research needed to support good decision-making on climate change and biodiversity, and on how this research should be organised. Common themes included strengthening interdisciplinary and transdisciplinary research, increasing participation of the social sciences and humanities, and strengthening the science-policy interface.

These key insights stemmed from responses that were classified into seven thematic groups, each presented in this report as a separate chapter. These thematic groups are: 1) Planetary Health, 2) Societal Values, Tipping Points, and Individual and Collective Action, 3) Economy and Finance, 4) Governance and Transboundary Collaboration, 5) Policy Instruments and Mixes, 6) Data and Emerging Tools, 7) New Paradigm of Science Information Exchange. For each thematic group (i.e., chapter), the report briefly outlines the specific topics requiring further research from the perspective of sustainability transformation and summarises them as a list of key research gaps.

In sum, this collective report aims to promote transformative research, through Horizon Europe and beyond. It is hoped that the report and the questions herein can be a resource for decision makers across any sector or geography, supporting research to address global challenges in climate and biodiversity.

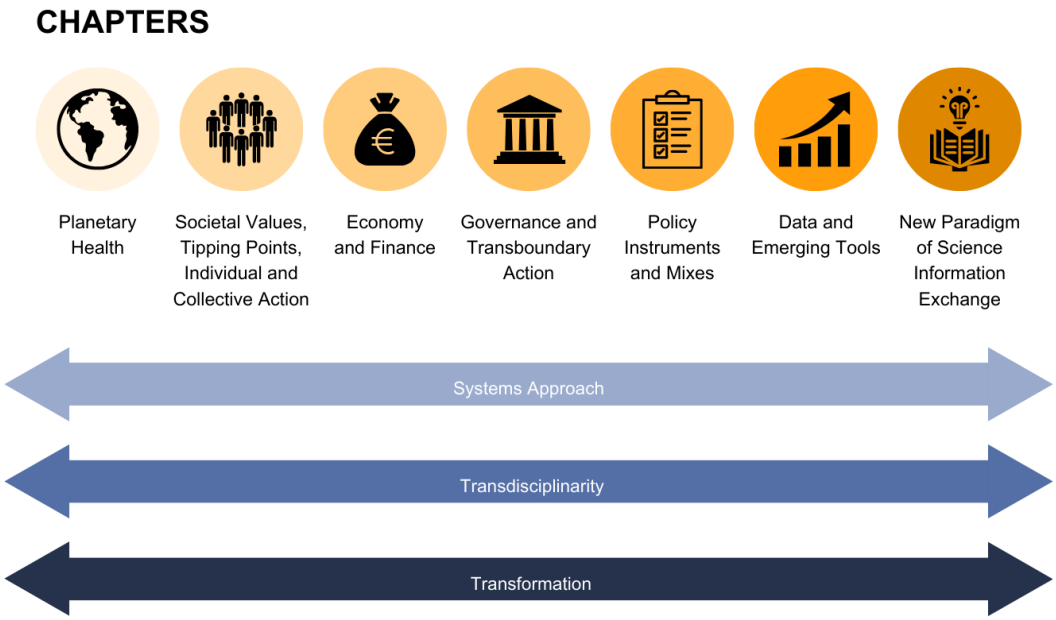

Figure 1. The horizon scanning survey resulted in seven chapters (round icons on top) – acknowledging that the responses do not represent a comprehensive assessment of all aspects of biodiversity and climate change relevant research areas. There were three cross-cutting elements in all chapters emphasising the importance of transdisciplinarity, a systems approach, and the need for transformation in research.

1. Planetary Health

1.1 Climate Change and Human Health

As defined by The Rockefeller Foundation–Lancet Commission on Planetary Health, planetary health is “the health of human civilisations and the natural systems on which they depend” (Whitmee et al. 2015). Health impacts of climate change has been a recurrent theme of the 10 New Insights in Climate Science since the first edition in 2017 (then called The 10 Science “‘Must Knows” on Climate Change). Almost all the editions have highlighted the multiple impacts on physical and mental health of climate change, via its effects on food security, heat and water stress, extreme weather, and infectious and non-infectious diseases. The 10 New Insights have also highlighted the significance of co-benefits for human health of action to reduce greenhouse gas emissions, as well as for ecosystem health of carefully implemented Nature-based solutions, sustainable land management, and generally the protection of terrestrial and marine ecosystems with a significant role in climate regulation.

The evidence shows that climate change affects human, environmental, and animal health (Vicedo-Cabrera et al. 2021; Ebi et al. 2020; Ristaino et al. 2021; Thonicke et al. 2024). However, the combined effects of climate change and biodiversity loss have been identified as a research gap. Additionally, current research results do not indicate what is needed to improve assessment, early warning capability, and adaptation strategies of the health impacts of climate change. These interrelationships among human, animal, and environmental health and climate change are

complex and insufficiently studied, highlighting the need for transdisciplinary research to address associated compounding and cascading risks (Ebi et al. 2020; Martin et al. 2022).

Key Research Gaps

How will climate change and biodiversity loss affect health, including disease patterns, and how can we prepare for these changes? What are the combined effects of climate change and biodiversity loss on planetary health including human well-being, disease patterns, and how can we prepare for these changes? Including research on:

- Understanding and preparing for shifting disease patterns resulting from climate change.
- Exploring the connections among weather, climate, and health.

How can societies be made resilient to overlapping hazards including climate change, and what indicators are needed to track progress, including transboundary climate risks? In particular, research on:

- Identifying the indicators needed to track progress towards building resilience to transboundary climate risks.
- Identifying which diseases are being more prevalent due to climate change and which illnesses are exacerbated by climate change.
- Understanding strategies needed to be implemented to enhance population resilience and protect biodiversity.
- Promoting resilience and sustainable development in vulnerable areas, like cyclone-affected regions, achieved through community-based interventions.
- Proactive planning and coordinated efforts essential in preparing for the rise of overlapping and compounding hazards.

1.2 Climate Change and Biodiversity

The links between climate and biodiversity are highly complex (Karger et al. 2023) and they are usually addressed separately (Pörtner et al. 2021). Biodiversity plays a central role in climate regulation, with biodiversity and ecosystems together contributing to the removal of around 50 per cent of CO2 emissions every year. Therefore, the ongoing and potential loss of ecosystems that play a critical role as carbon sinks has been a major concern (10 New Insights - Insight 4, 2019; Insight 3, 2020; Insight 4, 2023). Mapping the positive and negative effects of actions to mitigate climate change on actions to mitigate biodiversity loss and vice versa are well illustrated in the joint IPCC - IPBES scientific outcome report (Pörtner et al. 2021). Biodiversity can increase both populations' resilience and ecosystem resilience to extreme events and provides multiple ecosystem services (Isbell et al. 2015). Given the already massive pressures upon biodiversity worldwide (Murray et al. 2022), further loss of biodiversity due to climate change is a cause for great concern.

In light of these risks, a policy brief presented at COP 28 proposes seven considerations to reduce trade-offs and maximise synergies between biodiversity and climate action, stressing that the design of climate solutions, policies and strategies must consider biodiversity impacts (Karger et al. 2023). This underscores the importance of incorporating biodiversity impacts into the design of climate solutions, policies, and strategies. But identifying best practices and effective ways of measuring success warrants more research. How societies and the biosphere can build resilience and what indicators are necessary for monitoring progress in resilience efforts need further to be explored. The 10 New Insights in 2023 highlighted the need for "joint governance" to address the interlinked emergencies of climate change and biodiversity loss (Insight 5), specifically by increasing alignment between the UNFCCC and CBD, and introducing "nature-positive safeguards" to inform the allocation of climate finance.

Key Research Gaps

What are the most effective strategies for mitigating both climate change and biodiversity loss? In particular, research on:

- Exploring the synergies between climate change and biodiversity solutions.
- Protecting biodiversity amidst climate change.
- Investigating unintended consequences of mitigation measures for climate change and biodiversity loss upon each other.

1.3 The Role of Indigenous and Local Knowledge

Understanding the nature and type of actors involved in collective action for planetary health and climate solutions, must include Indigenous conceptualisations of human and non-human relationships. Indigenous and local knowledge refers to dynamic bodies of integrated, holistic, social and ecological knowledge, practices and beliefs pertaining to the relationship of living beings, including people, with one another and with their environments (Sustainable use assessment. IPBES 2021).

The recent Kunming-Montreal Global Biodiversity Framework acknowledges “the important roles and contributions of Indigenous Peoples and local communities as custodians of biodiversity and as partners in its conservation, restoration and sustainable use.” It emphasises that the Framework’s implementation should ensure that the "rights, knowledge, worldviews, values and practices of indigenous peoples and local communities are respected, […], including through their full and effective participation in decision-making” (CBD decision 15/4, 2022).

An increasingly recognised aspect of biodiversity and climate sciences is the invaluable contribution of Indigenous knowledge systems. Our understanding of ecosystem services and planetary health are enriched by traditional knowledge that is inherently multidisciplinary with unique insights on sustainable resource management, ecosystem dynamics, and planetary health (Zurba & Papadopoulos 2023). At the same time, the sovereignty of Indigenous Peoples faces strain due to the escalating impacts of global environmental changes like climate change and pollution in their territories, alongside threats to their land and water rights (Redvers et al. 2022).

The integration of Indigenous and local knowledge must be complemented with improved understanding of Indigenous research methodologies and a greater recognition of the works of Indigenous scholars in the environmental sciences and humanities (Windchief and Cummins 2021).

Key Research Gaps

What policies are needed to protect ecosystem services, particularly provisioning and cultural ecosystem services, in line with self-determination of Indigenous Peoples and local knowledge holders? Further research is required to:

- Develop inclusive and effective policies that adequately address the unique needs and rights of Indigenous communities in relation to ecosystem protection.

Key Research Gaps

- Explore the components of an Indigenous approach to planetary health action.
- Leverage Indigenous and local knowledge and methods in safeguarding ecosystems and securing ecosystem services.
- Integrate Indigenous and local knowledge into climate change and biodiversity research.
- Examine how diverse worldviews, particularly those of Indigenous Peoples and local communities, contribute to a comprehensive valuation of nature.
- Investigate the diverse characteristics of Indigenous communities across different regions of the world.

1.4 The Threat Posed by "Novel Entities"

"Novel entities" is a term increasingly used to denote plastics, pesticides, industrial chemicals, chemicals in consumer products, persistent pollutants, heavy metals, and antibiotics. The annual rate of production and release of novel entities is far outpacing the global capacity to monitor the risks, and ultimately, to manage their discharge into the environment.

According to Persson et al. (2022), several examples highlight the rapid escalation in the production of novel entities. For instance, the chemical industry ranks as the second-largest manufacturing sector globally. Plastic pollution has emerged as a significant concern among "novel entities" due to its production cycle, which not only contributes to climate impacts but also poses threats to biodiversity through physical interactions like entanglement or ingestion. Additionally, the release of new entities from the technosphere to the environment may lead to unexpected effects, such as alterations in ocean chemistry affecting sea spray formation - a critical component of the climate system - or the global proliferation of antibiotic-resistant bacteria.

The effects of novel entities on the Earth system are largely unknown (Richardson et al. 2023). Identifying which novel entities have the most significant impact and pose the greatest risks to human health and Earth system stability, constitutes a major research gap. Consequently, finding more sustainable alternatives remains a critical task for researchers.

Key Research Gaps

Which novel entities pose the greatest risks to human health and Earth system stability? Are there sustainable alternatives for the most harmful novel entities currently in use? Experts highlighted in particular:

- The exploration of innovative technologies and regulatory frameworks aimed at mitigating the proliferation of plastic residues in the environment.
- Research fostering multi-stakeholder engagement across the value chain to reduce plastic usage and minimise its environmental impact, thereby safeguarding marine and terrestrial biodiversity.

2. Societal Values, Tipping Points, Individual and Collective Action

2.1 Values, Moral Perceptions and Political Change

The deep transformative change needed to address global environmental goals requires justice, nurturing positive social tipping interventions (defined as an intervention in sub-system that can lead to macro level changes - Milkoreit et al. 2018; Otto 2020), and acknowledgement of the diversity in values, motivations, and interests across cultures and societies (Pörtner et al. 2021; Thonicke et al. 2022; Niamir et al. 2024, Rockström et al. 2024). Stadelmann-Steffen et al. (2021) highlight the challenges in understanding the multiple and complex factors driving social tipping dynamics, pointing out that there are different levels at which these factors interact: political, technological, and behavioral. In this context, there is a need for improved understanding about conditions that enable and promote the emergence of systemic transformations across multiple levels of social systems and the role that actors can have in them (Tàbara et al. 2021; Lenton et al. 2023; Alkemade et al 2023). The supply- and demand-side dimensions of so-called "positive tipping points" have also been featured in various editions of the 10 New Insights (Insights 10 in 2019, and 6 in 2021).

The causes of the climate and biodiversity crises are deeply rooted in moral principles regarding human interactions with nature and the valuation of nature in decisions at all levels (Islar et al. 2022). Transformative change thus requires shifting away from predominant values of individualism and materialism, to nurturing sustainability-aligned values (Islar et al. 2022; Pörtner et al. 2023a). How such value shifts can be implemented, and how they trigger behavioral and political changes, however, remain open questions.

A major knowledge gap concerns the role of agency – the human ability to influence the future through deliberative individual and collective action – in shaping responses to the intertwined climate and biodiversity crises (Stadelmann-Steffen et al. 2021; Niamir 2020). There is also still space for additional research on how policy can, in turn, contribute to enabling positive social shifts (Fesenfeld et al. 2022; Hallsworth 2023). Finally, further research is warranted to understand how and to what extent individual and collective behavioral changes are influenced by psychological and social factors (e.g. norms, values, culture), infrastructural and technological improvements and availabilities, as well as institutional and political settings (Hampton and Whitmarsh 2023).

Key Research Gaps

How are values about nature developed and how do they influence political, economic, and social responses to environmental challenges? Experts highlighted in particular:

- The influence of moral values on responses to environmental degradation spanning political, economic, and social spheres.
- Understanding the perspectives and valuations of individual and collective actors regarding the climate and biodiversity crises.
- Exploring the development of values about nature.

What motivates individual and collective actors to engage in activities that hinder or support sustainability transformation? How does cultural and political context influence behavioral change? In particular:

- The influence of differences in value and moral perceptions on the effectiveness of climate and biodiversity policies, especially in the context of power asymmetries, marginalised communities, and transnational action.
- Mechanisms to ensure accountability of those with a greater degree of responsibility for climate damages.

Key Research Gaps

- Investigating motivations of individual and collective actors to engage in activities that hinder or support sustainability transformation.
- Understanding the level of awareness among high consumers about the consequences of their behaviour and possible incentives to encourage them to adopt more sustainable consumption practices.
- Understanding how individual decisions (social, political, cultural, technological, and economic) reflect state systems and policies.

2.2 Cultural Influences, Environmental Crossroads, and Collaborative Responses

Social innovations are considered to be a part of social transformations (Wittmayer et al. 2019). Social innovations contribute by introducing new ways of doing, organising and knowing but they may not alone be sufficient in driving a transformation - they may require explicit political tactics and strategies to institutionalise new practices (Haxeltine et al. 2017). In this context, progress towards tackling climate change and preventing biodiversity loss will depend crucially on reaching a societal consensus about these problems and the actions necessary to remedy them. Bayes et al. (2020) pointed out that “while many technological challenges remain surrounding how to best respond to climate change, an equal or greater challenge will be building greater social and political consensus for action”.

Key Research Gaps

What is the role of social innovation in promoting progress and enabling change for sustainability transformations? How can positive social innovations be coordinated and promoted? In particular:

- Investigating how historic environmental movements act as an inspiration for present and future generations for climate action and biodiversity protection - but also how to create new inclusive forms of social organisation and collective action.
- Exploring how to integrate values and justice concerns in ecosystem management.
- Identifying coordinated societal responses to address the challenges posed by biodiversity loss and climate change, while minimising unintended negative outcomes.
- Investigating how to achieve cooperation on planetary health among increasingly complex actors and compositions.
- Developing strategies for addressing intergenerational implications in climate change mitigation and adaptation efforts, particularly in ensuring equitable outcomes and justice for future generations.

2.3 Mitigation and Litigation for Environmental Protection

Impacts of climate change and biodiversity loss are particularly detrimental to vulnerable communities or groups, and cascading effects can lead to the breaching of socially accepted thresholds and trigger social destabilisation (Martin et al. 2022; IPCC 2023 SPM.A2). At the same time, policies aimed at climate change mitigation, adaptation, or biodiversity preservation often face resistance by societies. Sometimes they also come with tradeoffs and require consideration of possible negative consequences on certain groups and communities

(Bustamante et al. 2023). Climate litigation has become increasingly important in the fight against climate change, either through a lens of Human Rights or Right of Nature (Insight 10, 2020).

Activities such as illegal logging, trade in protected flora and fauna, and illegal fishing are major contributors both to biodiversity loss and climate change. While these activities are recognised as crimes in most countries, they are often weakly enforced or treated as regulatory offenses with relatively limited penalties (Lirëza and Koci 2023). Many countries also provide a legal right to remedy when the environment is harmed, yet environmental liability litigation is virtually absent from practice across much of the Global South, including in many biodiversity hotspots (Phelps et al. 2021). It has been argued that more aggressive use of environmental liability litigation could be a powerful mechanism for countering biodiversity loss.

The European Union has in fact become the first international body to criminalise wide-scale environmental damage, that is, actions that cause widespread, substantial and irreversible or long-lasting damage to large or important ecosystems, habitats or the quality of air, soil or water. The environmental crime directive was formally passed in spring 2024, and member states will now have two years to put it into national law (European Commission, Directive (EU) 2024/1203). Also encouraging are efforts to now catalog the practice of ethics dumping, a topic that warrants further investigation (Global Young Academy 2023).

Key Research Gaps

What legal, social or other mechanisms can be employed to address and mitigate the drivers of environmentally destructive activities? In particular:

- Investigating the extent of environmental crimes as drivers of biodiversity loss and climate change.
- Assessing the effectiveness of the various mechanisms that have been deployed to mitigate the effects of environmental crimes.

3. Economy and Finance

3.1 Mainstreaming of Biodiversity and Climate in the Economy

Efforts to integrate biodiversity and climate concerns into the economic sector, known as mainstreaming, have faced challenges, resulting in slow overall progress. Mainstreaming, however, remains an important task, also from an economic point of view. The risks associated with biodiversity loss and reductions in the productivity and resilience of ecosystems for various strategic supply chains have significant macroeconomic and financial implications; simply put, more than half of global economic activity depends on nature (Dasgupta Review 2021; Tobin-de la Puente et al. 2021).

Research is needed to understand the benefits and risks of different strategies for making biodiversity and climate core concerns in the economic sector. Additionally, special attention should be given to sectors with the greatest impact potential, such as “Energy”, “Buildings and Cities”, “Agriculture, Food and Waste”, “Industry”, “Nature-Based Solutions”, and “Transport” (Emissions Gap Report 2020).

Furthermore, there is a need for research to “reform dominant economic and sociopolitical systems that drive climate change and biodiversity loss” (Dasgupta 2021) and to “re-appraise indicators of economic and social development” (Regulation (EU) 2022) to better address systemic biodiversity and climate-related risks (Kedward et al. 2022; Bustamante et al. 2023; 10 New Insights - Insights 5 (2021), and 10 (2022)).

Key Research Gaps

What finance mechanisms are needed on national and global levels to achieve both climate and biodiversity goals and how could they be implemented? In particular:

- Developing, implementing, and evaluating sustainable economic policies and market mechanisms for biodiversity conservation to improve planetary health and wellbeing. It is important to understand how incentives can be designed to yield improved outcomes concerning biodiversity conservation.
- Evaluating the effectiveness of existing and potential mechanisms - economic, political, financial, and societal - that target the mitigation of biodiversity and climate crises.
- Implementing biodiversity mainstreaming effectively into economic sectors that drive biodiversity loss and degradation.
- Exploring how to leverage finance mechanisms to address both climate and biodiversity goals.
- Designing carbon offset mechanisms for climate objectives to also encompass biodiversity goals.
- Enhancing comprehension of climate mitigation and adaptation finance dynamics to optimise co-benefits across different systems and livelihood contexts.

What are the direct and indirect environmental, economic and social benefits from combined action on climate change and biodiversity loss (e.g. financing nature-based solutions)? Including:

- Investigating the direct and indirect benefits for planetary health by investing in nature-based solutions.
- Examining the co-benefits of addressing both climate change and biodiversity loss.
- Exploring the interplay between climate change impacts, system productivity, and economic losses across sectors like forests and agriculture.
- Understanding how climate change adaptation strategies can prevent losses and foster positive outcomes instead of maladaptation.
- Assessing the indirect costs of biodiversity loss and climate change to various societal sectors.

3.2 Empowering Action Through Finance

Considerable efforts have been made since the Paris Agreement to make “finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient emissions and climate-resilient development” (Zamarioli et al. 2021). Similarly, a growing number of countries are applying financial instruments, including taxes, fees and charges, tradable permits and subsidies, to meet their biodiversity goals (OECD 2021). Finance is a critical point for the just transitions needed across economic sectors (10 New Insights 9, 2019; 5, 2021, 2022 and 2023/24). Nonetheless, insufficient mobilisation of finance both for climate and biodiversity continues to be an issue.

Regarding climate, adaptation finance has come predominantly from public sources, and a small proportion of global tracked climate finance was targeted to adaptation and an overwhelming majority to mitigation. Current global financial flows for adaptation, including from public and private finance sources, are insufficient and constrain implementation of adaptation options, especially in developing countries. In addition, adverse climate impacts

can diminish the availability of financial resources by causing losses and damages and hindering national economic growth. This exacerbates financial constraints for adaptation, especially in developing and least developed countries (IPCC 2023 SPM.A.3.6). Future levels of climate finance are dependent on the ability of public finance interventions to mobilise private finance and, thus, on the characteristics of public finance, e.g. in terms of thematic split, geographic destination and financial instrument (OECD 2021). The recent growth in global climate finance largely results from significant increases in clean energy investment in a handful of geographies. China, the US, Europe, Brazil, Japan, and India received 90 per cent of the increased funds. While this marks promising progress, large climate finance gaps remain even in these geographies, and climate finance in other high-emission and climate-vulnerable countries has shown meager progress in meeting their needs (CPI 2023). Exploring pathways to end fossil fuel subsidies, which in the EU increased from EUR 56 billion in 2021 to EUR 123 billion in 2022, is a critical piece in climate change mitigation. According to the European Environment Agency, "[m]ost EU Member States have no concrete plans on how and when they will phase out these subsidies" (European Environment Agency 2023).

Regarding biodiversity, current levels of biodiversity finance are estimated at no more than USD 143 billion annually. That leaves an annual biodiversity conservation financing gap of USD 598–824 billion per year by 2030. Today most of the funding comes from public sources (80-85%), but the private sector can increasingly play a critical role to help close the financing gap, through financial mechanisms that generate revenues for biodiversity infrastructure (Tobin-de la Puente et al. 2021). Greater global support is required for research initiatives aimed at improving the comprehension and awareness of nature-related financial risks among financial institutions, leveraging insights from advancements in understanding climate-related financial risks (Dasgupta Review 2021).

Key Research Gaps

What are the social and economic mechanisms, including power asymmetries, that drive environmental degradation and how can they be overcome? Particularly:

- Examining the mechanisms, including harmful subsidies, by which economic structures drive environmental degradation.
- Investigation into the feedback loops perpetuating the crises at hand.
- Studying how the re-appraising of economic and social development indicators leads to wider reforms of economic and sociopolitical systems.

What are the economic and natural resource implications of elevating global living standards to a level characterised by decent quality of life for all, considering current deprivations and inequalities? How can this goal be met while minimising additional use of resources? In particular:

- How will climate change and biodiversity loss affect the productivity and economic viability of key sectors (including agriculture) over different time horizons and in different places?
- Quantifying the extent of additional resources required to elevate global living standards to a level characterised by a decent quality of life for all, considering current deprivations and inequalities.

3.3 The Role of Circular Economy

By reducing resource consumption, the circular economy has a fundamental role in preventing biodiversity loss and mitigating climate change. There is financial opportunity wherein the circular economy could tackle biodiversity loss by eliminating waste and pollution

to reduce threats to biodiversity, circulating products and materials to leave room for biodiversity, and regenerating nature to enable biodiversity to thrive (Ruokamo et al. 2023). A recent study proposed that embracing a circular economy in the food and agriculture sector, emphasising regenerative production and innovative business models, could significantly curb biodiversity loss by 2050 (Forslund et al. 2022). Further research is required to better understand the economic and financial viability of various circular practices and stakeholder perceptions of these practices (Velasco-Muñoz et al. 2022).

4. Governance and Transboundary Collaboration

4.1 Governance for Equity and Justice

Governance plays a crucial role in considerations over equity and justice, as well as addressing both climate change and biodiversity loss (Pascual et al. 2022). Governance is understood here as collective decision-making across multiple scales with and by various actors – including the state, the private sector and individuals – through various policy processes and instruments (Lemos and Agrawal 2006).

Justice discussions have proliferated in the last years within both climate and biodiversity governance. For climate change, this means accounting for equity and justice in a green transition (Sovacool 2021) and in adaptation (Juhola et al. 2022; Bustamante et al. 2023) and how we govern complex systems such as food production. The components of justice that require consideration have been defined as: distributive, epistemic, restorative, procedural, and recognition (Bustamante et al. 2023). Each component of justice requires specific governance approaches to ensure inclusivity and prevent unjust outcomes.

When it comes to decision-making around biodiversity and climate, questions remain around how just and equitable decision-making structures, processes and outcomes are currently (Lenzi et al. 2023; Juhola et al. 2022). Understanding is needed on how environmental harm and its costs become dispersed, i.e., distributive justice, who is involved in the governance of these resources, and are the associated processes fair. Given that there is evidence of exclusion of vulnerable groups, it is important to know whether all groups are recognised in the collective decision-making processes. The question about justice and power asymmetries also extends to decision-making in science and technology.

Key Research Gaps
How can political awareness, scientific capacity and literacy, and governance systems be strengthened without exacerbating existing inequalities? Including, • Studying how misinformation and political polarisation can hamper action to combat climate change and biodiversity loss.
How can governance in climate and biodiversity be improved in the most vulnerable regions of the world?
What are the most consequential power asymmetries that influence decision-making processes in science and technology, and how they contribute to the current environmental crises?
How do transitions towards sustainability in the Global North, including individual actions and policy initiatives, impact sustainable development in the Global South? Including:

Key Research Gaps

- Exploring the influence of EU institutions and policies on sustainable development worldwide.
- Investigating the impacts of sustainability transitions in the Global North on conditions in the Global South.

What is the significance and impact of multi-level governance in addressing complex societal and environmental challenges? In particular:

- Investigating the science-policy interface in planetary health governance.
- Exploring measures that would better facilitate and enhance science and policy interactions.
- Incorporating these individual elements into global policy processes.
- Studying ways to enable inclusive multi-level governance that allows for local autonomy and preferences.

4.2 Redefining Planetary Health Governance

From a planetary health perspective, growing governance challenges within the three-fold problem of biodiversity loss, climate change and pollution reflect the state of our planet's health. Much of the biodiversity debate has focused on the concept of multispecies justice (Pineda-Pinto et al. 2023) and multispecies sustainability (Ruppercht et al. 2020), which both stress the need to move away from anthropocentrism. The anthropocentric approach focuses on human health at the expense of other elements of the planet. In this regard, other elements of the planet are at the mercy of humans, who exploit them for their benefit. This human-centered approach to health and wellbeing falls short.

Realising the inadequacy of the anthropocentric approach in addressing global challenges (Whitmee et al. 2015 – in Özdemir 2019), scholarly and policy communities have begun to explore novel ideas and innovative approaches to planetary health governance, often scrutinising the idea of "health". Özdemir (2019) asserts that to conceive of and adopt the needed innovative, inclusive and critical approach to planetary health governance, a good starting point would be underscoring the all-encompassing nature of health. This means perceiving and addressing health as planetary and not just (human-centered) public, or human only, or human v. animals, plants and all the other organisms of the planet. While adopting a holistic, "post-anthropogenic" (Hoole 2017; Özdemir 2019) view of planetary health – and hence its governance (Horton et al. 2014) – is advocated by several scholars, it remains an unexplored subject of research. There is a further research need to understand how to navigate and address the complexities that arise from diverse, and still largely anthropocentric, value systems.

A further framing guide for planetary health governance is the concept of "One Nature" – that is one-ness of all planetary inhabitants (humans, plants, animals, living and nonliving, or broadly human, non-human, and nonliving) as the underlying principle. In this respect, humans must not assume the sole source of capacity to govern the planet (Özdemir 2020). While the concept of one-nature is novel in mainstream scientific research, the view is prevalent and indeed constitutes the approach to human-nature relations and planetary or nature governance in Indigenous cosmovisions. These different framings highlight opportunities for further research into the role of non-human agency in planetary health governance.

Key Research Gaps

What are the potential impacts of a governance system based on a concept of planetary health that recognises the agency of non-human elements in the environment, such as plants and animals? In particular:

- Investigating methodologies for estimating, comprehending, and harnessing non-human agency in the governance of planetary health.
- Exploring frameworks for governance that incorporate non-human elements and acknowledge their agency.
- Examining components and manifestations of animal agency, plant agency, and non-human agency more broadly.
- Analysing existing governance processes to identify synergies that can inform post-anthropocentric policies for planetary health governance.
- Examining how (global) policy communities can engage with and integrate contextual perspectives on governance framing, particularly from Indigenous cosmovisions.
- Assessing the receptiveness of various global constituencies and communities to the concept of one-nature and the inclusion of non-human agency.
- Understanding the role of state systems (or broadly societal compositions, which include Indigenous Peoples) as a driver of performance and behaviour on planetary health governance.

4.3 Transboundary Collaboration

Effective action on biodiversity loss and climate will require greatly increased international collaboration and governance. In the case of biodiversity, Mason et al. (2020) stated that "coordinated approaches towards managing transboundary species are now essential to prevent further declines of many endangered species, and global policy efforts must do more to produce and enact legitimate mechanisms for collaborative action in conservation". They note, however, that no research has been undertaken at a global level to determine the state of, opportunities for, and challenges for terrestrial transboundary conservation. Similarly, in the Global Transboundary Climate Risk Report 2023 (Anisimov & Magnan 2023) concluded that "transboundary climate risks are a global concern, yet the international, regional and local mechanisms to adapt to climate change are not yet equipped to meet this common challenge." Such risks and the inescapable need for transboundary collaboration are clearly exemplified by the emergency of "vulnerability hotspots" across extensive swaths of territory at a regional scale (10 New Insights 2, 2022). In both areas, research is needed to develop a robust evidence base on the diversity and complexity of transboundary issues as a basis for designing governance and policy solutions, as well as assessments of the proposed solutions in terms of their cost implications and distributive effects.

Key Research Gaps

What is the state of, opportunities for, and challenges for transboundary collaboration and governance on biodiversity protection and climate action? In particular:

- Investigating strategies to enhance international collaboration for biodiversity protection and climate action.

Key Research Gaps

- Examining ways to optimise the utilisation of international and national legal frameworks and administrative structures in addressing climate change and biodiversity loss.
- Assessing the impact of international negotiations on encouraging participation from the Global South and exploring mechanisms to ensure equitable representation.

5. Policy Instruments and Mixes

5.1 Synergistic Policies Across Sectors

Treating climate, biodiversity and human society as coupled systems is key to successful outcomes from policy interventions (Pörtner et al. 2023b). In practice, this entails "mainstreaming of biodiversity into climate policy and vice versa, and of both into initiatives to advance human development and good quality of life" (Pörtner et al. 2021; 10 New Insights - Insight 5, 2023/24). To achieve this ambition, research is needed on how to develop policy mixes that are effective in achieving sectoral objectives while maximising synergies amongst them and contributing to the systemic goal (Van Den Bergh et al. 2021). A key question is "how to distinguish a policy mix from a policy mess, or in economic terms, how to determine the conditions under which a combination or overlap of instruments is welfare enhancing" (Bouma et al. 2019).

One of the challenges of treating climate, biodiversity and human society as coupled systems is ensuring policy coherence among different sectors of public administration (Wülser et al. 2020). It is inevitable that some goals will conflict with others, and the challenge for the policymaker is to minimise those trade-offs; on the other hand, some goals can support each other, and the aim should be to identify and exploit those potential synergies or co-benefits. Dealing with such interdependencies requires new forms of transdisciplinary collaboration, not only within government, but also among actors in academia, the private sector, politics and civil society. Inclusive policies that embrace a systems approach may help overcome typical challenges of the science-policy interface resulting from reasons such as locational and contextual differences between researchers and policymakers (Pattanayak & Haines 2017). New structures and processes will be needed to avoid one-sided actions that have negative consequences for progress in other sectors. In doing so, explorations of what incentive systems can enable such activities will be needed.

Key Research Gaps

What are the main challenges of mainstreaming biodiversity into climate policy and vice versa, and of both into initiatives to advance human development and good quality of life?

How effective are current legal mechanisms and instruments, operating on national, regional, and global levels, in protecting the environment, and what measures could be implemented to enhance their effectiveness?

How can synergies and trade-offs amongst policy instruments in different sectors be anticipated and dealt with?

Key Research Gaps

What are the institutional obstacles to effective collaboration on biodiversity and climate change, both within public administrations and the private sector? How can these be overcome?

5.2 Policies to Halt Overconsumption

There is one particular policy challenge that lies at the root of most environmental problems, including biodiversity loss and climate change, and that has received limited attention – overconsumption (Creutzig et al. 2022a; Creutzig et al. 2022b). In 10 New Insights this driver has been discussed together with the notion of "sufficiency" in household level consumption patterns (Insight 6, 2021). Wiedmann et al. (2020) present evidence showing that "consumption of affluent households worldwide is by far the strongest determinant and the strongest accelerator of increases of global environmental and social impacts". They go on to propose a number of concrete policies for reducing overconsumption, from a green growth approach focused on resource efficiency, renewable energy and decoupling, to reformist approaches which include strong limits and social justice in policies, reforming important social institutions and changing lifestyles and cultures, all the way to more radical approaches which are based on changing economic structures, reforming institutions and increasing social control over economic actions. They also acknowledge that all of the proposed approaches require scrutiny and further research in sustainable consumption and production. Evidence from IPCC AR6 WGIII chapter 5 highlights that well-being is enhanced primarily through a demand of services, rather than energy and physical resources (Creutzig et al. 2022). According to a literature review by Castano Garcia et al. (2021), high-consuming households have rarely been the focus of academic studies or policy initiatives, despite the fact this group has the greatest potential to reduce resource consumption. A research agenda which seeks to gain a better understanding of the role of high consumers in transitions to more sustainable consumption practices is warranted (Castano Garcia et al. 2021).

Key Research Gaps

At what level (or levels) can social transformation be initiated, and through which mechanisms? What policies could be introduced to halt overconsumption? In particular:

- Exploring mechanisms, such as specific policies, that can facilitate the transition of societal values regarding nature towards responsibility, stewardship, and justice.
- Identifying the societal and economic levers required to shift attitudes towards sustainable transformation.
- Exploring what policies can be introduced to halt overconsumption as a key strategy for addressing both climate and biodiversity challenges.
- Studying the effectiveness of current legal mechanisms and instruments, on local, national, regional, and international levels, in protecting the environment and how they could be improved.

6. Data and Emerging Tools

6.1 Data Integrity and Access

Progress towards sustainability will depend crucially upon the availability of data that is reliable, relevant, peer-reviewed, openly and easily accessible and generally accepted as trustworthy. The European Commission's Data Governance Act aims to promote data sharing, data availability and the reuse of data across European sectors for the benefit of citizens and businesses (Regulation (EU) 2022/868, 2022).

While considerable advances have been made, there are still deficiencies in data reporting and production, quality, consistency and availability across the planet. For example, progress towards achieving 41 per cent of the 92 environmental SDGs indicators, cannot currently be globally measured owing to a lack of interoperable data and standardised reporting. Overcoming this fragmentation and adopting global environmental data standards are critical to enabling action to address the triple planetary crisis (climate change, biodiversity loss, and pollution) (United Nations Executive Office of the Secretary-General / UN Global Digital Compact, 2023).

A 2021 assessment of the availability of statistical and spatial data, analytical methods and visualisations based on SDGs indicators concluded there was an urgent need to prioritise the development of SDGs indicator methodologies, including an elaboration on the need for disaggregated and geospatial information. The report also called for a more consistent and integrated approach to data management, including reducing data fragmentation and supporting data sharing in accordance with national e-government[2] and open data frameworks (UNEP 2021, Measuring Progress).

Key Research Gaps

How to ensure FAIR (Findable, Accessible, Interoperable, and Reusable) access to data about biodiversity and climate change to support decision making and foster public awareness? Including:

- Enhancing data availability and access while reducing gaps and bias.
- Utilising open data to bolster decision-making and foster transdisciplinary collaboration and action.
- Developing transdisciplinary collaboration by facilitating data transfer between communities using Artificial Intelligence (AI).

[2] According to the Communication of 26 September 2003 from the European Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions "The Role of eGovernment for Europe's future" [COM(2003) 567 final - Not published in the Official Journal], "eGovernment" * means the use of information and communication technologies * (ICT) in public administrations combined with organisational changes and new skills. The objective is to improve public services, democratic processes and public policies.

6.2 Leveraging AI for Better Data

Leveraging the large amounts and types of environmental data being collected every day to extract meaningful information is no simple task. There is growing awareness that AI may play a key role in fueling progress in modeling and predictive capabilities of very complex systems, including the climate-biodiversity-society interface (Reichstein et al. 2019; Huntingford et al. 2019).

For example, remote sensing is a potent tool, offering objective evidence across processes, providing insights into ecosystem dynamics at different scales. Remote sensing has the potential to support policy making across all stages and sectors, serving as a comprehensive source for multidisciplinary research and diverse policy applications. However, currently, remote sensing is predominantly utilised in the early stages of the policy cycle, with limited application in policy formulation, implementation, and evaluation. Interdisciplinary approaches and studies focusing on transnational policies are also lacking (Bell et al., 2023).

To explicitly account for the impacts of AI in long-term climate and energy projections, and in the design of related policies, the research community needs to develop a holistic and operational understanding of the different ways in which AI and machine learning tools can positively and negatively impact climate change mitigation and adaptation strategies (Kaack et al. 2022).

By increasing transparency, connectivity, and access to data, digital technologies have the potential to transform current governance systems and catalyse transformations towards the SDGs. For example, digital paradigms have the potential to address many research gaps in SDGs by offering new sources of data and improved analytical capabilities, thereby aiding in bridging these gaps (Del Río Castro et al. 2021). However, digitalisation and data acts and policies must be aligned with national, regional, international sustainability agendas to minimise rebound effects and other negative impacts while also capitalising on the potential of digital innovations to support transformations towards sustainability (Creutzig et al. 2022; CODES 2022).

Key Research Gaps

How can AI be used to advance understanding about physical, ecological and social systems and their interactions, provide early warning of extreme events, and improve decision making? In particular:

- Investigating the potential of AI tools to review evidence and support policy design for tackling biodiversity and climate change challenges.
- Developing machine learning to advance understanding about physical, ecological and social systems and their interactions, and improve early warning systems and risk reduction for rare and extreme events.
- Developing advanced deep learning techniques that can integrate data and models of different nature, granularity and types seamlessly, across spatial and temporal scales.
- Exploring methods to merge remote sensing and field (in-situ) data collection to provide vulnerable countries with timely information, enhancing resilience, mitigating risks, and improving responses to extreme weather events.

How can improved data synthesis and visualisation techniques be used to support sustainable decision-making and public participation in policy development? In particular:

- Understanding likely consequences of different scenarios for biodiversity and climate change through data visualisation.
- Investigating the impacts of improved data synthesis and visualisation techniques to support citizens in sustainable decision-making.

Key Research Gaps

- Investigating the role of new digital technologies to promote public participation in policy development and acceptance of adopted policies.

How can remote sensing and other automated data-collection systems be used to support environmental policy and reporting, especially in regions with limited scientific and/or technical capacity? How can the quality and consistency of such data be improved? In particular:

- Investigating criteria for data appropriateness and most efficient data collection methods to support policy forecasting and development of AI tools and models.
- Developing ways to use automatic data-collection systems to support policymaking in regions of biodiversity hotspots and limited scientific capacity.
- Enhancing data quality and consistency at a global scale, and improving data collection and integration in post-disaster conditions as a basis for sustainable and resilient recovery planning.

6.3 The Ethics of Digital Innovation and Data Collection

Without appropriate governance systems in place, digital innovations can exacerbate rather than help address current environmental and social sustainability challenges and widen inequalities (Galaz et al. 2021). It is critical to understand and quantify the rebound effects of the digital age including but not limited to, increased greenhouse gas emissions in the manufacturing of digital devices, accelerated resource extraction for raw materials, production of e-waste, overall increases in consumption and production due to easy access provided by digital platforms, and lack of governance frameworks related to privacy, data ownership, and security (Creutzig et al. 2022; CODES 2022; Garard et al. 2022). From the equity and justice point of view (Graves Jr. et al. 2022), understanding what data is missing, why it might be missing, and how data is accessed globally, is key. FAIR (Findable, Accessible, Interoperable, and Reusable) data guidelines are attempting to provide structure for how scientific data is and should be shared (Wilkinson et al. 2016). Scientific data will have a greater impact when we understand the different regional and national needs for data format, access, and training for analysis and optimising data access. This is especially important in data-poor regions of the world (von Wettburg et al. 2022 and references therein).

Scientific research should offer insights into both the potential risks and benefits of digital technologies, along with the ethical considerations they entail. Furthermore, possible new governance structures should also be explored, such as a Big Data-driven “transnational sustainability agency”, or polycentric governance structure (Luers et al. 2020).

Key Research Gaps

What are the potential risks and benefits of large-scale development and application of emerging digital technologies in support of biodiversity and climate change policy? In particular:

- Exploring biases that Big Data-based analyses can pose if used for decision making.

What are the ethical considerations on the use of AI to support decision making in climate change mitigation and biodiversity preservation? In particular:

- Evaluating the costs and benefits of the emerging tools over more traditional decision-making methods.

Key Research Gaps

What would a digital and data governance framework look like for climate change and biodiversity-related policy, at each level of governance? Particularly:

- Exploring how to improve digital and data governance to reduce the environmental impact of large-scale digital tools.
- Researching how to establish inclusive digital and data governance frameworks.

7. New Paradigm of Science Information Exchange

7.1 Science Communication and Engagement

Science communication is key to advancing climate change and biodiversity research and making informed political decisions. However, there is a need for better understanding of what the most effective scientific communication strategies are. Despite decades of effort by scientists and scientific organisations to inform the public about the consensus on climate change, a persistent gap between the views of scientists and uptake by the public exists, questioning the overall efficacy of current approaches to communicating scientific consensus (Kahan 2015; Lewandowsky et al. 2022).

Social science research can support good communication of scientific consensus to the public. In fact, “social scientists have a crucial role to play: we cannot move forward to encouraging adoption of effective communication strategies without first delineating the boundaries of those strategies, by looking at what motivates people when they form beliefs about climate change, within which populations, and with what outcomes” (Bayes et al. 2020).

More social science research is also needed on the role of social media and digital narratives more broadly, in influencing knowledge about climate change and biodiversity issues. This also applies to well-educated audiences and their understanding of environmental challenges. Because social media is a many-to-many asynchronous rapid exchange, groups form and reform around particular beliefs, values, and biases often driven by algorithms. Research is urgently needed to understand the underlying fears or hopes that feed narratives and impact motivations and inspirations around sustainability transformations (Helgeson et al. 2022).

Effective science engagement goes beyond communication. As Goodrich et al. have argued, “[m]eeting today’s environmental challenges increasingly requires individuals who are able to operate at the boundary between science and policy.” In addition to communicating knowledge, these skills involve mediating, bridging, and brokering knowledge. In practice, however, “a range of challenges limit both the capacity and number of individuals who are able to serve, and serve effectively, in these roles” (Goodrich et al. 2020). Better understanding is needed about the challenges as well as the effectiveness of different approaches of science engagement.

Finally, there is a need for academic institutions and research funders to support researchers’ efforts more systematically in science communication and public engagement related to climate change and biodiversity loss. This is particularly true for researchers from marginalised groups (due to e.g. gender, age, sexual orientation, socioeconomic status, geography, disabilities, and many other aspects). Increasing diversity in climate and biodiversity policymaking is important not only to make institutions more equitably represent

the people most affected by climate change and biodiversity loss, but also to expand knowledge and perspectives that can inform potential solutions (Swain 2023).

Key Research Gaps

What are the most effective strategies for communicating scientific information about climate change and biodiversity loss as a basis for transformative change? In particular:

- Understanding the role of science communication in addressing climate change and biodiversity concerns.
- Evaluating the effectiveness of science communication and public awareness strategies: where people obtain their information, how they evaluate that information, and what factors – economic, political and societal - influence them in forming their opinions?
- Identifying the most effective information feedback mechanisms that promote transformative change.
- Examining the factors (e.g., educational, political, economic, psychological) that influence how people respond to messaging about the scientific consensus on climate change and biodiversity.
- Understanding how digital narrative tools can be best utilised for effective science communication.

What are challenges as well as the effectiveness of the various possible approaches of science engagement?

7.2 Science Education and Culture

Ensuring equity and access to science information globally and improving society's collective capacity to utilise it, is a critical need (Fung et al. 2022). How can scientific insights be translated into something K-12 students, rural, urban, vulnerable individuals, and all working people and all communities can see that they benefit from? To succeed, individuals and communities must be the driver of this transformation. Project-based learning, community endeavours, science and engineering challenges, climate clubs, the arts and more can encourage engagement with critical science information (Fung et al. 2022). More research is needed to investigate the role of education, determine which educational approaches may prove most effective in building capacity and awareness, and which type of messaging would lead to social transformation.

Furthermore, embedding climate and biodiversity research evidence into cultural products and culture-based action that provide pluralistic perspectives, remains an important opportunity (Rodriquez 2020).

Key Research Gaps

How does information about the causes of environmental problems increase awareness and contribute to transformative change, and how can it be conveyed most effectively? In particular:

Key Research Gaps

- Understanding how knowledge about the impacts and risks associated with climate change and biodiversity loss can contribute to change values, behaviors, and promote social transformation.
- Exploring ways to build stronger bonds between science and culture to drive sustainability transformation.

What are the best ways to engage with diverse communities (based on backgrounds, perspectives, and knowledge systems) to build capacity to respond to climate change and biodiversity loss? Including:

- Investigating best practices in capacity building to engage with diverse communities and knowledge systems.
- Connecting diverse knowledge systems.
- Understanding which attitudes, beliefs, and behaviors impact consensus messaging.

How to ensure equity and access to science information globally and improve our collective capacity to utilise it? Particularly:

- Investigating the ways in which marginalised communities receive, process and act on science information.
- Investigating strategies to improve access to science information and the capacity to utilise it in marginalised communities.

8. Ways Forward: Re-imagining the Research Approach

The research questions outlined in this report underscore the pressing need for a radical shift in the way society approaches complex issues, particularly those related to sustainability, climate change, and biodiversity. The chapter themes and questions, characterised by their transdisciplinary nature, represent a departure from traditional academic methodologies. They necessitate the *collaboration of interdisciplinary teams*, involving scientists from all backgrounds, including social sciences and humanities, and require academic institutions to evolve in their capacity to engage with policy makers and stakeholders effectively.

Our findings here echo the conclusions of the most recent OECD Science, Technology and Innovation Outlook (2023), which emphasise the essential role of Science, Technology and Innovation (STI) in sociotechnical systems transformations, and argue that “governments must be more ambitious and act with greater urgency in their STI policies to support them” (OECD 2023). The findings further echo two recent reports of the International Science Council (2023a and 2023b) that call for major investment in research and innovation for sustainability. An overall look at the key research questions that emerged propose that innovative research structures require the following characteristics: *systems focused; transdisciplinary; cross-disciplinary and; including a well-defined process of engagement*.

In a similar vein, Wuelser and Edwards (2023) argue that one of the most effective ways to support sustainable development through research and innovation would be through large, highly interdisciplinary funding programs, which they refer to as “lighthouse programs”. International transdisciplinary research funding initiatives, such as the Belmont Forum, have already done pioneering work in advancing a more holistic approach to research development and funding, supported by Future Earth and several national research funding agencies. These efforts, however, are insufficient as they represent only a small fraction of public and private funding for research, most of which is organised along disciplinary lines (Schneider et al. 2023).

Furthermore, the challenges posed by these innovative research approaches extend beyond technical hurdles; they permeate the very fabric of academic institutions which require careful navigation (Harris et al. 2024). Adapting to this new style of research requires a significant *shift in the mindset of both researchers and institutions* (Harris et al. 2024). Moreover, the call to integrate the best science and technology while aligning policies across countries, sectors, and mindsets adds an additional layer of complexity.

The shift towards transformative change, systemic action, and robust governance and policy support is emphasised as crucial in addressing the current needs of our society. It is acknowledged that not all research on climate change and biodiversity necessitates the proposed transdisciplinary approaches; however, a growing consensus supports the idea that novel approaches and institutional structures are vital for tackling the most critical problems of sustainability.

As we move forward, *it is imperative for institutions to recognise the need for change and establish incentives that promote and reward this transformative shift in research methodologies*. Implementation strategies for this type of research should be carefully considered, drawing on the insights provided by reports such as the one on lighthouse programs. In doing so, we can pave the way for a more effective and impactful approach to research, aligning our efforts with the urgency and complexity of the challenges we face in the realms of sustainability, climate change, and biodiversity.

APPENDIX – METHODS

Framing

The European Commission DG RTD Unit B.3 on Climate and Planetary Boundaries invited Future Earth to issue an independent expert report identifying knowledge gaps and research priorities on climate change and biodiversity science to inform the development of future EU R&I work programmes. The aim of this report is to provide recommendations to DG RTD on what thematic areas should be prioritised for prospective research and innovation interventions in view of maximising impact of EU publicly funded research and innovation.

By accepting the invitation, Future Earth committed to develop a process to provide an evidence-based assessment with the aim to encompass broad thematic areas representing research gaps spanning climate science and biodiversity. For potential transformation and societal impact sustainability science areas, human dimensions, and the associated social sciences were incorporated.

The horizon scanning process is the systematic outlook to detect early signs of potentially important questions, developments, and changes that may mature into trends (Sutherland et al. 2011). Embracing this approach, Future Earth consulted its German and Swiss National Committees who compiled thematic horizon scanning reports in the previous year, as well as built on its years of experience assembling the 10 New Insights in Climate Science (10 New Insights).

The German Committee's "Research Priorities for Sustainability Science" position paper combines insights from global environmental change research and the environmental social sciences and humanities for a programmatic framework that will form the basis of the future work programmes of the committee itself. This contribution addresses agents in science, science management, and science funding in a national and an international context.

The Swiss National Committee's "Priority Themes for Swiss Sustainability Research" report outlines the most urgent research needs in order for Switzerland to meet the UN Sustainable

Development Goals. The priority themes were developed by 30 experts from science and practice on the basis of a broad-based dialogue with over 100 stakeholders from science, business, administration and civil society.

The 10 New Insights in Climate Science is a partnership between Future Earth, the Earth League, and the World Climate Research Programme (WCRP), and presents key insights annually from the latest climate change-related research. 10 New Insights responds to clear calls for policy guidance to be delivered each year at the UNFCCC COP. Taking this process one step further, this horizon scanning report identifies the key knowledge gaps to provide an evidence-based assessment.

Our process

Building on the processes of those reports, Future Earth began by bringing together the people needed to initiate this horizon scan, forming the Oversight Committee. This committee created a timeline that would allow for an agile process within a ten-month timeframe that was initially envisioned. The Oversight Committee further ensured operations and processes went smoothly.

Using a curated approach, Future Earth network members were identified for an Advisory and Engagement Committee, which assisted in providing feedback to the open call for inputs and for Editorial Board composition. Their expert recommendations promoted the importance of this report and supported broad engagement from Future Earth's global networks.

A call for Editorial Board Members was launched for two weeks reaching 49 nominations, and 10 members were selected for this board keeping in consideration Future Earth's Principles & Core Values, which includes its diversity policy. Following the project kick-off and survey design meeting, an open call for inputs was conducted for two months, which also included two hybrid dialogue sessions to gather a broad perspective.

A total of 119 submissions from 34 countries and researchers from various fields and backgrounds as well as practitioners in sustainability research from 78 institutions were analysed by the Editorial Board. They distilled the insights and narrowed down the potential topic areas, grouping and categorising the inputs. Finally, the most important potential questions were selected and framed with their expertise.

During this process, additional experiences were drawn from participating in the UNEP Strategic Foresight North America regional contextualisation workshop as well as the Lighthouse Programmes in Sustainability Research and Innovation report. These were checkpoints confirming our process corresponds with other similar activities working in this landscape.

After finalising the initial draft, further feedback was solicited from subject matter experts who provided comments and reviewed the selected topic areas and key insights. They are acknowledged in the section below.

Composition of committees

Oversight Committee
The project as whole was steered by the Oversight Committee. Responsibilities included:

- Determining and overseeing overall focus, scope, and process,
- Making decisions on Editorial Board organization and composition,
- Supporting writing process based on Editorial Board inputs, and
- Liaising with the European Commission DG RTD.

Committee members include:

- Monika Bauer, Project Lead and Coordinator, Future Earth Global Secretariat Hub USA seconded by the International Institute for Applied Systems Analysis (IIASA)
- Jakob Lundberg, Deputy Director, Future Earth Global Secretariat Hub Sweden
- Veera Mitzner, Associate Director, Future Earth Global Secretariat Hub USA
- Giles B. Sioen, co-lead, Research and Innovation, Future Earth Global Secretariat Hub Japan; Research Associate, National Institute for Environmental Studies
- Judit Ungvari, co-lead, Research and Innovation, Future Earth Global Secretariat Hub USA
- Joined as Chief Copy Editor in September 2023: Andréa Ventimiglia, Science Editor & Advancement Officer, Future Earth Global Secretariat Hub Canada

Advisory and Engagement Committee

The Advisory and Engagement Committee consisted of Future Earth Secretariat and Community members and provided advice and inputs into the process, especially through engagement.

- Sharing the call for inputs actively with their networks and supporting the workshops at SRI2023.
- Providing writing inputs to the report if applicable.

Members include:

- Natalie Chong, (Former) Future Earth Science Officer, Future Earth Global Secretariat Hub France
- Rebecca Fenn, (Former) Co-lead, Capacity & Networks, Future Earth Global Secretariat Hub France
- Sophie Hebden, Research Liaison, European Space Agency & Future Earth Global Secretariat Hub Sweden
- Cornelia Krug, bioDISCOVERY Director, Future Earth Global Research Network
- Shihu-Yu Lee, Deputy Director, Future Earth Global Secretariat Hub Taipei
- Xiao Liu, Associate Director, Future Earth Global Secretariat Hub China
- Debashis Nath, Associate Director, Future Earth Global Secretariat Hub China
- Michael Nxumalo, Future Earth Africa Hub Director
- Daniel Ospina, 10 New Insights in Climate Science Coordinator, Future Earth Global Secretariat Hub Sweden
- Gabriela Wuelser, Swiss National Committee Representative
- Giles B. Sioen, co-lead, Research and Innovation, Future Earth Global Secretariat Hub Japan; Research Associate, National Institute for Environmental Studies
- Judit Ungvari, co-lead, Research and Innovation, Future Earth Global Secretariat Hub USA

Editorial Board

The Editorial Board (EB) made the scientific and content decisions for this synthesis report. 10 members were selected for their scientific excellence in relevant fields, with a focus on diversity regarding academic background, ethnicity, gender, and nationality.
Responsibilities included:

- Participating in 9 EB meetings throughout the year to identify the knowledge gaps, and to distill the key thematic areas and develop the overall framing.
- Participating in stakeholder workshops at Future Earth flagship event Sustainable Research and Innovation Congress (SRI2023).
- Identifying the main themes that will be presented in the report as well as the format they will be presented in following the template provided by the European Commission DG RTD.
- Providing timely written feedback for full draft of the synthesis report as well as drafts at different stages.
- Suggesting and approving the process for writing the report.

- Providing high-level insights for the writing process to present a coherent message, well-suited for the intended target audiences.

Members include:

- Timothy A. Balag'kutu, Centre for Peace and Security Research, University of Professional Studies, Accra, Ghana
- Ana Bastos, Max Planck Institute for Biogeochemistry
- Anthony Capon, Monash Sustainable Development Institute, Australia; co-chair Health Knowledge-Action Network
- Fabrice DeClerck, EAT Forum/Alliance of Biodiversity and CIAT, CGIAR, Germany; Earth Commission
- Langley DeWitt, University of Colorado, Boulder, USA; International Global Atmospheric Chemistry (IGAC) Project
- Peter Edwards, ETH Zurich, Switzerland - Chapter Lead
- Sirkku Juhola, University of Helsinki, Finland, Emergent Risks and Extreme Events Global Research Network - Chapter Lead
- Leila Niamir, International Institute for Applied Systems Analysis
- Lisandro Roco, Faculty of Economics and Government, Universidad San Sebastián, Valdivia, Chile
- Pallavi Saxena, Department of Environmental Sciences, Hindu College, University of Delhi, India; The Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) - Chapter Lead

The final Editorial Board comprised colleagues from 6 continents, 5 male and 5 female, and from a variety of disciplines, with a slight majority coming from natural sciences.

Survey

A global call was opened to identify where new research evidence is critical and needed, and shared with us what is considered currently missing in climate change and biodiversity science research. The framing of the questions used the Delphi method (Dalkey, Helmer 1963). The survey was open for two months. The call was shared with the Future Earth's Global Research Networks community, National Committees, and the Early Career Network of Networks. It was also shared by the International Institute for Applied Systems Analysis (IIASA) with its staff and networks. The survey was also publicized over Future Earth social media channels with a reach to over 25,000 individuals. We were particularly interested in perspectives taking a systems approach and linking to the goals set out by the Paris Agreement, the Kunming-Montreal Biodiversity Framework, and UN Sustainable Development Goals.

Workshops

Two dialogue sessions titled Horizon scanning for climate science and biodiversity research priorities were organized at the 2023 Sustainability Research and Innovation Congress. The dialogues were open to all Congress attendees including early career researchers and practitioners from any region of the world. The aim was to bring together scientists, policymakers, and stakeholders to address the knowledge gaps in climate change and biodiversity science in a workshop setting. Participants were invited to identify key research questions and prioritize areas for the current horizon scanning. Considering the global reach of the congress the participants brought insights from well beyond Europe.

The first workshop was held during the Sustainability Research and Innovation congress in Panama, June 20-25, 2023. The hybrid workshop began with a short introduction to the horizon scanning and goals of the session. Participants were guided by an online facilitator and in person moderators. The audience split up into groups to identify knowledge gaps in climate change and biodiversity. The goal was to take a systems approach and investigate

what is currently needed to address these issues in today's society. This stakeholder engagement workshop built off of the inputs received by an open call and aided in identifying key themes that need to be addressed.

The in-person workshop In Panama was facilitated by Judit Ungvari and Giles B. Sioen Research and Innovation co-leads at Future Earth, from Global Secretariat Hub US and Japan, respectively, with support from Jakob Lundberg from the Global Secretariat Hub Sweden. The open access virtual session was facilitated by Monika Bauer from the Global Secretariat Hub US and by Daniel Ospina, Science Officer and Coordinator for the 10 New Insights in Climate Science at the Global Secretariat Hub Sweden.

The Sustainability Research and Innovation congress, Asia Spotlight Event workshop was fully virtual facilitated by Giles B. Sioen, Judit Ungvari, and Monika Bauer and brought in a broader perspective of the issues at hand from Asia and the Pacific. The same questions were asked as the premise of the in-person workshop and discussion points were noted from the participants. Research questions were captured and added as further input for the horizon scan.

Individual inputs

A total of 119 inputs were received via the survey and workshop responses. Relevant topics span a very broad scholarship on the underlying dynamics and impacts of climate change, biodiversity, nature-based solutions, earth observations and other related sustainability science areas. The human dimension and the associated social sciences (such as behavioral science, economics, etc.) are important cross cutting themes in addressing these issues and integral when confronting the climate emergency. The geographic diversity expanded over 32 countries and 6 continents.

Editorial board processes

After initial observation and description of the survey responses that were received, the Editorial Board went through the inputs and created research questions that embraced them. The process was repeated to have a second individual with different expertise to provide further framing.

The research questions identified were grouped using a shared miro board using various iterations. During the grouping exercises, the EB identified interconnectedness and proposed the idea to use the matrix from the Global Development Report 2023. Using the levers from the report certain entry points were emerging as sections and is how initially three chapters were identified.

The Editorial Board then split into three groups to identify what were the key knowledge gaps and what was missing from the inputs that were received. After the initial full draft, a workshop with Chapter Leads led to restructuring and distilled the key insights further. The iterative process led to seven final chapters with three to four key insights identified in each chapter. This was further expanded upon with targeted literature reviews for each chapter to validate the topics, provide background and sufficient context for the readers of the report to understand the topics, and fill gaps.

Review process within Future Earth networks

The following individuals provided written feedback and comments on the key insights presented in the report, focusing on specific chapters that were in line with their expertise. This peer-review process ensured a critical assessment of the key insights and accompanying research questions.

- Wendy Broadgate, Future Earth Global Secretariat Hub Sweden
- Jeremy Campbell, George Mason University, USA
- Ilan Chabay, Research Professor, School for Global Futures and School for Complex Adaptive Systems; ASU Barrett & O'Connor Center, Washington, DC; Arizona State University, USA, Founder and Co-Director, KLASICA, the Knowledge, Learning, and Societal Change International Research Alliance; Chair, External Research Evaluation Committee, Research Institute for Humanity and Nature, Kyoto, Japan
- Ching-Cheng Chang, Institute of Economics, Academia Sinica
- Lisa Jacobson, Future Earth Global Secretariat Hub Sweden
- Erica Key, Future Earth Global Secretariat Hub USA
- Rakhyun E. Kim, Utrecht University
- Ben Orlove, School of International and Public Affairs, Columbia University, USA
- Paula Ribeiro Prist, EcoHealth Alliance, USA
- Paul Shrivastava, Pennsylvania State University & Club of Rome

Limitations

The Future Earth community, although large, diverse in terms of geography and expertise, still has a limited reach with bias in majority natural science and academia based membership. When assembling the committees that guided this report, attempts were made to ensure broad expertise and views. Participation was limited by the lack of resources and strict time frame of the delivery. Despite the potential limitations in terms of the range of inputs, we relied on the expertise of the Editorial Board and the internal peer-review process to justify that the content is thorough. More extensive review of published manuscripts would bring about more topics of interest to complement and expand upon the expert solicitation and workshops, but this was not possible with limited resources and time available to deliver the project. To this end, identified research gaps are not meant to be exhaustive but offer a perspective from the Future Earth expert community.

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