Emergence of transdisciplinarity in global environmental change research : Moving from system understanding to systemic sustainability solutions

Handbook of Transdisciplinarity

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9. Emergence of transdisciplinarity in global environmental change research: moving from system understanding to systemic sustainability solutions

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INTRODUCTION

Earth-system science has a long history (Steffen et al., 2020). Initially, it was dominated by geologists who study the liquid and solid Earth, its rocks, and the slow processes by which they change over time. The implementation of the International Geophysical Year in 1957 and the International Biology program in the 1960s triggered the emergence of another Earth-system science that included ecology, hydrology, atmospheric, and other environmental sciences. Currently, Earth-system science is an interdisciplinary field that embraces not only the natural sciences but also the social and behavioral sciences (Ignaciuk et al., 2012). It studies not only the global systemic processes (e.g., atmospheric composition, biochemical cycling, and ocean circulation) but also local and regional phenomena (e.g., land-use change and biodiversity loss) that cumulatively affect the Earth's processes. Contemporary Earth-system science covers understanding the dynamics and behavior of the Earth system as well as the problems that humans cause and are affected by.

Earth-system science shows that many human activities now match and exceed natural processes within the Earth system (Steffen et al., 2003). Ice-core data, for example, show that current levels of carbon dioxide and methane are well outside the range of natural variability over the last 800 000 years (Jouzel et al., 2007). Over half of the Earth's land surface has been used or degraded by human activities. Humans now fix more nitrogen than nature does (Erisman et al., 2008). Biodiversity loss is nowadays faster than in any historic era (Díaz et al., 2019). Greenhouse gas emissions from human activities alter the planet's energy balance and warm the climate (Intergovernmental Panel on Climate Change [IPCC], 2021). This climate change has adverse effects on, for example, agriculture, water supply, extreme weather events, ecosystems and biodiversity, and human health. Human choices about their resource use are at the heart of many of these changes, which superficially seem unrelated issues.

All local, regional, and global environmental changes in the physical, biogeochemical, and social environments, either caused naturally or influenced by human activities, affect the Earth system, which is the unified set of physical, chemical, biological, and social components, processes, and interactions that together determine its state and dynamics. This system contains all biota, including humans. Humans currently have the largest impact through their activities (e.g., deforestation, fossil-fuel consumption, urbanization, agricultural intensification, freshwater extraction, and waste production). The degree to which all these activities and issues are interlinked is now better understood. This interconnectivity and its unprecedented scale led Crutzen (2002) to label the modern era the Anthropocene.

This rapid emergence of relevant knowledge and understanding stems from many scholars who collaborated in the international global environmental change programs (Box 9.1). These programs were established in the 1980s and coordinated national research initiatives. They were initially strongly natural science based. This is illustrated by the Bretherton Diagram (Earth System Sciences Committee & NASA Advisory Council, 1986) that depicts all the Earth system's processes and their linkages as driven by three "external" factors: the sun, volcanoes, and humans. Only in the 1990s, with the founding of the International Human Dimensions Program (IHDP) on Global Environmental Change and DIVERSITAS, social sciences became slowly more accepted in Earth-system science, but they only became an integral part after the approval of the Amsterdam Declaration that defined major environmental challenges (Moore et al., 2001), and the launch of the Earth System Science Partnership (ESSP). The International Global Change Conference "Planet Under Pressure" (Stafford-Smith et al., 2012) further stimulated this interdisciplinary integration, and this conference initiated a new research network "Future Earth," which focused not only on global environmental change, but also on solutions to global change problems and pathways to sustainability (Reid et al., 2010). Scholars who were leading this network were also instrumental in helping to develop the UN Sustainable Development Goals (SDGs; https://sdgs.un.org/) that were adopted by all the world's nations in 2015. The scientific contributions ensured that all 17 SDGs have specific targets and evidence-based indicators to measure progress. The programs also advised the international conventions, such as on biodiversity (Convention on Biological Diversity [CBD]) and climate change (United Nations Framework Convention on Climate Change [UNFCCC]), and linked them with the SDGs. For example, the Paris Agreement to keep global mean temperature change well below 2°C is both the main aim of the UNFCCC and SDG13 on combating climate change. Overall, the programs successfully coordinated and initiated integrated global change research and created effective interdisciplinary research networks (van der Hel, 2019).

BOX 9.1 GLOBAL CHANGE RESEARCH PROGRAMS

The World Climate Research Program (WCRP, 1980–present; see https://www.wcrp-climate.org): WCRP addresses frontier scientific questions related to the coupled climate system to determine and project the extent of human influence on climate. The World Meteorological Organization (WMO) strongly sponsors WCRP.

The International Geosphere–Biosphere Program (IGBP; 1987–2016): The vision of the IGBP was to provide scientific knowledge to improve the sustainability of the living Earth. IGBP studied the interactions between biological, chemical, and physical processes and how they impact (and are impacted by) human systems.

The International Human Dimensions Program on Global Environmental Change (IHDP; 1990–2014): IHDP was dedicated to promoting, catalyzing, and coordinating interdisciplinary research on the human dimensions of global change. IHDP took a social science perspective on global change and worked at the interface between science and practice.

DIVERSITAS (1991–2015) was an integrated program of biodiversity science. Its mission was to promote an integrative biodiversity science, linking biological, ecological, and social disciplines to produce socially relevant new knowledge, and to provide the scientific basis for the conservation and sustainable use of biodiversity.

The Earth System Science Partnership (ESSP; 2002–2013), which was established by these four programs, facilitated the study of this system in order to understand how and why the Earth system is changing, and to explore the implications of these changes for global and regional sustainability.

Future Earth (2012–present; see https://futureearth.org), which merged IGBP, DIVERSITAS, IHDP, and ESSP, is an active global research network that strategically, and in a transdisciplinary way, collaborates on sustainability challenges. Its focuses on sustainable global futures by developing a deeper interdisciplinary understanding of complex Earth systems and human dynamics. Future Earth especially addresses the interconnectedness of Earth's major systems (climate, water, land, ocean, urban, economic, energy, health, biodiversity, and governance) and develops evidence-based strategies for global sustainable development. Future Earth currently consists of 21 core global change projects.

This recent focus on understanding problems and assessing solutions made clear that traditional research communication (e.g., by publishing in the peer-reviewed literature) is insufficient to make a societal impact. More appropriate transdisciplinary approaches were needed (Leemans, 2016). This chapter describes the emerging transdisciplinary approaches within the global change programs over the last three decades and how they have been mainstreamed in Future Earth. It provides a history of the application of global change research for regional and national policy responses and how these are endorsed internationally. Initially, the programs' societal impact was largest through the so-called science-policy assessments; later, individual projects within the programs experimented with different participatory and co-design/co-production approaches (i.e., emergence of transdisciplinarity); and finally, transdisciplinarity became common in Future Earth's research networks. This chapter presents this history, provides the (early) lessons learned, and gives a short outlook.

THE EARLY TRANSDISCIPLINARITY OF SCIENCE-POLICY ASSESSMENTS

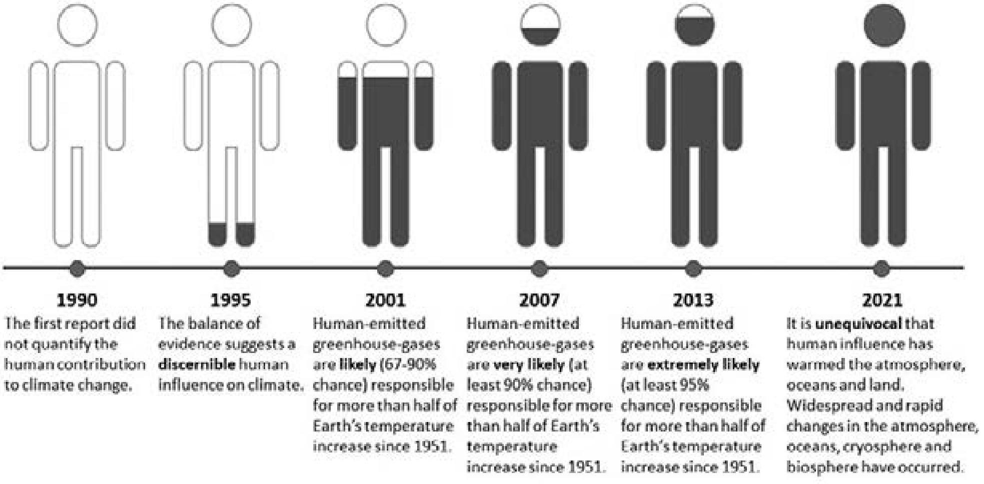
In the 1980s, as understanding the Earth system became more robust and uncertainties were reduced, the global change programs started to influence environmental policies. The first major problem that was assessed and presented to policy makers was stratospheric ozone depletion. Since the late 1970s, scientists observed a steady lowering of the ozone concentrations in the Earth's ozone layer and a much larger springtime decrease in stratospheric ozone around the Earth's polar regions. Later, the so-called ozone hole was detected over Antarctica (Farman et al., 1985). Ozone depletion is caused by several human-made chemicals (e.g., halocarbon refrigerants, solvents, and propellants) that mix well and reside for centuries in the atmosphere. Together with nitrous oxide, they catalyze the ozone to oxygen reaction.

In response to attacks on the science and lobbies to governments by representatives of the halocarbon industries, WCRP (Box 9.1) scholars started to collaborate with national and international organizations to synthesize all relevant knowledge (including knowledge gaps and uncertainties) on ozone depletion and its consequences in a so-called *science-policy assessment*. This multidisciplinary assessment informed governments on the actual ozone depletion's "state-of-the-art" science and its consequences. The first was published in 1985, and others followed (e.g., https://csl.noaa.gov/assessments/ozone/). These assessments strongly influenced policy makers and facilitated the quick political realization of the Montreal Protocol on reducing ozone-depleting substances in 1987. Many nations reduced and phased out their use of ozone-depleting chemicals, and industries developed alternatives. Currently, the ozone hole is getting smaller, and ozone depletion will soon be reversed.

The success of the ozone assessment spurred several other international assessments. In 1986 the United Nations Environment Program (UNEP), the World Meteorological Organization (WMO), and the International Council of Science (ICSU) jointly established the Advisory Group on Greenhouse Gases, which was expected to produce a report on the greenhouse effect and its consequences. WMO and ICSU, however, disagreed with UNEP's strong political mandate to this group. This jeopardized the scientific quality and impact of the report. They encouraged Dr. Bolin, a Swedish WCRP meteorologist, to initiate a more rigorous, science-based assessment process (Bolin, 2008). This resulted in the IPCC, whose first assessment report (Houghton et al., 1990) was published in 1990. This report helped to frame the objective of the UNFCCC, which was to "achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992). The IPCC assessment report has been updated every six years. Over time, the assessed science became more robust, and uncertainties were reduced (Figure 9.1). The IPCC's third assessment report also motivated the well-below 2°C target in UNFCCC's Paris Agreement (Leemans & Vellinga, 2017; Smith et al., 2001). Although worldwide greenhouse gas emissions have continuously increased since 1990, the IPCC assessments have always shown climate change mitigation scenarios that comply with the Paris Agreement. These scenarios are only possible, however, if ambitious mitigation measures for all greenhouse gases are implemented by all countries, and if the available carbon sinks are strengthened. Global emissions and carbon sequestration should be net zero by 2050. Such carbon neutrality is already politically pursued by several countries. The IPCC reports have been instrumental in providing the motives for such policies.

The IPCC's motto has always been to be policy relevant and not policy prescriptive. Its strength is not only how its procedures combine scientists' understanding and policy makers' needs (cf. co-design), but also the rigor and transparency of its review processes, the use of published peer-reviewed literature (and clear guidelines on how to handle, cite, and make available grey literature), and the useful hierarchy of its products (each assessment report consists of three independent working group reports and a synthesis report; each report consists of chapters, with a summary, synthesizing the scientific literature, a long technical summary, and a concise summary for policy makers).

Every IPCC assessment process starts with IPCC's plenary meeting that includes national governmental delegations and observers (e.g., UNEP, ICSU, WMO, and representatives of the global change programs). This plenary discusses and agrees on the report's outline, which covers all the policy questions that need to be addressed. Then author teams are identified and approved by the plenary. These teams draft their chapters, following the outlines and guided by IPCC instructions on, for example, characterizing uncertainties. All chapters are thoroughly reviewed by international experts and IPCC's member countries and their experts. All comments and responses are documented and archived. The summary for policy makers, which is drafted by selected authors, follows a different path. The assessment's final plenary meeting discusses this summary verbatim, and all delegations agree on the content and the final wording. The lead authors participate in these discussions and guarantee that the summary is consistent with the science. The final acceptance of this summary means that the text not only



Note: Shading indicates the likelihood of human-caused warming.
Source: Adapted from https://www.ipcc.ch/.

Figure 9.1 Summary of the findings and wording of the subsequent IPCC reports on human influence on the climate system

provides the scientific consensus but, more importantly, is also agreed upon by all countries and thus their governments. Despite some criticism (e.g., Adler & Hirsch Hadorn, 2014; Sanford et al., 2021), IPCC's assessment reports always had a large policy impact (Hulme et al., 2011; Lynn, 2018).

Envious of the success and policy influence of the IPCC reports, a group of ecologists and social scientists started a global biodiversity assessment in 1993. An impressive synthesis of the biodiversity literature was published (Heywood & Watson, 1995), but it was ignored by policy communities and CBD delegates, who were unaware of the assessment process and thus had no influence on its content, like in the IPCC. Having learned from this fiasco, the Millennium Ecosystem Assessment (MA) reached out in 1998 to various constituencies, such as UN agencies (e.g., UNEP, the Food and Agriculture Organization [FAO], and Development Programs [UNDP]) and conventions (e.g., on desertification, biodiversity, wetlands, and climate change), governments, conservation organizations, and other nongovernmental organizations (NGOs, such as ICSU, CGIAR Consortium of International Agricultural Research Centers, World Bank, World Resources Institute, and the World Conservation Union), and businesses (e.g., World Business Council for Sustainable Development). This assessment thus had a much broader constituency than IPCC and therefore was not governed by an intergovernmental plenary, but a board that represented its diverse constituency (Leemans, 2008). This created more effective transdisciplinary interactions between scientists and all the stakeholders.

The Assessment Board obtained funding from many different sources and established a multi-scale assessment with several working groups: Current Status (last century); Scenarios (next century); Policy Responses; and Regional Assessments (including Indigenous information). Each working group was led by two chairs: one ecologist and one economist; one from a developed and one from a developing country. Other issues, such as gender and geographical representation, were also contemplated. Addressing these diversities appropriately also better represented the "Global South." The MA suffered less from the "northern hemisphere" science domination of IPCC. For example, the Southern African Assessment (Scholes et al., 2004) set the tone for many other local and regional assessments.

In all meetings, representatives from the constituents collaborated with experts. The concept of ecosystem services (e.g., Daily, 1997; de Groot, 1992) was selected to link biodiversity to ecosystem management, locally and regionally. The first meetings focused on developing a conceptual framework to better integrate the different scientific disciplines and user communities (MA, 2003). This framework kickstarted MA's interdisciplinary approaches and helped to integrate the natural and social sciences with various management and economic fields. DIVERSITAS was strongly involved in the MA. The assessment process started in 2001 and was concluded in 2005 with the publication of the working group reports and press conference and seminars in 13 major cities. The Board published a synthesis report and stimulated the writing of dedicated reports for different constituencies (https://www.millenniumassessment.org/en/Reports.html). Ecosystem services are now fully established in conservation management, and this boosted biodiversity management outside the already protected areas in many countries.

The MA was organized as a one-time project. However, in 2010 the biodiversity policy and research communities established another assessment body, the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES; https://ipbes.net/stakeholders). This platform brings together scientific experts and policy makers and advises various biodiversity and other conservation conventions and multilateral environmental agreements. It is now well established, has strong outreach and unique capacity-building, and includes participatory components of not only national policy makers and internationally renowned scientists, but also other stakeholders, including Indigenous people. In response to requests from (Indigenous) stakeholders, IPBES altered the ecosystem services concept and is now focusing on nature's contribution to people and the fabric of life (Pascual et al., 2017). IPBES is thus the most transdisciplinary of all science-policy assessments. It published guidelines on how to assess information and on methodologies for models and scenarios, and assessed biodiversity, pollination, and food production and pandemics. All their reports undergo a rigorous review process that is similar to that of the IPCC, and they are highly appreciated by the international, national, and regional policy and conservation communities (Díaz et al., 2019).

Although the earlier assessments already inspired policies, the assessment processes have matured over the years and their societal and policy impacts increased. This is also illustrated by their frequent and detailed media coverage. They now provide an excellent information and knowledge base (including uncertainties and confidence statements, and highlighting the consequences of specific, combinations of, or no-policy measures) to address major environmental challenges. Their review processes have resulted in scientific consensuses and mainstreamed new concepts and insights. Although not intended by the assessments, they also advanced research agendas. Additionally, they are now affecting not only international policy makers but also various other constituencies that either cause or are affected by the problem. Advanced assessment toolkits and guidelines (e.g., Pereira et al., 2021) are now available, and these help to further delineate other assessments, including local and national ones that many countries recently initiated.

In conclusion, science-policy assessments have pioneered how scientists interact better with policy makers and other constituencies. One important lesson learned is that these assessments are not just literature reviews but broader syntheses of the scientific understanding. Literature reviews are done by one or more researchers (probably with a specific research agenda) and target other researchers, but rarely explicitly address broad societal problems and their uncertainties. Science-policy assessments are conducted by large and varied expert groups, include several layers of review, and explicitly involve policy makers and other constituencies. They must highlight uncertainties and synthesize all information so that the whole problem's complexity is tackled (Leemans, 2008). These assessments provide a rich and credible knowledge base for policy development. Finally, the most important lesson is that assessments' constituencies must be included from the start. This has certainly contributed to their societal and policy impacts and makes the science-policy assessments transdisciplinary *avant-la-lettre*.

EMERGENCE OF TRANSDISCIPLINARITY GLOBAL CHANGE RESEARCH

Science-policy assessments generally only synthesize the latest scientific developments and their consequences and uncertainties. They only focus on existing knowledge and do not aim to develop or evaluate policies. In the 1990s, policy-relevant *integrated assessment models* were developed to fill this void. These models simulate the future of complex environmental problems and test plausible solutions, for example, through scenarios. These models soon became imbedded in the different global change programs and were their most important integrating tools. Initially, the models were strongly based on economics or technology (e.g., Nordhaus, 1993), but they quickly became more interdisciplinary and included also physical, chemical, and ecological processes and a spatial differentiation to assess emissions and impacts in different regions and sectors (e.g., RAINS, Alcamo et al., 1990; and IMAGE, Alcamo et al., 1998). The successors of these models are, to date, essential to quantify the scenarios that are used in the science-policy assessments (e.g., Riahi et al., 2017; van Vuuren et al., 2011). Although these advanced models described society and assessed (policy) responses, they were often only used as scientific tools to understand the underlying complexity (e.g., interactions and feedbacks between processes, and spatial heterogeneity) and to project plausible future trends. Their results were published scientifically and used in the science-policy assessments (e.g., emission scenarios), but their modelers did not systematically connect with policy communities.

A few exceptions existed. In 1995, the Dutch government, for example, initiated a science-policy dialogue with the IMAGE team and UNFCCC negotiators from European and vulnerable developing countries, including the Alliance of Small Island-States (AOSIS) countries (Alcamo et al., 1998). This dialogue illustrated how the policy needs rapidly changed over time and poorly met the scientists' possibilities and tools. Initially, the policy makers were highly interested in the robustness of the IMAGE model and the lessons learned from its long-term scenarios. This part of the dialogue importantly developed trust between the IMAGE team and the negotiators, but after 1996, when the Kyoto negotiations approached, the negotiators' needs switched. As industrialized countries (the so-called Annex-1 countries in the UNFCCC; United Nations, 1992) should reduce their emissions first, the focus shifted to these countries and to their possibilities for short-term emission reductions. This new focus jeopardized IMAGE's utility because its long-term scenarios only diverged after several decades. One of the negotiators, however, proposed to link the necessary long-term climate protection goals with the required short-term emission reductions. He simply asked which reductions would comply to the long-term goals. This challenging question resulted in an innovative regression model, the "safe-landing" approach (Alcamo et al., 1998), which indicated how much emissions must be reduced to allow for long-term climate protection. The negotiators took the approach and its results into the Kyoto negotiations, and this probably influenced its final emission-reduction targets. Another effect was that other countries became interested in this not-yet-scientifically published approach (as documenting and publishing in the peer-reviewed literature takes time), and requested their national experts to validate the results. This stimulated others to implement similar approaches in their models. Later, such approaches became mainstreamed as guardrail approaches (Dowlatabadi, 1999), but few were used in science-policy dialogues because the window to influence the Kyoto targets quickly closed after 1997. The success of such science-policy dialogues showed that co-design/co-production or transdisciplinary approaches were essential to improve integrated assessment models, add innovative applications, and enhance their utility for policy making.

However, such transdisciplinary model- or scenario-based approaches remained rare in the 1990s, and most of them were criticized as being incomplete, too simple, too future oriented, and certainly not scientific. Currently they are more conventional, but this acceptance process took much time, debate, and persuasion (by seminal publications in high-impact journals). Part of this debate focused on the question of whether transdisciplinary approaches were always needed or even preferred to identify, test, and implement solutions (Figure 9.2). This debate concluded that simple environmental problems (i.e., known causes and effects) could be best addressed by disciplinary approaches. Their solutions can be straightforwardly implemented by regulation or by creating unambiguous (national or local) legislation. More complex problems (multiple causes and effects, and deep uncertainties) require insights from multidisciplinary research (i.e., multiple disciplines contribute their own insights, that are subsequently integrated) to develop solutions that are integrated into skeleton legislation with desirable targets (e.g., ozone depletion). Complex environmental problems (multiple causes, effects, and interactions that together create non-linear systemic dynamics and behavior, and poorly known uncertainties; heterogeneous worldviews and social and cultural norms; and interacting regional, national, and international dimensions) require interdisciplinary research (i.e., disciplines collaborate based on a common conceptual framing or integration from the start), science-policy dialogues, and (inter)national policy negotiations to build agreements on effective and consensual policy-response strategies. Such problems can best be addressed by transdisciplinary inquiries that involve scientists from multiple disciplines, and policy makers who operate at various scales (Mauser et al., 2013).

The Amsterdam Declaration (Moore et al., 2001) affected Earth-system research by broadening the curiosity-driven and basic research to research that contributed to solving the identified environmental challenges. Earth-system research started to shift toward more inter- and transdisciplinary research. The establishment of ESSP (Box 9.1) stimulated collaboration between the various global change programs and established several successful integrated and interdisciplinary projects on carbon, water, health, and food, to which all other programs contributed (Ignaciuk et al., 2012; Uhrqvist & Linnér, 2015). In general, such interdisciplinary teams were slow to become scientifically productive (in comparison to disciplinary research), but their publications were much better cited scientifically and in the media, and thus had

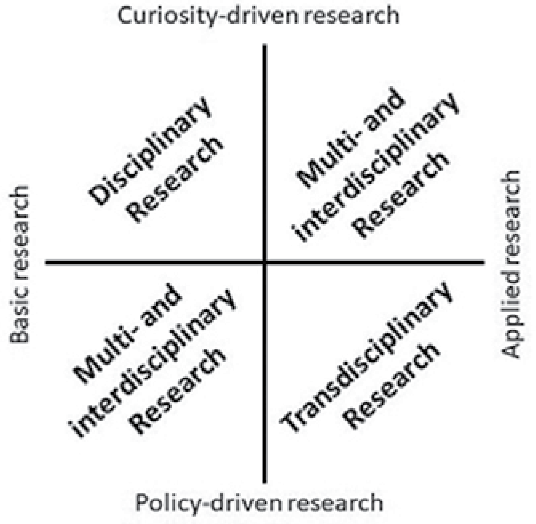


Figure 9.2 *The domain of transdisciplinary research within an ordination of various research motivations*

a larger impact (Hall et al., 2012; Larivière & Gingras, 2010). The global change programs' focus on solving problems and sustainability led to several policy-evaluation studies. For example, the questions, "Are the politically agreed 2010 biodiversity targets met?" (Mooney & Mace, 2009), "Are the Copenhagen climate accords adequate?" (Rogelj et al., 2010), and "How can we avoid biodiversity loss (Pereira et al., 2010) and climate change?" (van Vuuren et al., 2011) were carefully addressed.

Over time, several global change research projects also incorporated stakeholder involvement. This was stimulated by a few funding agencies. For example, the European Union's (EU) fifth and subsequent framework-research programs aimed to enhance the project's policy relevance, and requested stakeholder involvement to improve the timeliness and utility of a project's research.[1] Additionally, such involvement stimulates mutual learning among researchers and stakeholders, and this likely increased the project's societal (or policy) relevance. This is illustrated by the ATEAM project (Schröter et al., 2005), which assessed the vulnerability of Europe's sectors (e.g., agriculture, forestry, water, and tourism) and ecosystem services (e.g., biodiversity, biomass, and carbon sequestration) through a set of harmonized climate, land-use, and adaptation change scenarios. Stakeholders were essential to define sectoral or regional vulnerabilities. When land-use scenarios indicated that land would be abandoned in the Mediterranean, the scientists assumed that this would revert to natural vegetation (and thus more carbon sequestration and biodiversity), but stakeholders feared for bush encroachment and subsequent forest fires (that are currently observed). These insights led to including modeling forest-fire risks and multiple adaptation pathways. Although the interactions with stakeholders proved useful and productive, some pitfalls were also observed. For example, some stakeholders promoted their local hobby horses. Additionally, ATEAM did not fund the stakeholders to connect to their constituents, and they therefore did not start

Table 9.1 Guiding principles for Future Earth

Promote scientific excellence	FE supports science of the highest possible quality
Link Earth systems research to global sustainability	FE focuses on integrated Earth systems research and global sustainability but builds on national environment and development research
Is international in scope	FE focuses on areas where international research coordination is needed
Promote integration	FE draws on expertise in natural and social sciences, as well as engineering, the humanities, and professions such as planning and law
Encourage co-design and co-production	FE's research agenda and programs are co-designed and, where possible, co-produced by researchers in collaboration with various stakeholders in governments, business, international organizations, and civil society
Is bottom-up driven	FE's approach emphasizes the importance of "bottom-up" ideas from the research community and other stakeholders in designing projects that respond to sustainability challenges
Provide solution-oriented knowledge	FE provides foresight of changes and risks, evaluates the effectiveness of responses, and supports a knowledge base for new innovations and policies
Is inclusive	FE includes existing international global change programs and projects and related international activities; regional engagement, geographic and gender balance, capacity-building, and networking are emphasized
Is responsive and innovative	FE's governance and organizational structure are fit-for-purpose, leave room for adaptation as FE develops, and enable changes in the delivery of sustainability research
Is sensitive to its environmental footprint	FE considers its environmental impacts; for instance, its operations should be climate neutral

Source: Adapted after Liverman et al. (2013).

adapting or reducing their vulnerabilities. ATEAM's societal impacts were probably small, as solutions were not implemented.

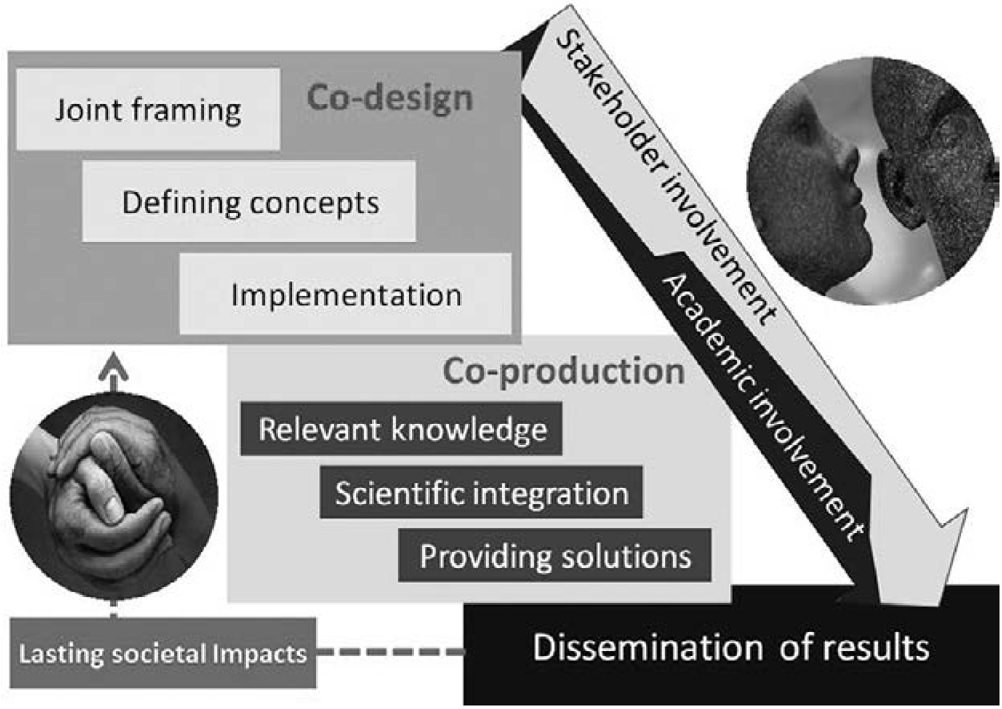
In 2012, the global change programs organized the Planet Under Pressure Conference (Stafford-Smith et al., 2012) as a response to the grand challenges of sustainability (Reid et al., 2010). Here, the programs[2] announced that they and other activities would merge into a new program called Future Earth (https://futureearth.org/; see Chapter 29). Future Earth endorses critical knowledge to help societies face the challenges posed by global environmental change and identify opportunities for the urgent sustainability transition. It delivers high-quality research, integrating natural and social sciences disciplines (including economic, legal, and behavioral research), engineering, and humanities. Its research is co-designed and co-produced, and governed by academics, governments, business, media, and civil society, including Indigenous communities, and involves people from all regions of the world. It not only focuses on understanding changing environments and societies, but also provides solutions and helps stakeholders to implement them (Liverman et al., 2013). Future Earth is an obvious evolution of ESSP's integrated projects and its observation that the societal challenges require overarching integrated nexus approaches that cover different dimensions and scales. Future Earth's guiding principles (Table 9.1) facilitate and stimulate transitions to sustainability. Future Earth is not just a new international and interdisciplinary research program, but operates more as a coordinated research network that establishes communities of practice that engage in co-design/co-production approaches and collaborate with international stakeholders to address sustainability challenges (Schneider et al., 2021; van der Hel, 2019). Schneider et al. (2021) develop, for example, different transdisciplinary actions: "connecting actors and scales"; "supporting network communities"; "pushing the community's transformative power"; and "innovating networks."

Early in Future Earth's planning phase, a workshop on co-designing/co-producing knowledge was organized (Mauser et al., 2013), recognizing that applied and policy-driven research questions are derived from societal needs. Established scientific methodologies should be supplemented by new, innovative transdisciplinary approaches and processes so that research results assist societies to act. Although valuable, science-policy assessments, science-policy dialogues, and just informing stakeholders were deemed inappropriate (cf. Fraude et al., 2021). Workshop participants immediately also accepted that lack of disciplinary integration rarely resulted in adequate knowledge and applications.

Additionally, Mauser et al. (2013) elaborated on the different dimensions of knowledge integration: *scientific* (knowledge, theories, and concepts from different disciplines); *international* (including relevant knowledge across countries, regions, cultures, and societies); and *sectoral* (expertise from institutions, markets, and civil society sectors that helps to achieve a mutual understanding of the necessary research domains). They also proposed a framework of co-design and co-production integration (Figure 9.3). This framework consists of three steps in which stakeholders and scientists have different responsibilities. In the co-design phase, stakeholders pose questions on their actual global change or sustainability problems and discuss them with researchers who check if these questions are "researchable." This framing defines the research, after which researchers select appropriate (disciplinary and interdisciplinary) approaches to address all questions. Consistency, uncertainties, and robustness of the resulting findings are explicitly addressed, and findings are regularly exchanged with the stakeholders. This could lead to rephrasing a question (or creating a more precise new question) but also to accepting successful solutions. The researchers publish the findings in academic publications, and the stakeholders encourage their constituencies to implement the solutions and hopefully document this process (which can also be done by researchers). The implemented solutions probably will lead to new research questions, which again should be jointly framed. This initiates a new transdisciplinary research cycle.

Finally, Mauser et al. (2013) identified essential challenges for co-design, co-production, and co-dissemination of knowledge:

- *Develop new processes and skills:* Integration and stakeholder involvement requires both strong social and process-oriented skills (inter-personal, communication, and facilitation) and organizational and managerial competencies. This likely requires professional support (a facilitator) or training;
- *Deal with inertia to change:* Integration requires critical reflections on the role of science (and its disciplines) in transdisciplinary inquiry and on the limitations of doing traditional multidisciplinary research. This probably requires an uncomfortable willingness to change and shift to new (uncharted) approaches;
- *Clarify roles, responsibilities, and rules of engagement:* Integrated research coordination bridges the entire research process. Different stakeholders likely have different roles in different parts of the project (see Figure 9.3). This requires clarity about their roles and responsibilities, about who makes decisions when, and about how to appropriately maintain scientific integrity and quality standards;
- *Establish integrated institutions:* The discipline-based practices and structures of existing educational and research systems rarely favor integrated and transdisciplinary research efforts. They need to be supplemented with new, better-integrated structures;



Source: Adapted from Mauser et al. (2013) and Liverman et al. (2013).

Figure 9.3 The conceptual approach of transdisciplinarity or co-design/co-production of research in Future Earth's initial design

- *Develop support systems:* Academic reward, review, and career-advancement systems and funding mechanisms must be adapted. Integration and transdisciplinarity calls for a critical review of such systems; and
- *Remove persistent inequalities:* Academic research is inundated by persistent inequalities in terms of access to power and resources, and research capacities. This makes the necessary collaboration with different stakeholders that transdisciplinarity calls for challenging.

Over the last decade, science-policy dialogues and stakeholder involvements have been mainstreamed. However, too many project proposals and projects still only inform stakeholders on the outcomes at the project's completion. Stakeholders therefore do not have equal power and influence (see Chapters 5 and 27). They do not pose the questions, and the resulting research is probably irrelevant. Stakeholders should be integrated into the project from the start. Mauser et al. (2013) proposed an approach (but with major challenges) to achieve this, and Future Earth has started to implement it.

IMPLEMENTATION OF TRANSDISCIPLINARY GLOBAL CHANGE RESEARCH

Many co-design and co-production processes in global change research projects have been implemented, but most of them are still ongoing and not yet fully documented or reflected upon. We will present and discuss the early lessons learned from these ongoing transdisciplinary studies within Future Earth by focusing on their goals and societal achievements.

Strong and successful co-design and co-production projects, which are coordinated by researchers, generally focus on better understanding the relevant global change challenges to develop actionable products by meaningfully combining and applying insights and data (e.g., Findlater et al., 2021). The main responsibility of researchers are these products (e.g., indicators and scenarios), while the stakeholders apply them to make informed decisions (and define policies). This has been, for example, apparent in the development, supply, and application of climate services, which aim to link climate science to policy needs and to build capacity to anticipate, plan for, and adapt to climate change. Alpízar et al. (2019) describe how three years of climate-adaptation services research and local stakeholder workshops on many community water systems in an arid region of Central America did not lead to better water management practices. They show that add-on and poorly funded workshops do not create impact. Buy-in and building trust between the stakeholders and their communities and scientists was insufficient. Continuous interactions that focused more on the stakeholders' needs and research possibilities should have been organized throughout the research project (see Figure 9.3) to develop better products and applications, and not just "academic" products (Tengö & Andersson, 2022). This trap was already obvious from the science-policy assessments and earlier stakeholder involvements.

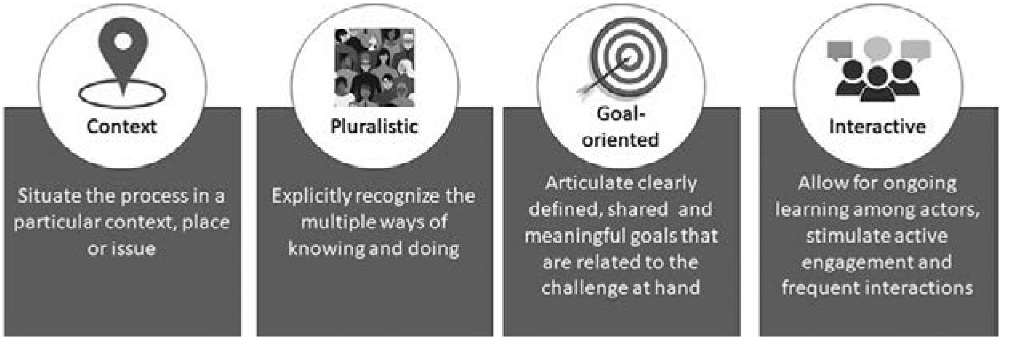
Moreover, the currently generated knowledge products generally refer to one system, region, country, or sector. This hampers their applicability, as many interactions between systems, regions, countries, and sectors exist (e.g., trade between countries, rivers that link land to oceans, land–ocean–climate interactions). These interactions are generally ignored, and this results in inadequate system descriptions and models. Recently, however, interactions are explicitly addressed in so-called NEXUS approaches that combine multiple challenges, systems, or regions (e.g., Cremades et al., 2019). These approaches that also include a feasible science-policy integration and cross-scale inequalities, and that address path-dependencies in infrastructure and socio-institutional practices (Romero-Lankao et al., 2017), are, however, still rare in co-design/co-production research.

Alpízar et al.'s (2019) example also shows that the implementation of transdisciplinary research is likely also hampered by the lack of funding and institutional support. A strong policy impact of scientific knowledge commits researchers to engage with policy and practitioner communities beyond their conventional research (cf. Ruckelshaus et al., 2020). Such engagement also requires funding, but transdisciplinary approaches are rarely funded by "traditional" science-funding foundations. Even the Belmont Forum (an international partnership of national funding agencies that sponsors collaborative research for Future Earth; http://www.belmontforum.org/) focused mainly on interdisciplinary research projects. Only its last call, "Pathways 2020," specifically addressed transdisciplinary research for sustainability.

Chambers et al. (2021) comprehensively analyzed 32 transdisciplinary local, regional, and global projects from around the world. The projects dealt with several sustainability issues, such as climate change, habitat degradation, wildfires, and supply chains, and clearly showed the increasing interests in transdisciplinary research. All projects involved collaborations among researchers, governments, NGOs, and community actors. The stakeholders ranged from business CEOs and urban planners to Indigenous leaders and artists. The projects applied very diverse approaches for co-design and co-production (e.g., participatory modeling or learning networks). The projects' purpose (What is co-produced?), power (How is human agency conceptualized?), politics (How are power relations changed?), and pathways (How are impacts catalyzed?) were determined. This resulted in six co-production modes, which are summarized below:

1. *Researching solutions* aims to produce policy-relevant knowledge. The resulting insights supported the already motivated decision-makers who participated. This mode is effective when relationships, questions, and methods evolve and are adapted to relatively small policy changes.
2. *Empowering voices* addresses ecosystem management and policy challenges. Interdisciplinary researchers led these projects and (marginalized) community and/or government stakeholders participated and were actively engaged. Meaningful local solutions were created and useful narratives were produced. However, the outcomes were often ignored by top decision-makers, and this hindered the desired outcomes.
3. *Brokering power* engaged powerful stakeholders to develop long-term innovative institutions to address sustainability challenges by fostering a dialogue around synthesized knowledge. The stakeholders took immediate policy management actions.
4. *Reframing power* engaged both marginalized and powerful stakeholders to reframe technocratic narratives and shift practices and policies that marginalize social concerns. The leading researchers explicitly tried to shift power toward the marginalized stakeholders by reframing dominant views. However, only few cases slightly shifted policy and practice.
5. *Navigating differences* emphasized managing processes to collaborate, learn, and empower. Stakeholder groups explored conflicts and reframed worldviews, while allowing new institutions, regulations, and practices to emerge. This reframing focus (instead of generating solutions) allowed stakeholders to identify and solve conflicts, and build complementary policy and management processes.
6. *Reframing agency* used co-production to solve environmental problems. Systems-thinking researchers led the projects and created safe spaces to address systemic governance issues. Diverse knowledge forms were expressed and motivated change in local contexts. Emotional and psychological anxieties related to questioning power and beliefs were explored. This effectively triggered reframing and trained all participants to employ co-production approaches in their own work.

Recently, several other reflection papers were published on principles and modes of co-production (e.g., Cremades et al., 2019; Norström et al., 2020). Norström et al. (2020) advocated for specific principles to which co-production projects should be assessed and adhered (Figure 9.4). These principles show how to engage in meaningful co-productive practices and how to evaluate their quality and success. These papers observe that the inclusion of stakeholders with a narrow mandate (e.g., biodiversity conservation officers) recently shifted to broader communities that also include (informal) users and other (potentially) reliant stakeholders (e.g., Indigenous people, entrepreneurs, and tourists). They also show that the production, application, and uptake of scientific knowledge is currently viewed as complex, iterative processes that are interlinked and co-evolve. Cairney and Oliver (2020) go even further by stating that transdisciplinary researchers should also become "policy entrepreneurs" to "find out where the action is, learn the rules of the game, form alliances, frame your evidence in relation to the dominant language of policy debate, and respond to socioeconomic context and events which help create windows of opportunity" (p. 238). All these valuable insights will certainly help to mainstream co-design and co-production in global change research and show funding agencies that these approaches are important to have societal impacts and thus should be funded as an integral part of a project and not as just an add-on.



Source: Adapted from Norström et al. (2020).

Figure 9.4 Principles for knowledge co-production in sustainability research

CONCLUDING REMARKS

We described the development of transdisciplinarity in the international global change programs. These programs initially informed society and affected policies through successful science-policy assessments that synthesized the state-of-the-art understanding of global change issues. This success was largely because of their credibility (scientifically correct information), salience (relevant stakeholder information), and legitimacy (unbiased processes and all necessary values, concerns, and perspectives are considered; Cash et al., 2003). Later, the programs developed more interdisciplinary approaches and applied integrated assessment models, science-policy dialogues, and stakeholders' participation. These approaches primed the programs to tackle not only individual global change problems but also the overarching sustainability challenges. The programs recently merged into the research network "Future Earth" (Box 9.1) that effectively links to and collaborates with NGOs, UN organizations, and conventions (Schneider et al., 2021; van der Hel, 2019). Future Earth also mainstreams transdisciplinarity to strengthen these collaborations.

Various studies (e.g., Chambers et al., 2021; Norström et al., 2020; Schneider et al., 2021) clearly show that Future Earth's transdisciplinary research is now mature. Their analyses also imply that many different approaches have evolved, each tailormade to specific needs and conditions. Future Earth's communities combine and focus differently on policy actions and needs (see Chapter 29). Their objectives and the selected approaches and activities are thus heterogeneous, depending on specific applicability domains.

Transdisciplinarity in global change research will likely continue to advance the science, identify new stakeholders, address emerging problems, develop new methods, and incorporate insights from more disciplines, such as political, management, and engineering sciences. Transdisciplinarity thus continues to evolve. Advancing transdisciplinarity and inspiring sustainability transitions urgently need institutional recognition, appropriate funding mechanisms, and active communities of practice that engage young scientists.

NOTES

1. This stakeholder involvement, together with the EU's commitment to involve smaller enterprises in research projects, led to the establishment of companies, such as PROSPEX, to facilitate stakeholder involvement.
2. WCRP continued as a separate international research programme, sponsored by WMO and ICSU, but closely collaborates with Future Earth.

REFERENCES

Adler, C. E., & Hirsch Hadorn, G. (2014). The IPCC and treatment of uncertainties: Topics and sources of dissensus. *WIRES Climate Change, 5*, 663–676.

Alcamo, J., Leemans, R., & Kreileman, G. J. J. (1998). *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*. Pergamon & Elsevier Science.

Alcamo, J., Shaw, R., & Hordijk, L. (1990). *The rains model of acidification*. Kluwer Academic Publishers.

Alpízar, F., Bernedo Del Carpio, M., Ferraro, P. J., & Meiselman, B. S. (2019). The impacts of a capacity-building workshop in a randomized adaptation project. *Nature Climate Change, 9*, 587–591.

Bolin, B. (2008). *A history of the science and politics of climate change. The role of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Cairney, P., & Oliver, K. (2020). How should academics engage in policymaking to achieve impact? *Political Studies Review*, *18*, 228–244.

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., … Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences, 100*, 8086–8091.

Chambers, J. M., Wyborn, C., Ryan, M. E., Reid, R. S., Riechers, M., Serban, A., … Pickering, T. (2021). Six modes of co-production for sustainability. *Nature Sustainability, 4*, 983–996.

Cremades, R., Mitter, H., Tudose, N. C., Sanchez-Plaza, A., Graves, A., Broekman, A., … Marin, M. (2019). Ten principles to integrate the water–energy–land nexus with climate services for co-producing local and regional integrated assessments. *Science of the Total Environment, 693*, 133662.

Crutzen, P. J. (2002). Geology of mankind: The Anthropocene. *Nature, 415*, 23.

Daily, G. C. (Ed.). (1997). *Nature's services. Societal dependence on natural ecosystems*. Island Press.

de Groot, R. S. (1992). *Functions of nature: Evaluations of nature in environmental management and decision making*. Wolters-Noordhof.

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., … Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science, 366*, eaax3100.

Dowlatabadi, H. (1999). Climate change thresholds and guardrails for emissions – An editorial comment. *Climatic Change, 41*, 297–301.

Earth System Sciences Committee, & NASA Advisory Council. (1986). *Earth system science. A program for global change*. National Academies Press.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience, 1*, 636–639.

Farman, J. C., Gardiner, B. G., & Shanklin, J. D. (1985). Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. *Nature, 315*, 207–210.

Findlater, K., Webber, S., Kandlikar, M., & Donner, S. (2021). Climate services promise better decisions but mainly focus on better data. *Nature Climate Change, 11*, 731–737.

Fraude, C., Bruhn, T., Stasiak, D., Wamsler, C., Mar, K., Schäpke, N., … Lawrence, M. (2021). Creating space for reflection and dialogue: Examples of new modes of communication for empowering climate action. *GAIA – Ecological Perspectives for Science and Society, 30*, 174–180.

Hall, K. L., Stokols, D., Stipelman, B. A., Vogel, A. L., Feng, A., Masimore, B., … Berrigan, D. (2012). Assessing the value of team science: A study comparing center- and investigator-initiated grants. *American Journal of Preventive Medicine, 42*, 157–163.

Heywood, V. H., & Watson, R. T. (Eds.). (1995). *Global biodiversity assessment*. Cambridge University Press.

Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (Eds.). (1990). *Climate change: The IPCC scientific assessment*. Cambridge University Press.

Hulme, M., Mahony, M., Beck, S., Görg, C., Hansjürgens, B., Hauck, J., … van der Sluijs, J. P. (2011). Science-policy interface: Beyond assessments. *Science, 333*, 697–698.

Ignaciuk, A., Rice, M., Bogardi, J., Canadell, J. G., Dhakal, S., Ingram, J., … Rosenberg, M. (2012). Responding to complex societal challenges: A decade of Earth System Science Partnership (ESSP) interdisciplinary research. *Current Opinion in Environmental Sustainability, 4*, 147–158.

Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., … Wolff, E. W. (2007). Orbital and millennial Antarctic climate variability over the past 800 000 years. *Science, 317*, 793–796.

Larivière, V., & Gingras, Y. (2010). On the relationship between interdisciplinarity and scientific impact. *Journal of the American Society for Information Science and Technology, 61*, 126–131.

Leemans, R. (2008). Personal experiences with the governance of the policy-relevant IPCC and millennium ecosystem assessments. *Global Environmental Change, 18*, 12–17.

Leemans, R. (2016). The lessons learned from shifting from global-change research programmes to transdisciplinary sustainability science. *Current Opinion in Environmental Sustainability, 19*, 103–110.

Leemans, R., & Vellinga, P. (2017). The scientific motivation of the internationally agreed "well below 2°C" climate protection target: A historical perspective. *Current Opinion in Environmental Sustainability, 26–27*, 134–142.

Liverman, D., Rockström, J., O'Brien, K., Visbek, M., Leemans, R., Abrahamse, T., … Seitzinger, S. P. (2013). *Future Earth initial design*. The Science and Technology Alliance for Global Sustainability.

Lynn, J. (2018). Communicating the IPCC: Challenges and opportunities. In W. Leal Filho, E. Manolas, A. M. Azul, U. M. Azeiteiro, & H. McGhie (Eds.), *Handbook of climate change communication: Vol. 3: Case studies in climate change communication* (pp. 131–143). Springer International Publishing.

Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B. S., Hackmann, H., Leemans, R., & Moore, H. (2013). Transdisciplinary global change research: The co-creation of knowledge for sustainability. *Current Opinion in Environmental Sustainability, 5*, 420–431.

Millennium Ecosystem Assessment. (2003). *Ecosystems and human well-being: A framework for assessment*. Island Press.

Mooney, H., & Mace, G. (2009). Biodiversity policy challenges. *Science, 325*, 1474.

Moore, B., Underdal, A., Lemke, P., & Loreau, M. (2001). The Amsterdam Declaration on global change. In W. Steffen, J. Jäger, D. Carson, & C. Bradshaw (Eds.), *Challenges of a changing Earth: Proceedings of the Global Change Open Science Conference* (pp. 207–208). Berlin Springer-Verlag.

Nordhaus, W. D. (1993). Rolling the DICE: An optimal transition path for controlling greenhouse gases. *Resource and Energy Economics, 15*, 27–50.

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., … Österblom, H. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability, 3*, 182–190.

Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., … Yagi, N. (2017). Valuing nature's contributions to people: The IPBES approach. *Current Opinion in Environmental Sustainability, 26–27*, 7–16.

Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P. W., Fernandez-Manjarrés, J. F., … Walpole, M. (2010). Scenarios for global biodiversity in the 21st century. *Science, 330*, 1496–1501.

Pereira, L., Kuiper, J. J., Selomane, O., Aguiar, A. P. D., Asrar, G. R., Bennett, E. M., … Ward, J. (2021). Advancing a toolkit of diverse futures approaches for global environmental assessments. *Ecosystems and People, 17*, 191–204.

Reid, W. V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y. T., Mokhele, K., … Whyte, A. (2010). Earth system science for global sustainability: Grand challenges. *Science, 330*, 916–917.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., … Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153–168.

Rogelj, J., Chen, C., Nabel, J., MacEy, K., Hare, W., Schaeffer, M., … Meinshausen, M. (2010). Analysis of the Copenhagen Accord pledges and its global climatic impacts: A snapshot of dissonant ambitions. *Environmental Research Letters, 5*, 034013.

Romero-Lankao, P., McPhearson, T., & Davidson, D. J. (2017). The food–energy–water nexus and urban complexity. *Nature Climate Change, 7*, 233–235.

Ruckelshaus, M. H., Jackson, S. T., Mooney, H. A., Jacobs, K. L., Kassam, K.-A. S., Arroyo, M. T. K., … Ouyang, Z. (2020). The IPBES global assessment: Pathways to action. *Trends in Ecology & Evolution, 35*, 407–414.

Sanford, M., Painter, J., Yasseri, T., & Lorimer, J. (2021). Controversy around climate change reports: A case study of Twitter responses to the 2019 IPCC report on land. *Climatic Change, 167*, 59.

Schneider, F., Tribaldos, T., Adler, C., Biggs, R., de Bremond, A., Buser, T., … Zondervan, R. (2021). Co-production of knowledge and sustainability transformations: A strategic compass for global research networks. *Current Opinion in Environmental Sustainability, 49*, 127–142.

Scholes, R. S., Biggs, R., Cooper, J. J., Fleming, G. J., Malungani, T. P., & Misselhorn, A. A. (2004). *Ecosystem services in southern Africa: A regional assessment*. Council for Scientific and Industrial Research.

Schröter, D., Cramer, W., Leemans, R., Prentice, I. C., Araujo, M. B., Arnell, N. W., … Zierl, B. (2005). Ecosystem service supply and vulnerability to global change in Europe. *Science, 310*, 1333–1337.

Smith, J. B., Schellnhuber, H.-J., Qader Mirza, M., Fankhauser, S., Leemans, R., Erda, L., … Yohe, G. (2001). Vulnerability to climate change and reasons for concern: A synthesis. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, & K. S. White (Eds.), *Climate change 2001. Impacts, adaptation, and vulnerability* (pp. 913–967). Cambridge University Press.

Stafford-Smith, M., Gaffney, O., Brito, L., Ostrom, E., & Seitzinger, S. (2012). Interconnected risks and solutions for a planet under pressure: Overview and introduction. *Current Opinion in Environmental Sustainability, 4*, 3–6.

Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H. J., Dube, O. P., Dutreuil, S., … Lubchenco, J. (2020). The emergence and evolution of Earth system science. *Nature Reviews Earth & Environment, 1*, 54–63.

Steffen, W., Sanderson, A., Tyson, P. D., Jäger, J., Matson, P. A., Moore, B., … Wasson, R. J. (2003). *Global change and the Earth system. A planet under pressure*. Springer.

Tengö, M., & Andersson, E. (2022). Solutions-oriented research for sustainability: Turning knowledge into action. *Ambio, 51*, 25–30.

Uhrqvist, O., & Linnér, B.-O. (2015). Narratives of the past for Future Earth: The historiography of global environmental change research. *The Anthropocene Review, 2*, 159–173.

United Nations. (1992). *United Nations framework convention on climate change*. United Nations.

van der Hel, S. (2019). Research programmes in global change and sustainability research: What does coordination achieve? *Current Opinion in Environmental Sustainability, 39*, 135–146.

van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. (2011). The representative concentration pathways: An overview. *Climatic Change, 109*, 5–31.