Transdisciplinary Research, Sustainability and Social Transformation

Governance and Knowledge Co-production

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Transdisciplinary research, sustainability and social transformation

Knowledge co-production and governance

Tom Dedeurwaerdere

To Brice, Mathilde and Samuel,
for their love and inspiration,
may they see the timely advance of pathways to just and sustainable futures

Contents

Figures

Tables

Introduction

The current crisis of the resource-intensive development model has had a major impact on how human societies envision sustainable and global futures. In particular, the convergence of multiple social and ecological crises in the first decades of the new millennium raises new challenges that necessitate an evolution in our modes of living, a deepening of democratic decision-making processes, and society-wide knowledge mobilization to foster long-term social and ecological sustainability. In this context, citizens, entrepreneurs, and public officials place great hope on collaborative research and innovation to improve our comprehension of scientifically credible and socially desirable sustainability transformations.

Much transformative research has addressed specific sustainability issues and proposed solutions for specific actors. However, many of the problems we face today defy settlement because they are characterized by very heterogeneous and boundless problem features (Polk, 2014). For this reason, they are often referred to as "wicked" (Rittel and Webber, 1973). They involve multiple and often strongly contested societal values, are causally complex, and engage actors from multiple sectors and societal spheres of activity (Harris, Brown and Russell, 2010; Polk, 2015).

These different features of wicked problems suggest that the traditional division of labor between scientific and societal actors' expertise in societal responses to the crisis is insufficient to address complex sustainability problems (Haasnoot et al., 2013). In particular, wicked-problem situations have led to a set of research questions on sustainability challenges that cannot be addressed through conventional multidisciplinary and academic expert-led only approaches.

A study directed by the Organization for Economic Cooperation and Development (OECD) on "Addressing Societal Challenges" (OECD, 2020) stated that engaging societal actors across the boundaries of science and practice will be crucial to addressing the urgent social and ecological challenges. As highlighted in the report, the impacts of global warming, biodiversity loss, natural disasters, economic migration, and health pandemics are manifested at multiple scales and require both technological and social innovations" (Ibid., p. 9). To achieve such innovations, "different scientific disciplines, including natural and social sciences and humanities need to work together and fully engage other public and private sector actors, including policy-makers" (Ibid.).

In response to these new societal demands for collaborative research and social innovation, scientific researchers and societal actors have initiated different forms of knowledge co-production and partnerships for interdisciplinary socio-ecological research in all fields of sustainability, both in basic and applied research. However, less effort has been made to understand the institutional conditions for moving beyond the myriad of these incipient and piecemeal efforts toward a more systematic reform of social practices and institutional rules within the modern science fabric. Nevertheless, to address the scale and urgency of contemporary socio-ecological challenges, researchers, societal actors, and science officials underline the need for such systematic reform.

Therefore, the discussion of in this book proposes taking a fresh look at the collective action challenges involved in building large-scale boundary-crossing interdisciplinary research collaborations among researchers and societal actors – including citizens, members of associations, teachers, entrepreneurs, public officials, and policymakers. These collaborative research practices are described in scholarly literature under the umbrella of "transdisciplinary research." Indeed, transdisciplinary research has

been promoted as a novel approach to produce societally relevant, value-laden, and scientifically robust knowledge on sustainability transformations that transcends established boundaries among scientific disciplines and between science and society.

The objective of the investigation of transdisciplinary research in this book is to identify the appropriate mix of governance mechanisms for organizing knowledge co-production processes that contribute to the generation of actionable knowledge outputs in real-world sustainability transformations. Two core lessons emerged from our inquiry into the governance challenges. First, to generate actionable knowledge outputs, researchers and societal actors must look beyond knowledge integration and actively co-design research questions, frameworks, and approaches. Second, to build capacities for research co-design in transdisciplinary research, funders and research managers must build a flexible polycentric institutional organizational environment for boundary-crossing knowledge exchange, acquisition of competencies for knowledge co-production beyond academia, and transdisciplinary team formation.

By addressing the issue of governance of knowledge co-production in transformational sustainability research through the lens of the theory of collective action, our analysis intends to add value to the existing literature both theoretically and practically. First, at the level of tools for theoretical analysis, this book presents an innovative framework for successfully navigating collective action challenges in boundary-crossing collaborations, based on insights from the literature on the governance of knowledge commons. This framework is introduced by discussing the various types of collective action failures encountered in building partnerships between scientific researchers and societal actors involved in value-laden and multifaceted sustainability transformations. To highlight the significance of institutional rules for knowledge co-production in overcoming these collective action failures, the framework is applied to various institutional rules for organizing research co-design, social learning on sustainability values, and the institutional enabling of boundary-crossing collaboration.

Second, to examine the practical implementation challenges of these collective action arrangements, this study adopts a bottom-up empirical approach. Through a comparative assessment of the process design of transdisciplinary research in a sample of 44 projects, we analyze the conditions for the successful co-production of usable knowledge on value-laden socio-ecological transformations. This sample is constructed through a "most different" case study selection, with the view to encompassing a broad diversity of research traditions ranging from technological and biophysical research to socioeconomic and socio-cultural research approaches. This comparative assessment aims to identify robust combinations of conditions that lead to effective collaborative research with societal actors. Subsequently, the analysis delves deeper into capacity building for partnership research through fostering social learning about sustainability values among research partners and through organizing transdisciplinary training and knowledge exchanges at higher education institutions.

To present the findings of the analysis, various governance mechanisms are illustrated with a wealth of in-depth case studies from various thematic areas of sustainability transformation. The overall aim is to present collective action challenges in transdisciplinary research in an accessible and broadly interdisciplinary manner to a large audience of sustainability scholars and practitioners. Indeed, writing this book would not have been possible without the intensive experimentation and collective learning on transdisciplinary research by a growing community of societal actors and scholars from all scientific disciplines and professional backgrounds over the last three decades. The upscaling of transdisciplinary research on society-wide sustainability transformations is therefore likely to benefit from the mutual learning that occurs between researchers and societal actors across all these disciplinary backgrounds

and accross different types of science and society interfaces. This book also aims to invite its readers to embark on that mutual learning journey with transdisciplinary scholars and practitioners.

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The project for this book began as a side activity of a starting grant of the European Research Council (ERC), in 2013. With a group of research fellows, we started to reflect on the integration of knowledge from academic research with knowledge from societal actors involved in real-world sustainability transformations. The article produced from this side activity, with Florin Popa and Mathieu Guillermin, sparked the interest of societal actors and colleagues at university and led us into a much deeper investigation into the broad field of transdisciplinary sustainability research, which is the topic of this book.

Since then I had the pleasure of discussing these issues in the large community of scholars and societal actors that have made seminal contributions over the last three decades in trying to understand the many challenges to overcome, in the building of research partnerships for transformational sustainability research.

The debts incurred in writing this book therefore started to accumulate well before the actual writing. A major impetus for the work is the personal experience of facing knowledge co-production challenges in large-scale fundamental research programs based on partnerships between researchers and societal actors. This experience – and the possibility for trial and error learning in this relatively young field – would not have been possible without being part of the research environment at the Centre for Philosophy of Law, Université catholique de Louvain. I take this opportunity to thank the co-directors of the Centre, Jacques Lenoble – now emeritus – and Marc Maesschalck, for their confidence and pathbreaking work in understanding the conditions of critical and transformational partnership based research. Two prominent scholars of the digital knowledge commons, Jerome Reichman and Paul Uhlir, directly participated to several of these collaborative research projects. Their insights and their important role in connecting high profile research on global knowledge commons to the international negotiations around the implementation of the Access and Benefit Sharing provisions of the Convention on Biological Diversity was enormously helpful in the present endeavor.

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1 Transdisciplinary research partnerships for environmental justice and citizenship within planetary boundaries

> *"I have an allegiance to community, which includes both my human community and the biological community that surrounds me in this habitat. And I have an allegiance to the possibility of their collective, maybe even collaborative survival into the future."*
>
> Interview with Barbara Kingsolver, Pulitzer Prize winning American novelist, essayist and poet (Kingsolver, 2012).

The increase in human knowledge and advances in technological innovation, along with the expansion of globally integrated economic activities, has allowed advanced industrial societies to evolve into mass consumption societies during the second part of the 20th century (Matsuyama, 2022). This transformation, especially strong during the so-called golden sixties, yielded considerable growth in material well-being and was accompanied by improved social welfare provisions in many countries worldwide. In the following decades, emergent and developing economies adopted many features of this development model (Stearns, 2006).

This model is now in crisis. As extensively documented by researchers and international organizations, the current path of resource-intensive growth is rapidly exhausting the non-renewable resources and already disrupts global life-supporting processes on the planet, such as the global carbon cycle or the ecosystems serving as habitats for many endangered species (Rockström et al., 2009). Further, the current development model raises important global and local social equity issues, as the average per capita resource use of the persons living in the advanced economies cannot be generalized to the entire world population without further aggravating the ecological crisis (Chancel and Piketty, 2015). Moreover, the multi-scale and multi-sectoral sustainability problems raise new governance challenges that call for new forms of multistakeholder collective action at local, regional, and global scales (Jordan et al. 2015; Dorsch and Flachsland, 2017).

Some interdependencies in socio-ecological systems*[1] are not a new feature of human societies. Historical agro-pastoral land use practices directly impacted many of the ecosystems we know today. Further, natural resources have been exploited on a large scale by all major empires (Costanza et al., 2007). However, the current planetary challenges seem to dwarf these historical examples of socio-ecological interdependencies, both by the scale of the impacts, the speed of the process, the scope of the potential risks, and the diversity of stakeholders involved and impacted from various sectors of human activity (Aarts and Drenthen, 2020). Moreover, the current interaction path between the natural dynamics of planetary ecosystems and dynamics of social systems has produced irreversible exhaustion of natural resources and living organisms and a lock-in of socio-ecological systems in development paths that further promote the over-exploitation of the stock of exhaustible nature resources (Norgaard, 1984).

Although necessary in the short term, piecemeal adaptations to address the undesirable consequences of the development model are likely to be insufficient to address the large-scale and society-wide interdependencies between social and ecological systems. As shown in many models of resource use, if human beings wish to live within safe planetary boundaries now and for future generations, human

societies must transform society-wide systems of production and consumption, including the field of energy, housing, mobility, and agri-food production among others (Falk et al., 2020).

In response to this challenge of society-wide sustainability transformations, researchers, social movements, social entrepreneurs, and policymakers have developed a broad array of new approaches to human progress and well-being around an alternative narrative of living within planetary boundaries, ecological justice, and environmental citizenship (Petit, Froger and Bauler, 2022). These three societal value frameworks aim to address the social and ecological sustainability* challenges in a just and socially legitimate manner.

First, the mobilization around planetary boundaries acknowledges the need for urgent action to maintain the functioning of basic life-supporting systems and processes on Earth (Gunderson and Holling, 2002; Folke et al., 2002; Rockström et al., 2009; du Plessis, 2012). This call for action is motivated by the awareness of potential risks generated by major system instabilities and the wish to preserve the diversity of human and non-human life forms and social practices that co-evolved with and depend on the planetary processes (Larrère, 1997, pp. 83–84).

Second, the overall objective of environmental justice regards the need to address the specific social justice issues that arise in interdependent socio-ecological systems (Larrère and Larrère, 2014, p. 320). Indeed, the growth in intensity and scale of socio-ecological interactions has important consequences for social justice and equity. The emergence of new ecological and technological risks induces distributional issues between those who endure the consequences of these risks and those who are not impacted or who can pay for adaptation measures. Such distributional issues also involve the question of who benefits from the new opportunities created by sustainability transformations. In short, societies face an array of choices to make between various sustainability transformation pathways to overcome the current crises, with different costs and benefits for different social groups (UN 2019).

More generally, environmental justice scholars highlight three important justice-related concerns for sustainability transformations (Fraser, 2009; Schlosberg, 2007, 2013, 2019; Coolsaet, 2016, 2020). They are often labeled in shorthand as the three concerns of “distribution, process, and recognition.” They respectively relate to individual distributive concerns based on criteria of socioeconomic justice (distribution), concerns over the fairness of the process of collective decision-making (process), and recognition of the contribution of all concerned sociocultural groups to the process of change (recognition). Further, environmental justice scholars also highlight power issues as an important cross-cutting category (Schlosberg, 2013). As will be seen in the case studies on sustainability research, addressing power asymmetries in knowledge co-production processes is crucial to promoting just sustainability solutions and the effective involvement of disenfranchised social groups in knowledge production on desirable and feasible sustainability transformations.

Third, promoting environmental citizenship addresses the innovations toward forms of collaborative governance and collective decision-making, which are needed to advance the objectives of sustainable development within the Earth’s planetary boundaries and in accordance with environmental justice (Dobson, 2007). Indeed, the current crisis involves a broad area of collective goods, such as human life supporting climate, air quality, biodiversity, or sustainable management of plant and crop diseases that require collective action beyond the conventional nation-state, involving societal actors at various scales and from highly diverse sectors of activity.

This third core value framework partially overlaps with the second, as it underlines the importance of building capacities for meaningful participation of all parties, beyond merely formal process guarantees for inclusive governance of all parties in societal transformations (Arnstein, 1969). However, the framework of environmental citizenship emphasizes the role of participation beyond the situations of environmental injustice and stresses the importance of new forms of participation by citizens and stakeholders in all forms of public and private collective action that are required to address the current sustainability crises in an effective manner (De Schutter and Dedeurwaerdere, 2022).

As this short overview shows, the current crisis of the resource-intensive growth model has major impacts on the relationship between the evolution of human societies and the various ecological and natural resource systems on Earth. The unprecedented scope of social and ecological interdependencies, if left on an unsustainable trajectory, can have disastrous consequences for the future survival of humankind on Earth. In response, societal actors and policymakers actively elaborate new value frameworks to envision a sustainable and socially just future within planetary boundaries, which, however, remain under intense social debate.

In this context, there is an urgent need to provide scientifically credible and socially legitimate perspectives on the feasible and desirable sustainability transformations required to address the crisis (UN, 2019). As will be argued in this introductory chapter, conventional specialized disciplinary science and expert-led advice are largely insufficient in providing the body of usable knowledge—applied and basic—needed to accelerate the incipient societal transformations toward a sustainable evolution of natural and social systems. Indeed, the achievement of sustainable human development objectives in interdependent social and ecological systems requires new modes of knowledge generation. These new modes must cross the boundaries of various disciplines for producing an improved understanding of the complex social and ecological interdependencies. Moreover, they must involve the concerned societal actors and researchers in mutual learning on the overall sustainability values that can guide human action in various specific societal transformation pathways.

1.1 Organizing research on integrated social and ecological systems

Over the last three decades, science policy officials and sustainability researchers developed major new modalities for organizing scientific research (Kates, 2011). These new modes of knowledge mobilization aim to overcome the failures of conventional disciplinary research for addressing cross-sectoral and value-laden sustainability issues. Two major features characterize this emerging landscape of scientific research in support of sustainability research: 1) an integrated* interdisciplinary approach encompassing social and ecological system dimensions and 2) a partnership approach based on knowledge co-production* and social learning* among scientific researchers and societal actors. The end goal of this combination of interdisciplinary and partnership approaches is the production of knowledge on specific sustainability transformations that is scientifically credible, socially legitimate, and socially relevant.

First, as per many scholars, the mere aggregation of specialized disciplinary expertise is insufficient to provide usable knowledge on sustainability transformations (Fernandez and Philippi, 2017). However, such interdisciplinary approaches do not constitute a new kind of “interdisciplinary discipline.” Rather, integrated interdisciplinary approaches of interdependent social and ecological systems require combining perspectives that mobilize radically heterogeneous epistemological, conceptual, and empirical perspectives (Norgaard, 1989; Goddard, Kallis and Norgaard, 2019). Therefore, for each

specific transformation pathway, researchers must actively collaborate to integrate heterogeneous perspectives into common research frameworks (Ostrom, 2007).

Second, the analysis of the integrated socio-ecological systems cannot be separated from the value-related discussions on the core sustainability values regarding environmental sustainability, justice, and citizenship (Brandt, 2013; Dedeurwaerdere, 2014). Indeed, in interdependent social and ecological system dynamics, the analysis of the biophysical, socioeconomic, and sociocultural levers of societal transformations cannot be conducted independently of a discussion on the value-related considerations, which co-define the basic orientations of the sustainability transformations of these systems. One set of examples that will be further illustrated in this book relates to the research on the thresholds for sustainable resource use. Defining such thresholds involves biophysical analysis and socioeconomic considerations and value-related positions in environmental or social ethics. For instance, how much territory do we reserve for pristine nature that plays an important role in rare species protection? How much territory do we dedicate to carbon capture in forests or wetlands relative to other possible land use purposes? Further, how do we consider the diverse societal actors' perspectives on social justice when analyzing various sustainable practices of natural resource use with different distributional impacts?

In practice, the discussions on the overall orientation of sustainability transformations involve a set of heterogeneous societal values or societal values that remain under intense debate. Therefore, reliable scientific knowledge production on the transformation pathways depends on involving societal actors in clarifying the various values at stake in framing a specific field of sustainability transformation.

The transgression of the conventional boundaries of academic disciplinary and interdisciplinary science – by integrating knowledge from societal actors in the research process – has three important purposes in the context of sustainability research (see Pohl et al., 2021). First, this collaboration with societal actors aims to construct a more integrative and complete approach to sustainability transformations by integrating empirical and analytic knowledge from scientific research with experiential knowledge on specific feasible and desirable pathways from societal actors. Second, the partnership with the societal actors has a transformational purpose by producing usable knowledge directly related to the social possibilities of change in specific interdependent social and ecological systems. Third, the partnership also has a critical dimension. Indeed, whenever societal or scientific debates over sustainability value are fraught with distorted communication processes, given rent-seeking or power imbalances, a critical approach is needed to deconstruct dominant structures of knowledge that perpetuate unsustainable development paths. This critical aspect of the knowledge integration from the societal actors calls for appropriate governance mechanisms of the collaborative practice within the research partnerships, which is at the heart of the analysis of sustainability research in this book.

As will be illustrated through the various case studies, to improve our understanding of feasible and desirable possibilities of change, societal actors and scientists embarked on innovative boundary-crossing research endeavors that combine interdisciplinary knowledge integration and collaborative research partnerships. Over the last three decades at least, these approaches are designated more generally under the umbrella of transdisciplinary sustainability research* (Hirsch Hadorn et al., 2008). The latter designates basic and applied sustainability research practices based on knowledge co-production among researchers from various scientific disciplines (for the interdisciplinary analysis of interdependent socio-ecological systems) and knowledge co-production among scientific researchers and societal actors (the partnership research aspect).

In this context, some transdisciplinary research approaches may give the impression that the mobilization of societal actors for improved contextual information gathering is sufficient to induce an effective production of usable knowledge on sustainability transformations. However, as discussed at length in this book, such focus on knowledge integration, although an important aspect, is insufficient to successfully organize transdisciplinary research. The organization of knowledge co-production in transdisciplinary research requires dedicated governance mechanisms to overcome a set of hurdles that can hamper collaboration among research partners. Major potential hurdles to be discussed include the lack of involvement in co-constructing common frameworks and the failures in mutual learning on the socially legitimate and relevant sustainability values. To introduce these issues, this chapter further presents the sustainability problems that motivate transdisciplinary sustainability research, introduces the key components of the transdisciplinary research process, and gives a short overview of the various book chapters.

1.2 The promises of transdisciplinary sustainability research

Throughout human history, science has played a key role in fostering progress in human well-being. One paradigmatic case is the contribution of theoretical knowledge in mathematics, physics, and biology to improvements in many areas of human activity, to cite just one well-known field of research with large-scale impacts. For instance, ancient knowledge of mathematics and physics played a key role in developing public infrastructure to channel drinking water into cities and organize complex irrigation systems in ancient civilizations from China and India to the Middle East and Europe (Swetz, 1979; Koutsoyiannis and Angelakis, 2003). In the 19th century, the control of many infectious diseases became possible with the pioneering work of Robert Koch and Louis Pasteur on the microbial theory of disease (Satcher, 1995). In the 1970s, the Consultative Group on International Agricultural Research set up a scientific crop breeding program in collaboration with research centers throughout the world, which majorly contributed to reducing global hunger through the huge increase in crop yields of cereals such as rice, wheat, and maize (Byerlee and Dubin, 2009).

Scholars document similar broad impacts of science on progress in human well-being throughout history, ranging from the biophysical sciences to the social sciences and humanities (Mokyr, 2011). In the process, science evolved from operating within small networks of well-connected individuals to large-scale collective endeavors (Ravetz, 2006). Especially after the second world war, public sector science underwent a rapid transformation, evolving toward so-called “big science,” organized around large-scale research consortia addressing various societal missions through publicly funded research (Nelson, 1993; Stokes, 1997; Mazzucato, 2018).

The reform of the science fabric by setting up large-scale expert-driven research consortia by national and international governments, however, falls short of addressing the knowledge needs for the cross-sectoral and multistakeholder sustainability issues. Indeed, except for specific research niches, post-war innovations in multi-disciplinary and interdisciplinary research consortia remain characterized by functional autonomy from society, led by independent scientists, and are largely self-governing in their scientific priorities, their procedures for information gathering, and in the quality assurance of the produced knowledge (Kitcher, 2011). Even though science policy increasingly requires democratic accountability and proof of societal relevance of functionally autonomous, so-called “ivory-tower” science, overall, the strict division of labor between scientific expertise and societal actors’ knowledge remains strong. In particular, the design of the scientific methods, the framing of the research approaches, and the organization of research processes remain outside of the remit of collaboration with societal actors (ibid.).

Among the noted large-scale science efforts is the Intergovernmental Panel on Climate Change (IPCC). This Panel organizes the writing of a report in intervals of approximately six years with a community of over 700 scientists (for the 2021–2023 sixth assessment report) to deliver state-of-the-art knowledge on climate change to policymakers. Despite being an authoritative and essential resource for decision-making on climate change, IPCC reports remain largely insufficient to guide specific societal transformations to address climate change. The latter is mainly because of the strong focus on the biophysical basis and impacts of climate change in the report (Bjurström and Polk, 2011). Indeed, rather than investigating in-depth the various interdependencies between biophysical, socioeconomic, and sociocultural drives for reaching effective climate change adaptation and mitigation, the main purpose of the report is to map the biophysical trends and discuss the policy targets for mitigation and adaptation action. Nevertheless, without integrated knowledge on specific feasible, socially relevant, and legitimate sustainability transformation pathways, such multi-disciplinary expert reports are unlikely to provide the necessary guidance to address the current social and ecological crises.

As noted, the emergence of new cross-sectoral research questions on sustainability transformations of interdependent social and ecological systems calls for the next stage in the contemporary science evolution in the direction of transdisciplinary knowledge co-production. Relative to the functionally autonomous "ivory-tower" science, transdisciplinary research involves societal actors in research partnerships with scientific researchers in a much more encompassing way.

Scholars have provided a more specific definition of the key components of transdisciplinary research projects. While multi-disciplinarity has been described as the mere juxtaposition of disciplinary perspectives, transdisciplinarity goes a step further (Hirsch Hadorn et al., 2008), in particular by :

(1) Integrating information from different disciplines and types of knowledge (from scientific researchers and societal actors) to address a common specific problem and research question through a jointly constructed framework
(2) Organizing a partnership between researchers and societal actors for co-managing the knowledge integration process and organizing social learning on the diversity of societal values

In short, transdisciplinary research is based on interdisciplinary knowledge integration and organizing knowledge co-production partnerships between researchers and societal actors, as illustrated in Figure 1.1.

Over the last decades, to navigate this emerging landscape of multi-disciplinary, interdisciplinary, and transdisciplinary research approaches, national and international research agencies have organized various international meetings with science and stakeholder communities. First, as per a state-of-the-art report based on a workshop organized by the United States National Academies of Sciences, interdisciplinarity is a research, education, and problem-solving mode that integrates methods, tools, concepts, and theories from one or more disciplines to address common problems (National Academy of Sciences, 2005, p. 306). According to the report, the concept of interdisciplinary research emerged in the early 20th century in response to the need to address complex problems or develop comprehensive general views of a problem area. As underlined by Klein et al. (2010), the scope varies from narrow interdisciplinarity, involving disciplines with compatible methods and epistemologies (e.g., physics and molecular biology), to broad interdisciplinarity that bridges disparate approaches (e.g., combining sociocultural history of land use practices and biophysical analysis of ecosystem functions).

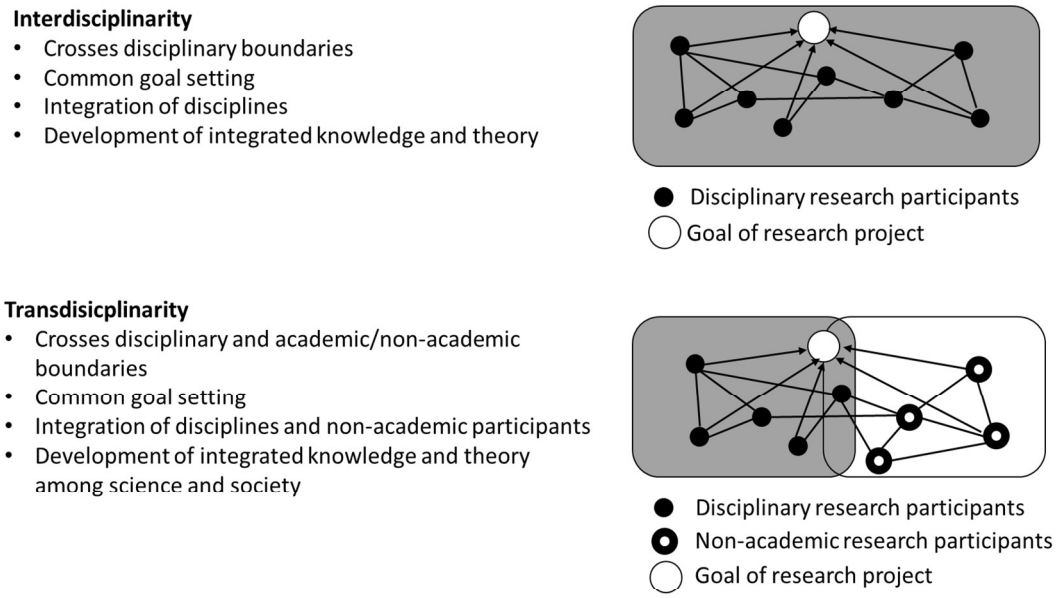

Figure 1.1. Comparison of key features of interdisciplinary and transdisciplinary research (figure by the author, based on an adaptation of the ideas developed in Tress et al., 2005).

This form of broad interdisciplinarity is most relevant (Pohl et al., 2021) to understanding society-wide sustainability transformations. Indeed, sustainability transformations require bridging disparate sources of knowledge on social and ecological system dynamics to cross boundaries between various sectoral and often disconnected decision-making processes in public and private organizations, which often address distinct aspects of social and biophysical systems. This requirement to develop broad interdisciplinarity research practices is strongly underlined in the first generation of transdisciplinary research in the 1970s by scholars such as Jean Piaget, Leo Apostel, and Erich Jantsch, who focused on the elaboration of overarching syntheses in specific domains of reality (Hirsch Hadorn et al., 2008; Klein, 2010).

A second generation of transdisciplinary research moved the analysis of socio-ecological systems beyond the walls of conventional academic and expert-led interdisciplinary science by involving societal actors and citizens in knowledge mobilization and social learning on society-wide sustainability transformations (Hirsch Hadorn et al., 2008). A major historical landmark event showcasing, for the first time, the broad international uptake of this move toward partnership-based research approaches to sustainability issues was the *International Transdisciplinary Conference* in 2000, organized in Zürich by the Priority Program Environment of the Swiss Academy of Sciences. This conference gathered over 700 participants from 57 nations to discuss their success and challenges in conducting transdisciplinary research. Although this research field is broad and shaped by various lines of thinking and heterogeneous approaches to research, participants widely shared the concern for transcending disciplinary paradigms and various types of knowledge to address real-world sustainability problems (ibid, p. 29).

In general, this second generation of transdisciplinary research practices additionally focused on building partnerships with societal actors to consider the diversity of legitimate value perspectives on the sustainability transformations in the design of the research process. Indeed, the goal of reaching a

socially robust understanding of sustainability transformations requires that sustainability researchers move from a general interdisciplinary analysis of all theoretically possible socio-ecological dynamics to an analysis of specific socio-ecological transformation pathways that are socially desirable and scientifically valid. The latter implies the identification of the problems considered most relevant by concerned societal actors and the matching of the research framework to real-world social possibilities of change. Hence, research partners must co-construct the research design in a way all partners consider relevant and socially legitimate.

Accordingly, per the study directed by the Organisation for Economic Cooperation and Development (OECD) on "*Addressing Societal Challenges"* (OECD, 2020) – referred to in the introduction, transdisciplinarity is defined as "the integration of academic researchers from unrelated disciplines and non-academic participants in creating new knowledge and theory to achieve a common goal, involving the creation of new knowledge and theory." According to the study, drawing upon the breadth of scientific and non-scientific knowledge domains, such as local and traditional knowledge, practitioners' know-how, and cultural norms and values, knowledge co-production aims to supplement and transform scientific insights. Thus, it offers a way to address issues involving diverse societal values being debated. Further, expanding on existing scientific evidence and organizing social learning processes can generate more innovative solutions and holistic understanding (ibid, p. 9).

Given the importance of the disciplinary organization of research in many research institutions and universities, science policy officials and research evaluators may face considerable challenges in situating transdisciplinary research in the current institutional landscape. In this context, it is important to highlight some possible misunderstandings. First, some scholars might tend to equate transdisciplinary research with more applied research. Nevertheless, the difference between transdisciplinary research and disciplinary research is not situated in the production of more direct applicable research results relative to more theoretical and basic approaches to reality. On the contrary, transdisciplinary and disciplinary research share basic and applied research strands (Mittelstrass, 2018, p. 72). Regarding transdisciplinary research for sustainability, practices may range from applied knowledge co-production within an action research setting to more basic strands of strategic research, foresight studies, or general theoretical syntheses of complex socio-ecological interdependencies that cannot be apprehended through disciplinary or multi-disciplinary approaches.

Furthermore, not all situations justify investment in transdisciplinary research. The choice of multi-disciplinary, interdisciplinary, or transdisciplinary research hinges on the type and representation of the research problem the research partners aim to address (Hirsch Hadorn et al., 2006, p. 123-124). The latter can be illustrated schematically through the case of sustainability problems regarding water management in a river basin, as in Table 1.1. Water management might concern local and isolated problem features or more encompassing interdependent socio-ecological problem features. For instance, the inhabitants and users of a river basin may focus on a set of well-defined problems, such as building a bridge over the river or solving a pollution problem caused by a local actor. Alternatively, they may be concerned with water management problems in so-called river basin contracts for addressing various interrelated social demands around biodiversity protection, recreation, and industrial use of water (Huitema and Meijerink, 2014). Such different problem situations have implications for organizing multi-disciplinary, interdisciplinary, or transdisciplinary research. Indeed, it may be that the involved partners prioritize solving some technical problems related to a well-identified local problem. In such a case, they likely opt for conducting disciplinary or multi-disciplinary research. Conversely, the focus may be on the problems generated by the dynamics of

interdependencies and value-laden controversies in the river basin contract, which are more adequately addressed through modes of transdisciplinary research.

Table 1.1. Illustration of sustainability research topics addressing situations with different degrees of socio-ecological interdependency and heterogeneity of societal value perspectives.

RESEARCH QUESTIONS RELATED TO RIVER BASIN MANAGEMENT	Rather homogeneous societal value perspective	Heterogeneous societal value perspectives
Various rather independent social and ecological dynamics	Research question on the architecture of a pedestrian bridge to cross the river	Solving a contentious local river pollution issue affecting diverse actors
Strongly interdependent social and ecological dynamics	Research on the adaptation of legal frameworks to new threats to valuable biodiversity in the river basin	Research on balancing objectives of recreational use, industry development and biodiversity in the river basin

In this context, Spangenberg (2011) suggests the distinction between science for incremental sustainability change (technical and disciplinary) and science of system-wide sustainability transformations (interdisciplinary and transdisciplinary). Regarding "science for incremental sustainability change," scientific research aims to bridge technical knowledge gaps that must be addressed to solve problems within a given sustainability transformation pathway. For such purposes, disciplinary knowledge and methods are well adapted to provide in-depth knowledge of a system component from a highly specialized perspective on sub-system features. In contrast, regarding the "science of system-wide sustainability transformations", the research process is designed to understand the overall dynamics of interaction between the social and ecological system features in given sustainability transformations. The latter is the specific object of analysis of transdisciplinary sustainability science, as illustrated in the lower right box of Table 1.2. Both interdisciplinary analyses of coupled socio-ecological systems and partnerships for knowledge co-production between societal actors and researchers are involved in this undertaking.

In general, transdisciplinary sustainability research aims to produce better knowledge and a better general understanding of sustainability problems characterized by strong system interdependencies and diverse societal values that play a role at multiple scales of socio-ecological interactions. As is the case with all scientific research, such knowledge will be provisional and subject to further refinement. Nevertheless, as the many case studies in this book show, integrating processes of transdisciplinary knowledge co-production in sustainability research is a key requirement to advance the undertaking of scientifically credible and socially robust knowledge production on multi-scale and multistakeholder sustainability challenges.

Table 1.2. Categories of sustainability problems typically addressed through disciplinary, multi-disciplinary, and transdisciplinary research.

APPLICATION DOMAINS OF SUSTAINABILITY SCIENCE	Rather homogeneous societal value perspective	Heterogeneous societal value perspectives
Various rather independent social and ecological dynamics	➢ Analyze components of social and ecological systems and their interactions ➢ Well identified research problems and purposes Typically addressed through disciplinary (one main system component) or multi-disciplinary research (parallel or sequential analysis of components)	➢ Analyze components of social and ecological systems and their interactions ➢ Multiple diverging perspectives on the research problems and purposes Typically addressed through multi-disciplinary research, to take into account the diversity of diverging perspectives
Strongly interdependent social and ecological dynamics	➢ Analyze emergent system patterns resulting from the reciprocal relationships between social and ecological system components ➢ Well identified research problems and purposes Typically addressed through interdisciplinary approaches	➢ Analyze emergent system patterns resulting from the reciprocal between social and ecological system components ➢ Multiple diverging perspectives on the research problems and purposes Typically transdisciplinary research when values have a strong impact on the research design of the socio-ecological system ; sometimes interdisciplinary if the research design can be settled outside the discussions on the value framing

1.3 Addressing governance challenges in partnerships between scientific researchers and societal actors

Scholarly discussions on transdisciplinary research have produced a wealth of research on approaches to knowledge integration among researchers from various disciplines and societal actors (Hirsch Hadorn et al., 2008; Bergmann et al., 2012). Subsequently, with the proliferation of researcher and social-actor partnerships in transdisciplinary sustainability research, scholars furnished insights into various aspects of knowledge co-production and social learning. However, except for some notable exceptions (e.g., Pohl et al., 2021), few systematic studies probe the overall institutional design of knowledge co-production in transdisciplinary research.

What is often implicit in this scant regard for governance issues of knowledge co-production is the assumption that the conventional disciplinary mechanisms of journal-based peer review, community building through scientific conferences, and dedicated training will also provide the key mechanisms for consolidating transdisciplinary research into larger communities and organizational frameworks (Benkler, 2008). However, through such imitation of existing organizational mechanisms, although useful to partially address issues of quality management of research outputs and training of young scholars among others, major organizational issues remain unaddressed.

Transdisciplinary research raises major questions regarding designing appropriate institutional rules* for governing the research partnerships at various levels. First, the organization of the knowledge co-

production process between societal actors and scientific researchers requires rules for collaboration among research partners mobilizing heterogeneous knowledge types (Pohl et al., 2021). Second, transdisciplinary research requires appropriate rules for organizing social learning on sustainability values among actors from different sectors of activity involved in society-wide transformations (Herrero et al., 2019). Finally, to consolidate transdisciplinary research efforts beyond small niche projects, transdisciplinary research requires organizational support for competency and capacity building for researchers, students, and societal actors to allow them to successfully participate in boundary-crossing knowledge co-production efforts (Pearce et al., 2018).

The first two governance challenges for building transdisciplinary research partnerships are situated at the project level and can be illustrated through a set of questions that must be addressed by the project partners. Given heterogeneous knowledge interests in transdisciplinary research partnerships, how can one avoid each of the partners pursuing their own research agenda once a project proposal has been approved and funded? In particular, how can one create mechanisms such that research partners invest time and resources in research methods and data-gathering priorities that best suit the joint boundary-crossing research issues? What tools can be used to foster a mutual understanding of how knowledge is constructed in each of the disciplines or practitioners' communities? Moreover, how can one create the appropriate balance between acknowledging the diversity of societal values developed in different communities and organizing a dialogue on the possible convergence or accommodation between these values as a basis of successful collaboration?

Thus, to tackle these questions, beyond methodological innovations in transdisciplinary knowledge integration, transdisciplinary research will require new forms of collaboration and partnership building, along with processes of social learning among the partners to foster mutual understanding of diverse societal values and methodological perspectives. Indeed, transdisciplinary research projects generate new governance challenges as they gather scientific researchers or societal actors with different research agendas and interests, who are often involved in different project contexts. For instance, a project on biodiversity in inhabited agricultural landscapes may assemble historians, sociologists, and biologists to understand the social legitimacy of various landscape management options. Hence, to successfully integrate such diverse knowledge, participating disciplinary scientists or non-academic experts must look beyond the methodologies that, at best, satisfy their interest (quantitative for some, interpretative or qualitative for others) and agree upon a set of research tasks that, at best, serve the common purpose.

Further, at a second level, transdisciplinary research faces governance challenges regarding consolidating transdisciplinary research projects in larger organizational units and capacity-building efforts. Indeed, how can one involve interdisciplinary or transdisciplinary researchers beyond small niche networks of jointly defined but specific research issues? What kind of networking activities can contribute to creating new interactions beyond such small niche networks? How can one decrease search costs to find new partners beyond the already well-known partners from prior collaborations? Finally, what kind of research resources can be shared across a heterogeneous network of boundary-crossing projects to build capacities for training and joint quality management on issues of common concern?

Indeed, to consolidate transdisciplinary research in more diverse and comprehensive research networks, researchers and science policy officials require a set of institutional mechanisms to build transdisciplinary research competences and research networks in larger communities. As will be discussed in-depth in chapter five, such larger organizational units can be organized around cross-

cutting thematic areas of sustainability transformations, be it in the fields of mobility, energy, or agri-food systems, or directly integrate researchers of various thematic communities in more generic research-enabling platforms.

To develop the various features of the enabling knowledge ecosystem for transdisciplinary research, this book is organized as follows. As highlighted throughout this chapter, research partnerships are prone to a set of governance failures. **Chapter two** reviews some of these failures and discusses the key concepts proposed to overcome them by building upon the core insights from the literature on collective action challenges in building scientific knowledge commons. **Chapter three** presents a comparative analysis of a broad set of cases of transdisciplinary research partnerships, with the view to identify core features of the knowledge co-production process that contribute to effective usable knowledge production on specific sustainability transformations. **Chapter four** probes the question of the various strategies for social learning on sustainability values among the project partners, by extending the typology of social learning situations proposed by Amartya Sen in his work on social choice. **Chapter five** uses the results of the comparative analysis at the project level in chapters three and four to tackle the question of the institutional design of the consolidation of transdisciplinary research in larger organizational architectures. **Chapter six** briefly discusses some limits and extension of the analysis, by highlighting the importance of building synergies between various modes and types of knowledge production within and beyond academia.

As announced in the introduction, through analyzing these various aspects of the enabling knowledge ecosystem, this book aims to provide added value both to the theoretical perspectives for analyzing the governance of knowledge co-production and to the comparative analysis of collective action challenges encountered in transdisciplinary sustainability research. First, in relation to the theoretical approaches, this book develops a multi-level approach to the institutional design of transdisciplinary research partnerships, building upon and extending the literature on the governance of scientific research commons*. Second, for deepening the analysis of institutional design principles, the book provides a comparative assessment of the conditions for the successful production of usable knowledge, based on a large sample of transdisciplinary research projects that encompasses a broad diversity of research traditions in academia, ranging from biophysical research to socioeconomic and cultural sciences. Finally, the book uses these insights to provide an analysis of the most appropriate organizational architectures, drawing upon governance mechanisms from the literature on flexible network organizations. Overall, these different strands aim to analyze the building blocks for constructing a consistent account of the new transdisciplinary modes for organizing scientific research, where the integration of societal actors' knowledge and social learning on societal values is an indispensable part of the knowledge generation process.

Note

1 Terms defined in the glossary are marked with an asterisk upon their first appearance in the text.

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6 Implementing knowledge co-production on sustainability transformations in academia and beyond

> *"Pluralism is not, then, an insurmountable epistemic or moral obstacle for public deliberation that abandons unanimity and seeks plural pubic agreement. The underlying difficulty is that cultural differences are more often than not associated with social inequalities, which ramify the difficulties of pluralist agreements. The broader the public sphere, the more difficult it is for certain groups to participate effectively in a framework that they have neither defined nor greatly influenced […]. The challenge for democracy is to correct for such inequalities in such a was as to promote public deliberation."*
>
> Quote from "Public Deliberation" by James Bohman, professor of Philosophy at Saint Louis University (Bohman, 2000, p. 105).

The analysis in this book of over three decades of transdisciplinary sustainability research shows the urgent need for new modes of organizing scientific research. The reform of the science fabric is particularly urgent, given the multiple social and ecological crises humanity is facing today. As aptly summarized by Christian Pohl et al. (2021, p. 19), these new modes of transdisciplinary research can be characterized by (1) specific process features based on knowledge co-production amongst partners who actively explore boundaries as learning opportunities and (2) specific research outputs regarding the production of transformative and critical knowledge on sustainability challenges.

The first characteristic highlighted by Pohl et al. (2021) requires the organization of knowledge co-production processes that transcend the conventional separation between various knowledge types, such as between practitioners' and researchers' knowledge and between descriptive and normative perspectives on societal transformation. Indeed, transdisciplinary sustainability research aims to grasp the complex coupled dynamics of social and ecological systems at multiple scales with heterogeneous societal actors. Thus, transdisciplinary research partners mobilize both case-specific knowledge, which is often non-codified, and more generic interdisciplinary scientific knowledge frameworks to analyse on feasible real-world transformation pathways.

The organization of these boundary-crossing knowledge generation processes is neither an attempt to produce an illusionary unity among heterogeneous perspectives nor a means to highlight irreducible differences that stifle all possibilities of collaboration. On the contrary, in transdisciplinary research, boundaries are actively explored as opportunities for learning from different perspectives. As underlined by Akkerman and Bakker (2011), based on this mutual learning, participants in boundary-crossing practices can develop various socially negotiated modes of interaction, ranging from the simple recognition of a shared problem space to coordinated action, continuous joint work, or the co-construction of new common action strategies.

The second characteristic, the production of transformative and critical knowledge, regards the open-ended and pluralistic nature of sustainability challenges. Indeed, the coupled dynamics between social and ecological systems can induce a plurality of feasible and desirable sustainability transformation pathways. Therefore, researchers and societal actors must understand the socially legitimate and relevant values that orient the context specific choices among this diversity of possible pathways. This understanding has a transformative dimension, for both societal actors and the researchers. First, understanding specific sustainability transformations requires the identification of the most relevant

sustainability challenges from the perspective of the societal change agents that drive the societal transformations in the specific context. Second, addressing specific sustainability transformations also involves a critical stance from the researchers. Indeed, some of the necessary changes may challenge the dominant value based frameworks that inform the socio-ecological modelling practices. By disregarding social learning on these value based frameworks, the research outcomes might perpetuate unsustainable practices or maintain unbalanced power relationships to the benefit of the incumbent actors.

However, for the individual researchers, societal actors, and research managers, given the long history of the specialized disciplinary organization of research, a main challenge regards the implementation of such boundary-crossing and transformative knowledge generation processes in in practice. For sure, there is no single best way forward, and each research organization must consider the local constraints in developing these tools and mechanisms. Further research is therefore needed to document the various options to do so and to build so-called "toolbox" environments providing inspiration and advice (see for example https://itd-alliance.org/ and https://transdisciplinarity.ch/en). Nevertheless, the literature review and case study analysis in this book give some indications of research questions on the measures that are needed to further build a larger organizational network of transdisciplinary research commons.

In the first place, the analysis shows that regarding transdisciplinary knowledge co-production, research funders, policy officials, and research managers should strive to multiply the opportunities for knowledge co-production by researchers and societal actors in research projects on sustainability transformations. These opportunities can be quite modest, such as through the inclusion of a transdisciplinary case study chapter in a Ph.D. project or a transdisciplinary analysis of a sub-topic by a researcher within a conventional multi-disciplinary consortium. Alternatively, they can include more comprehensive transdisciplinary initiatives, such as the funding of research projects or consortia that orchestrate the co-construction of research design and co-validation of results throughout the entire research cycle. Multiplying such opportunities for the emergence and implementation of transdisciplinary initiatives is especially important as no centralized approach to the consolidation of transdisciplinary research is likely to cover the diversity of societal actors and knowledge types mobilized in each case-specific transdisciplinary knowledge co-production process.

Further, to meet the social learning needs on sustainability values, each transdisciplinary research project should foresee the possibility to invest time and resources in structuring the space of the different value perspectives of the societal actors and researchers. Indeed, as in the various case studies, the growing scope and impact of the interdependencies between social and ecological systems imply the development of new environmental, social, and civic value orientations that forsakes the modern myth of continuous growth with unlimited resources. Most of these values, such as the orientation toward environmental justice or reconciliation of human prosperity with planetary boundaries, are intensely debated. Depending on the specific field of sustainability transformation and the involved societal actors, the disruptive learning of the sustainability values can be somewhat consensual among the partners, inducing various degrees of convergence. In other cases, the learning will be more critical, such as when powerful interests attempt to perpetuate unsustainable development paths.

Moreover, a set of measures at the level of the research organizations can contribute to consolidating the transdisciplinary knowledge commons. As discussed, important mechanisms for the integration of the boundary-crossing networks built around the transdisciplinary research projects are the overall

building of transdisciplinary competences, social networking for partner identification, and systematization of knowledge exchange on modes of organization of knowledge co-production and social learning. Hence, to support these cross-cutting mechanisms, research organizations can create new professional profiles and promote transdisciplinary research skills.

For instance, research organizations can organize a supporting service to accompany teachers who implement transdisciplinary competence building in teaching curricula. Such a service could train a dedicated staff person to assist organizational units and departments to promote teaching practices based on knowledge co-production with societal actors on specific sustainability transformation topics. As discussed in chapter five, such teaching curricula reform might include full-fledged transdisciplinary partnerships with real-world actors, such as in the collaborative visioning exercises organized with partners in the city of Gothenburg in the context of the course for doctoral students organized at the University of Gothenburg. In other cases, it may focus on specific transdisciplinary competences such as the analysis of real-world case studies in the courses on sustainable development at the TdLab of the Swiss Federal Institute of Technology (ETH).

Likewise, research organizations might organize supporting services for social networking among potential project partners of transdisciplinary research projects and teaching initiatives. These social network-building activities could take the form of the so-called "search conferences" discussed in chapter five. The search conferences are open-ended meetings to identify and define possible topics for knowledge co-production among societal actors and various disciplinary researchers. Examples of such meetings include the sandpit workshops funded by the UK Research and Innovation Council (Bridle et al., 2013; UKRI, 2021) or the transdisciplinary research fora on grand challenges organized by the Berlin University Alliance (see chapter 5), to cite just a few. Other initiatives for transdisciplinary network-building may be organized at the master's student level, such as the interdisciplinary and transdisciplinary master thesis project on sustainability development at UCLouvain (see chapter 5) or the master theses of the citizen academy organized by the University of Ghent (Block et al., 2022). The distinguishing feature of these various transdisciplinary network-building activities is the fact that the teams are constituted based on discussions to explore a common research design on interdependent social and ecological system dynamics. Given the partnership dimension of transdisciplinary research, the network-building activities cannot be dissociated from the identification of potentially productive areas of knowledge co-production on sustainability transformations.

A third area of organizational support for consolidating transdisciplinary research commons concerns the systematization of knowledge exchange on transdisciplinary process features. By organizing knowledge exchange on process features, research organizations can strengthen the capacities of researchers and societal actors to conduct transdisciplinary research on a broad variety of topics of concern. Moreover, by organizing various opportunities for knowledge exchange in thematic clusters and in more generic organization-wide initiatives, research organizations can create additional support for researchers and societal actors with less access to learning platforms on process features. An example of such a platform is the "Liaison and Transfer Organisations on Social Innovation," established at various universities in Québec. These platforms connect societal actors and researchers to create a discussion on the co-validation of transdisciplinary project results and transdisciplinary approaches in various thematic areas of socio-ecological research (Dagenais et al., 2008). As discussed in chapter 5, the cross-cutting activities of knowledge exchange on process features allow researchers and societal actors to identify further needs of co-validation or explore opportunities for using certain tools and mechanisms for knowledge co-production and social learning in new thematic areas of inquiry.

To wrap up this journey through these different organizational and institutional measures, it is important to indicate some limits of our analysis and highlight perspectives for future research. The analysis in this book focused on transdisciplinary knowledge commons for sustainability research. Though important, the analysis did not dig deeper into the contributions of the purely disciplinary, multi-disciplinary, and interdisciplinary research projects that address sustainability issues. In many cases, these more conventional approaches are mobilized to furnish more insight into well-identified sub-system components or operate within relatively well-defined value orientations, such as in calls for proposals on the implementation of policy measures for sustainability transformations, as defined ex-ante by research funders.

However, in practice, the boundary between purely transdisciplinary research, where co-constructing research design with societal actors plays a central role throughout the research, and conventional research practices are not always clear-cut (Klein, 2010). Conventional research practices often include consultation and feedback from societal actors, though without including them as full-fledged partners in the knowledge co-production process. When researchers and societal actors intensify the consultation and feedback activities, the research process may be gradually adjusted to include transdisciplinary process features.

The case of so-called broad interdisciplinarity can illustrate this point. According to the analysis of Klein (ibid), broad interdisciplinarity is characterized by research that bridges disparate approaches—for instance ecology and history—and develops comprehensive general views or synthetic frameworks (cf. also Pohl et al., 2021). In broad interdisciplinary research, research partners face heterogeneous methodologies, distinct approaches to problem identification, and a diversity of different conceptual frameworks. Hence, even when societal actors are not directly involved in building a common research design, the collective action challenges them to bridge the different knowledge types that are often similar to the case of transdisciplinary research. For instance, interdisciplinary knowledge co-production can also be hampered by the instrumentalization of the research process by one of the partners who mainly focus on their disciplinary knowledge interests or by unstructured diversity of conceptual approaches.

Given this proximity of the collective action problems, transdisciplinary research can benefit from the lessons learned from knowledge co-production in such broad interdisciplinary research projects. Moreover, from the case study analysis, broad interdisciplinarity is often a key ingredient of transdisciplinary sustainability research. In such cases, learning about knowledge co-production in broad interdisciplinarity may directly contribute to the successful implementation of transdisciplinary research processes.

Another illustration of the gray zone between transdisciplinarity and some more conventional modes of research organization is the case of so-called mission-oriented research. As discussed in a widely disseminated discussion paper by Mariana Mazzucato (2018), mission-oriented research is a key problem-solving-centered research approach to innovation that is often embedded in calls for proposals on grand societal challenges, such as cybersecurity, mental health, or sustainability issues. Often these calls for proposals do not formally require transdisciplinary knowledge co-production with societal actors. Moreover, these calls are often defined regarding measurable and time-bound targets or require project consortia to provide such targets regarding so-called key performance indicators.

However, as highlighted throughout the book, research funders can neither always specify ex-ante the full scope of relevant problems to address nor identify the list of societal actors to include to discuss the value-related issues. It may be related to the value-laden nature of the desirable societal solutions to some of the grand societal challenges or path-dependent constraints on real-world social possibilities for implementing these solutions. Therefore, in practice, research funders often favor projects that also propose some level of knowledge co-production with the societal actors throughout the research process. In such cases (as in the case of broad interdisciplinarity), the overlap between collective action problems encountered in mission-driven research and transdisciplinary research can create fruitful opportunities for cross-fertilization between successful research practices.

A second limit of the analysis in the book is related to the collaboration with other transdisciplinary researchers beyond the field of sustainability research. Indeed, the book focuses on transdisciplinary sustainability research and does not explore the many overlaps with other transdisciplinary areas of investigation that do not have a specific focus on sustainability (Hirsch Hadorn et al., 2008). Although such exploration is beyond the scope of this book, the general definition of transdisciplinarity that is used for the analysis hints at such a further dialogue.

Indeed, as specified in the introduction, the book uses a general definition of transdisciplinarity as an approach that is broadly interdisciplinary and based on a research partnership with societal actors. Moreover, as developed in-depth above, this partnership is characterized by a set of process features (regarding knowledge co-production for integrating different knowledge types) and the production of transformative and critical knowledge outputs. This general definition is highly relevant to the broad field of research on sustainability. As articulated through the various examples analyzed in the book, the combination of broad interdisciplinarity and knowledge co-production with societal actors can effectively tackle socio-ecological system interdependencies with heterogeneous value perspectives on the overall orientation of the system dynamics.

However, as amply illustrated by the systematic review of transdisciplinary scholarship by the Swiss Academies of Arts and Sciences (2023), this general approach is also highly relevant and widely used in other fields of advanced research on society-wide challenges. Some of the theoretical discussions in the book already referred to some of these fields, such as collaborative planning research in urban studies (see section 4.1.1) or the socio-technical approach to living labs (see section 3.2.1). The illustrations in this book focused on cases in these fields of research that deal with sustainability issues in socio-ecological systems. Nevertheless, many of these cases also covered research fields that address other issues, such as social welfare concerns in urban neighborhoods (see section 3.2.4) or research on socioeconomic distributional consequences of technological choice (see section 4.3.3).

Other prominent fields of research illustrate the use of this general approach for transdisciplinarity based on combining broad interdisciplinarity and partnership research. One case in point is the field of research in the social economy in Québec, which develop a broad set of transdisciplinary research practices through over two decades of research funding for so-called community research alliances (Hall and MacPherson, 2011). Other examples, in a different field, are partnerships between scientific researchers and societal actors for translation research in criminology, focusing on the process through which criminological research is generated and used by practitioners and policymakers (Pesta et al., 2019).

Obviously, even though these research fields all develop transdisciplinary modes of organization, the organization of the knowledge co-production and social learning process will be based on choices that

are specific to each area of investigation. Nevertheless, the use of broad interdisciplinarity and partnership approaches in different fields creates cross-fertilization opportunities. These opportunities cover knowledge exchange on transdisciplinary process features and their usefulness to tackle various collective action challenges in building transdisciplinary knowledge commons. Furthermore, at the institutional level, the experience acquired from successful transdisciplinary research in these different fields may also contribute to the broad recognition of transdisciplinarity as a promising mode of organizing scientific research on complex societal challenges. Therefore, this recognition may be promoted by identifying, within a given research organization, the similarities between various fields of transdisciplinary research and jointly exploring and supporting the design features for successful transdisciplinary knowledge co-production.

Finally, the analysis in the book mainly focused on transdisciplinary research at universities, high schools, and national research organizations as the key players for organizing transdisciplinary research of a more basic and applied nature. However, along with the development of transdisciplinary research in the academic environment, a wealth of associations, entrepreneurs, and managers in public administrations are using tools from transdisciplinary research in applied settings (OECD, 2020).

The strength of the academic transdisciplinary research approaches is to combine the production of transdisciplinary knowledge with an interest in generic methodological and theoretical development and contribute to knowledge transmission, education, and competence building. On the other hand, the strength of the applied and directly policy-related approaches is the strong motivation of the societal actors to reach a broad critical mass of transdisciplinary research practices. Even though such approaches do not systematically strive at peer review validation of the research outputs, as is the case in academic research, policy-related transdisciplinary research practices offer invaluable opportunities for further mutual learning on boundary-crossing research practices.

Overall, the entry point in this book on transdisciplinary sustainability research in academic research therefore hints at a much broader field of work, which includes broad interdisciplinary approaches with extensive social-actor interaction, related fields of transdisciplinary research on grand societal challenges, and directly policy-related transdisciplinary research practices. Given the many complementarities between the approaches, the best way forward to foster the urgently needed sustainability transformations is to explore the many synergies between the different approaches to support various collective learning processes on feasible and desirable interdependent sustainability transformations of social and ecological systems.

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Conclusion

Contemporary sustainability challenges, characterized by socio-ecological interdependencies of an unprecedented scale, require new modes of knowledge generation to identify feasible and desirable transformation pathways. In this context, conventional disciplinary and expert-led only modes of research organization seem ill-suited for managing the wicked problem features of many sustainability issues, such as strongly coupled social and ecological system dynamics, value controversies over sustainability orientations, and the involvement of societal actors in cross-sectoral and multi-scale actor networks.

Different types of transdisciplinary research have emerged over many years in response to these challenges, labeled partnership research (Hoekstra et al., 2020), community science (Khandor and Mason, 2011; Charles et al., 2020), participatory action research (Wittmayer et al., 2014; Chevalier and Buckles, 2021), mode 2 science (Nowotny et al., 2001) and team science (Killion et al., 2018) among others. This book builds upon the experience gained with these transdisciplinary research processes over the last three decades, with the objective of strengthening the effectiveness of transdisciplinary research methods that are mobilized to improve our understanding of society-wide sustainability transformations.

The core hypothesis of this book is that researchers and societal actors must overcome a series of collective action problems to meet the need for knowledge integration from science and practice in transdisciplinary sustainability research. This book examined the institutional design of transdisciplinary research processes from the perspective of the theory of knowledge commons, to disentangle the basic components of collective action challenges.

In fact, the collective action problems in transdisciplinary research, such as the instrumentalization of the collaborative process by one of the partners or the lack of coordination among heterogeneous value perspectives, show a great deal of similarity to the problems examined in the theory of decentralized collective goods production through non-state collective action, or the so-called theory of commons-based production? While the theory of the commons initially focused on the community-based management of natural resources, it has gradually broadened its scope to other commons-based production domains, including immaterial goods, such as knowledge commons.

As discussed in Chapter 2, scholars of the commons highlight the importance of three general design features that contribute to successfully overcoming collective action challenges, which also play a vital role in the case of transdisciplinary knowledge commons. First, to effectively manage the provision of common goods in decentralized settings—whether in the community management of natural resources or in scientific research commons—societal actors need entitlements to develop and implement self-organized strategies for decision-making and control over collective good provision. Second, as elaborated in the so-called “second generation collective action theory” by Elinor Ostrom (1998), such self-organized management is facilitated by the development of common value orientations. The latter contributes to building mutual trust and reduces the effort required to coordinate the production of common action strategies. Finally, decentralized solutions to collective-action problems require an appropriate supportive institutional environment. Such an environment plays a significant role in building the generic competencies of actors who wish to engage in decentralized collective action and social learning.

The transdisciplinary research practices reviewed in the different book chapters highlight how each of these design features is relevant to transdisciplinary sustainability research. Specifically, the qualitative

comparative analysis of cases of transdisciplinary sustainability research identified the following general design features that play an important role in enhancing the likelihood of successful co-production of usable knowledge on sustainability transformations.

1) First, regarding collective action for collaborating on a common transdisciplinary research purpose, the analysis of the various components of knowledge co-production in chapter three indicates
    i. the importance of effectively integrating societal actors' knowledge (along with knowledge from scientific researchers) in the analysis of sustainability transformations of interdependent social and ecological systems
    ii. the importance of the co-construction of the research design with societal actors, particularly in building a common framework of analysis between heterogeneous disciplinary perspectives and different types of knowledge from science and practice
    iii. the need to involve societal actors and scientific researchers in co-management processes of various degrees of strength
2) Second, regarding the common understanding of diverse value orientations, the analysis of social learning processes in chapter four shows
    i. the need to identify demands of societal actors and scientific researchers for social learning, including learning for reaching improved mutual understanding of sustainability values and structuring of the various perspectives on societal values
    ii. the contribution of social learning processes on societal values to fostering processes of convergence over core values and critical deconstruction of value perspectives that perpetuate rent-seeking and the undue exercise of power
3) Third, regarding the supportive institutional environment, the analysis of the building of larger organizational networks for transdisciplinary research in chapter five shows
    i. the importance of building flexible boundary-crossing networks among different disciplines, researchers, and societal actors
    ii. the contribution of the organization of cross-cutting activities for
        i. the development of transdisciplinary competences in the teaching curricula
        ii. the organization of knowledge exchange on transdisciplinary process features
        iii. the networking of researchers and societal actors around coproduced research frameworks on specific sustainability transformation topics.

The case studies of transdisciplinary research examined in this book and the analysis of scholarly literature aim to improve our understanding of these design principles. Nevertheless, additional comparative case study research, further fieldwork, and systematic surveying is needed to further develop this analysis of the most salient governance mechanism for collective action in transdisciplinary research.

Further work might also deepen the epistemological framework of pragmatist constructivism discussed in Chapter 4, which summarizes the core guiding principles of transdisciplinary research as an innovative mode of knowledge generation. This epistemological framework combines the key strengths of constructivism, reflected in design features such as the co-construction of research amongst researchers and societal actors, and philosophical pragmatism, reflected in design features sur as the practical building of communities of collaborative inquiry through co-management and social learning. From a pragmatist constructivist perspective, both scientific knowledge and knowledge from societal actors contribute to knowledge generation about wicked sustainability problems. Pragmatist constructivism allows searching for a middle ground in transdisciplinary research between the risks of

technocratic excesses and scientific dogmatism, on the one hand, and losing any idea of robust and validated scientific research outcomes as a common good, on the other, through the risk of the reduction of the validity to the outcome of power relationships and social conflicts.

Finally, the organization of institutional support for transdisciplinary research will involve the development of a new type of research-enabling environment, based on interactions within polycentric networks. In particular, the enabling of transdisciplinary research places emphasis on crossing disciplinary boundaries and building process competences for boundary-crossing learning in hybrid networks of societal actors and researchers. The latter competences are essential assets for dealing with different stakeholder contexts and transitioning from projects with relatively consensual sustainability values to those that necessitate carefully managing value conflicts.

The focus placed in this book on involving researchers and societal actors in integrated polycentric networks as an important governance feature of transdisciplinary research reflects similar developments in the more general analysis of polycentric approaches to deliberation in environmental governance. As emphasized by scholars of deliberation, such as John Dryzek, Simon Niemeyer, and David Schlosberg, the institutionalization of deliberative processes on a larger scale needs to integrate deliberation at local sites with a larger polycentric approach (Schlosberg et al., 2019; Niemeyer, 2020; Dryzek, 2022). This polycentric approach organizes capacity building in a system of nested governance, already called for by Elinor Ostrom in her work on polycentric network governance. However, as underscored by scholars of deliberation, for the wider activation of deliberative capacities, such a polycentric system also needs to implement different governance mechanisms for guaranteeing authentic deliberation in each of the problem-solving and social learning processes in local sustainability transformations (Owen and Smith, 2015; Niemeyer, 2020; Niemeyer et al., 2023).

Although the above arguments on local deliberative capacities are developed in a more general framework – analyzing the general conditions for authentic deliberation– they nicely summarize the key message on capacity-building for transdisciplinary research in this book. Indeed, the more general discussions on the conditions for effective deliberation hint at the danger of dissociating the building of larger institutional systems of transdisciplinary capacity-building from the context-specific activities of research co-design, co-management, and social learning. More specifically, it allows us to pin down, in a more general manner, the point made in Chapter 5 on combining the institutional enabling of transdisciplinary research with activities of knowledge co-production and social learning. In short, building larger nested polycentric institutional architectures relies on designing, testing and evaluating new modes of organization also through co-produced activities and processes by societal actors and researchers.

The articulation of knowledge co-production activities and institutional mechanisms for capacity building implies that a considerable upscaling of transdisciplinary co-production will only be possible by involving both academic researchers and a broad array of different societal actors in this endeavor. What is the role of citizens or professionals in contributing to transdisciplinary research on society-wide transformations in specific sectors? What kind of policy mix do we need to promote these collaborative processes that require intense social learning between the involved societal actors around new values and modes of coordination? How can universities support promising trends in transdisciplinary research and produce evidence-based knowledge to move from trial-and-error processes to robust and long-lasting societal transformations?

These questions are at the heart of initiatives by societal actors, scientists, and policymakers worldwide, who are building new networks and research partnerships to contribute to sustainable

human development. Regarding transdisciplinary sustainability research, citizens, members of social movements, and members of mission-driven organizations are partners that contribute knowledge and information to scientific endeavors. At the same time, they operate as societal actors fully engaged in collective action in their communities and social networks. Through their privileged position as change agents, societal actors acquire knowledge of possible solutions, first-hand knowledge of social drivers, and motivations for implementing feasible and desirable solutions for sustainability challenges. Hence, through knowledge co-production between scientific researchers and societal actors, new solution pathways actively promoted by societal actors can co-evolve with innovative scientific perspectives and accelerate sustainability transformation processes.

Effective policies must support transdisciplinary research partnerships. Public sector officials are directly involved in the design, planning, implementation, and evaluation of the support measures for public research funding. Moreover, through their expertise and access to various policies and social networks, public-sector officials provide and use many forms of expertise that can promote sustainability transformation. Policymakers, governments, and public administrators can play primary roles in supporting transdisciplinary research. This role can include both the direct participation of public sector officials in transdisciplinary partnership research and, more broadly, the organization of institutional recognition and support for scientific researchers and societal actors' knowledge co-production through transdisciplinary research.

Finally, universities play a pivotal role in the emergence and consolidation of relatively recent transdisciplinary research traditions. First, through the university's basic research mission, academic researchers add value to transdisciplinary research projects by offering innovative perspectives and critical reflections on transdisciplinary research methodologies. Second, and even more importantly, by actively engaging in transdisciplinary partnership research, universities can provide training and capacity building for a new generation of young scholars and students, who are not yet acquainted with the new set of tools and methods for scientifically credible and socially robust knowledge co-production processes through transdisciplinary research. Thus, universities can actively contribute to the integration of the various approaches developed in transdisciplinary partnership science into the overall science fabric.

However, the steps required to achieve these goals are challenging. Indeed, to address multiple social and ecological crises, we need new knowledge to understand the nature of large-scale regenerative societal systems, such as sustainable cities, rural territories, and production systems. Moreover, the systemic, multi-dimensional, and highly pluralistic nature of collaborative efforts is required to resist the traditional disciplinary and ivory-tower modes of conducting scientific research. Fortunately, as many examples in this book show, researchers at universities and research organizations actively experiment and innovate with integrated and collaborative modes of transdisciplinary research to address these challenges. This book aimed to take stock of these inspiring and crucial developments in the context of institutional challenges to further consolidate transdisciplinary research in the organization of contemporary scientific research.

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Annex 1. Glossary of key conceptual terms

Terms defined in the glossary are marked with an asterisk upon their first appearance in the text

Boundary-crossing learning

The literature on boundary-crossing learning defines a boundary as sociocultural differences leading to discontinuities in interaction and action (Akkerman and Bakker, 2011). Defining boundaries as discontinuities rather than differences without mutual interactions, it becomes clear how boundaries are real in their consequences while being malleable and dynamic constructs. Different forms of dialogue between multiple perspectives can be organized at the boundaries, which can induce boundary-crossing learning. Overall, people and objects that cross or stand between boundaries articulate meanings and perspectives of various intersecting worlds while negotiating meanings beyond the boundary from which something new may emerge (ibid.).

Incommensurability of societal values

In this book, we follow many authors who define the incommensurability of societal values in a broad sense. In this broad sense, it designates the impossibility to establish a comparison between the set of societal values at hand that allows for specifying what societal value choice is better or worse for each of the societal values (Chang, 1997). Thus, the term "measure" does not strictly refer to quantitative measures but to all kinds of justified choices based on a ranking of the values according to a better-worse scale. As argued in chapter five and the literature, incommensurability does not lead to the impossibility of choice, as various other criteria can be used to make a justified choice. One example among such justifications is choosing the option that is not overall better but improves the situation per one consideration of importance to all actors (Levi, 2004). Another justification is to choose the set of options that satisfies a partial ranking among the values, for which there is a reasonable consensus among the societal actors (Sen, 2009).

Institutions

The term "institution" is used in this book according to the convention in institutional analyses in the social sciences to denote rules governing the behavior of actors (Pahl-Wostl, 2009). Formal institutions are linked to the official channels of governmental bureaucracies. They are codified in regulatory frameworks or any kind of legally binding document. Correspondingly, they can be enforced by legal procedures. Informal institutions refer to socially shared rules such as social or cultural norms. In most cases, they are not codified or written down. They are enforced outside of legally sanctioned channels.

In this broad context, institutions can be defined as a structural feature of social systems that provides a certain degree of order and stability to social interaction by regulating and affecting the beliefs and behavior of the actors (Sørensen and Torfing, 2007). This definition covers various approaches in institutional analysis. For instance, in so-called rational choice institutionalism, institutions are analyzed according to the rules of the game to which individual actors respond based on their individual preferences (Ostrom, 1990; North, 1999). Sociological institutionalism refers to the set of rules, norms, and cognitive paradigms that shape the identities, capacities, and aspirations of societal actors (Hall and Taylor, 1996).

Integrated socio-ecological systems research

Socio-ecological system research differs in the degree to which the social and ecological are viewed as merely interacting sub-systems or part of a single, integrated system (Binder et al., 2013). The interactive approach considers the social and ecological as relatively independent sub-systems, with a one-way interaction between them, such as the impact of human behavior on ecological outcomes. The integrated systems approach focuses on the emergent system patterns that result from the strong social-ecological system interdependencies (Schlüter et al., 2019). The interdependencies can result from different types of feedback between the social and ecological systems, such as the relation between the impacts of human actions on the ecological systems, the adaptation of the decision-making process to the ecological impacts, and the link back to new types of behavior and impacts (Binder et al., 2013). In other approaches, interdependencies result in higher-level system properties, such as adaptive capacity building in the overall system by enhancing a diversity of solutions to deal with external perturbations (Pahl-Wostl, 2009).

Knowledge co-production in transdisciplinary research

It designates a mode of research based on collaboration between researchers and societal actors to generate scientifically sound, socially relevant, and legitimate knowledge (Polk, 2015; Pohl et al., 2021). Hence, the collaboration includes knowledge integration between researchers and societal actors, co-designing various components of the research framework (Schneider et al., 2019), and clarifying the societal background values of the research participants (Hirsch Hadorn et al., 2008; Herrero et al., 2019).

Research styles

The notion of research style is an analytical tool that allows for identifying the emergence of specific enduring approaches to scientific inquiry (Hacking, 2012). Historical examples are the research styles of Greek geometry, controlled experimentation, and statistical analysis (Crombie, 1995). Each research style introduces new types of objects and evidence related to these objects and involves specific standards of validity of the scientific statements about these objects (Sciortino, 2017). Moreover, each research style (an epistemological notion) can further be differentiated into so-called community-related thought styles. The latter is characterized by the emergence within specific research styles of communities with a common knowledge base, style of communicative behavior and literary expression, and approach to the problem of interest (Fleck, 1979).

Scientific research commons

In the general commons-based production framework, covering community-managed natural resources, urban commons, and knowledge commons, commons refer to collective goods that are jointly shared, used, and managed by groups of varying sizes and interests (Hess and Ostrom, 2007, p. 5). Especially since the mid-1990s, an increasing number of scholars started to analyze the conditions for commons-based knowledge production to counter the increased production of knowledge behind digital fences or privately owned knowledge providers with the rise of distributed, digital information (Kranich, 2007). Regarding scientific research, “scientific research commons” refers to the many collective aspects of scientific research that are jointly used and produced by research communities, networks, and umbrella organization researchers (Benkler, 2008). These collective aspects include the quality management of the research results, such as research community-managed peer review, the

organization of the dissemination of research results, the organization of sharing of pre-publication and post-publication research data and information in research consortia and beyond, and agenda-setting of promising research topics to advance research (Frischmann et al., 2014).

Social and ecological sustainability

This book defines the sustainability of socio-ecological systems from within the framework of mere sustainability, which is the pursuit of environmental sustainability while integrating environmental sustainability challenges with wider issues of justice, equity, and governance (Agyeman and Evans, 2004; Coleman and Gould, 2019). The issue of environmental sustainability can be defined along the lines of the definition of sustainable development by the 1987 United Nations Brundtland Commission as the goal of meeting the needs of the present without compromising the ability of future generations to meet their own needs. The latter implies, as an important sustainability component, considering the planetary resource limits in human development to maintain the functioning of basic life-supporting systems and processes on the planet Earth for present and future generations (Rockström et al., 2009). However, reaching these goals requires addressing the root causes of unsustainability, regarding the wider issues of justice, equity, and governance. As shown in the literature on environmental justice and environmental citizenship, socioeconomic and power-related distributive concerns, fair collective decision-making processes, recognition of the contribution of all sociocultural groups, and building capacities for meaningful participation of all parties beyond merely formal process guarantees for inclusive governance of all parties in societal transformations (Dobson, 2007; Schlosberg, 2013).

Social learning

Studies on governing socio-ecological systems conceptualize social learning as a process of change of understanding in the individuals involved that become situated in wider social units given the exchange of ideas, arguments, and information in social networks and communities of practice (Reed et al., 2010). This definition provides a criterion for evaluating whether social learning occurred in certain groups and networks without conflating the social learning notion with broader expected results, such as generating improved participation or governance outcomes that depend on contributions from other factors (ibid.).

Socio-ecological systems

Socio-ecological systems are complex adaptive systems characterized by feedback across multiple social and ecological dynamics scales (Fischer et al., 2015). In the literature on socio-ecological systems, the term “social” is used in a broad sense to include various behaviors of individual human beings in social contexts, the social relationships between human beings, and the evolution of cultural-cognitive meanings among human beings (Levin et al., 2013; Hicks et al., 2016). Thus, the term “socio-ecological systems” is used as a synonym for coupled human-environment systems (Scholz, 2011) or coupled human and natural systems (Liu et al., 2007).

Transdisciplinary sustainability research

Transdisciplinary research is an integrative mode of organizing scientific research to solve or transition societal and related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge (Lang et al., 2012). Transdisciplinary sustainability research designates basic and applied research to solve sustainability issues practices based on knowledge co-

production among researchers from various scientific disciplines from the natural science and social science (humanities) for the interdisciplinary analysis of integrated socio-ecological systems (Klein, 2010) and (among scientific researchers and societal actors) the improved understanding of the socially legitimate and relevant perspectives on the solution pathways (Lux et al., 2019).

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Annex 2. Case study list

Case studies from the "most different" case study sampling of well-documented transdisciplinary research projects within the five levers of change. Initial sampling from a keyword search in four journals between 2005 and 2020 (*Ecological Economics, Ecology and Society, Environmental Science and Policy, Sustainability Science*) and the case study volume by Bergmann et al. (2012). In a second step, the sample was completed to reach a minimum of five papers for each lever of change through a general search in google scholar on "transdisciplinary sustainability research" or "participatory sustainability research" and keywords representative of that lever of change (cf. the detailed discussion of the sampling strategy in section 3.1.2).

Projects with marked with "(*video*)" are documented with a short video interview and background materials on https://www.lptransition.be/td

	co-M	co-D	SL	C4	C5	C6
None or very few usable knowledge outputs						
Green infrastructure in Eindhoven to combat the summer heat, the Netherlands				L1		Bodilis, 2018
Intensive grazing in mountain landscapes, France				L2		Lamarque et al., 2013
Sustainable land use in the Upper Valais mountain area, Switzerland				L2		Brand et al., 2013
Housing insulation for the energy transition in Bottrop, Germany (*video*)				L2		Bierwirth et al., 2017
Loss of peatland through reforestation, Finland				L3		Saarikoski et al., 2019
Scenarios for biofuel use in Europe				L3		Baudry et al., 2018a; 2018b
Sustainable energy options, (electricity, heating) in Ebhausen, Germany				L3		McKenna et al., 2018
Sustainable energy options (electricity, heating) in Urnach, Switzerland				L3		Trutnevyte et al., 2011; 2012
Nature conservation and agricultural production in the Elbe valley, Germany				L4		Bergmann et al., 2012, ch. III.K
Understanding values and impacts of bicycle infrastructure, Auckland, New Zeeland				L5		Macmillan and Woodcock, 2017
A framework for housing refurbishment, United Kingdom				L5		Macmillan et al., 2016
Water management in an urban context, Switzerland				L5		Pahl-Wostl and Hare, 2004
Sustainable mobility and urban densification in Las Vegas, Nevada, US				L2		Stave 2002, 2010
Assessing the social and environmental value of urban green in Gothenburg, Sweden				L3		Klingberg et al., 2017; Andersson-Sköld et al., 2018
Partnerships with housing renovation companies in the Rhine-Main area, Germany				L4		Bergmann et al., 2012, ch. III.G
Moderate to significant usable knowledge outcomes, for a limited part of the intended users/beneficiaries						
Citizen science in Manchester neighborhoods with industrial pollution, United Kingdom				L1		Newman et al., 2020
Scenario building and empowerment in rural development, India, Philippines, and Indonesia				L5		Bourgeois et al., 2017
Farming activities in biodiversity-rich mountain areas in the Piedmont, Italy				L4		Höchtl et al., 2006
Sustainable agriculture and small-scale tourism in a mountain area, France (*video*)			-	L4		Lavorel et al., 2019

Income generation activities from mangrove ecosystems, Kenya			SL	L5	78	Galafassi et al., 2018; Fortnam et al., 2019
ATD Food assistance project with the urban poor in Brussels, Belgium (*video*)			SL	L5	64	Joos-Malfait et al., 2019; Osinski, 2020
Mitigation in Urban Context, Rotterdam, the Netherlands (*video*)				L5	65	Roorda et al., 2014; Tillie et al., 2012
Renewable energy options through local/regional energy sources, Austria				L2		Binder et al., 2014

	co-M	co-D	SL	C4	C5	C6
Moderate to significant project outcomes, for a large part of the intended users/beneficiaries						
Nuclear radiation around mines, Niger and Namibia				L1		Conde, 2014
Renovation of historic houses in the inner city of Cahors, France				L1	47	Claude et al., 2017
Digital services for sustainable mobility solutions in Stockholm, Sweden (*video*)			SL	L1	79	Bieser et al., 2021; Sjöman et al., 2020
Public transport in park-and-ride facilities for urban mobility in Potsdam, Germany				L3	55	Schmale et al., 2015; 2016
Changing a rural diet with high saturated fat, Finland				L4		Puska et al., 2009
Mobility style analysis in various cities, Germany				L4		Bergmann et al., 2012, ch. III.B; Hadorn et al., 2008, ch. 6
Indigenous knowledge of basket weaving in the Brazilian Amazon				L4		Athayde et al., 2017
Energy poverty in the informal urban settlements of Enkanini, South Africa			SL	L5	62	Van Breda and Swilling, 2019
Protection of lobster fisheries and sensitive coastal habitats, Belize				L2	53	Verutes et al., 2017; Arkema et al., 2019
Community mapping of land use and ecosystem-based plan, Xáxli'p community, Canada			SL	L4		Diver, 2017
Urban traffic slowing and cultural identity, Australia				L2	51	Macmillan et al., 2014; Macmillan and Mackie, 2016; Mackie et al., 2018
Very comprehensive usable knowledge outcomes, for a large part of the intended users/beneficiaries						
Seed selection for forage autonomy, France			SL	L1	49	Goutiers et al., 2016; Lacombe, Couix et Hazard, 2017
Adding value to the food value chain in small-holder dairy farming, Kenya				L1		Restrepo et al., 2020
Creation of a Nature Park designation in the Black Forest, Germany				L4		Rhodius et al., 2020, ch. 6
Small-scale sustainable forestry in Larzac, France			SL	L2	53	Simon and Etienne, 2010
Conservation management in Scottish Moorlands, United Kingdom			SL	L4	77	Ainsworth et al 2020
Management and re-use of organic waste in Brussels, Belgium (*video*)			SL	L2		Bortolotti et al., 2019
Community health surveying of asthma prevalence from pollution in New York, USA			SL	L4	58	Corburn, 2005
Urban homeless communities field surveys in Toronto, Canada				L4		Khandor and Mason, 2011

Improved access to health services for nomadic pastoralists, Chad			SL	L4	80	Bergmann et al., 2012, ch. III.F; Hirsch Hadorn et al., 2008, ch. 17
River pollution and recreational fishing, Switzerland			SL	L2		Burkhardt and Zehnder, 2018

Legend

- List of case studies represented in 4 clusters of increasingly strong co-production of usable knowledge outputs (cf. annex 3 for the coding scale that was used)
- Co-M (co-management), Co-D (co-design), SL (social learning): average values of the Likert scale, for the cases listed in each of the 4 clusters (cf. annex 3 for the coding scale that was used)

	very strong and comprehensive
	very strong
	strong
	moderate
	weak

- SL: in the column on social learning, cases with extensive documentation of the social learning process (independently of the level of social learning) are indicated with SL; these cases served as the basis for the cluster analysis in chapter 4.
- C4: Thematic field according to one of the five levers of change, as defined in section 3.1.2: (L1) Socio-technical levers of change, (L2) Biophysical levers of change in socio-ecological systems, (L3) Socioeconomic levers of change, (L4) Multistakeholder governance for policy implementation, and (L5) Including the diversity of sociocultural perspectives
- C5: Page number of discussion of the case in the main text
- C6: References of the project publications

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Annex 3. Coding Scales

Coding scales used to code the cases from the case study list, for the core explanatory variables research co-design, co-management, social learning, information gathering and communication) and the outcome variable (co-production of usable knowledge outputs). Similar scales were used to code the control variables (types of involved societal actors, disciplines and thematic fields), however they did not lead to significant correlations with the usable knowledge outcomes.

EXPLANATORY VARIABLES

Research co-design

Did the project publication explicitly mentions the co-construction of research questions or research frame as a core component of the research process ?

Likert scale

1) **not at all**
2) **on very little aspects of the produced knowledge**
3) **on a few key aspects**
4) **covering a substantial number of the aspects**
5) **covering nearly all aspects**

Process co-management

Did societal actors participated in governing the research process at least through one of the following types ?

- co-research (societal actors jointly organizing the data gathering with the researchers)
- co-intervention (joint organization of real-world interventions as part of the research protocol)
- co-decision (joint supervision of doctoral or post-doctoral research or joint decision-making in the consortium board, if applicable).

Likert scale

1) **not at all**
2) **on very little aspects of the produced knowledge**
3) **on a few key aspects**
4) **covering a substantial number of the aspects**
5) **covering nearly all aspects**

Organized processes of social learning

Was there an explicit workshop for social learning among the project members, situated within one of the four social learning categories of the main text, defined in section 4.3:

- Agreement on process values for common inquiry into the problem identification,
- Common action strategies accommodating divergent perspectives,
- Identifying converging and diverging perspectives, and
- Common action program with a substantial overlap in the value rankings

Likert scale

1) **not at all**
2) **on very little aspects of the produced knowledge**
3) **on a few key aspects**

4) **covering a substantial number of the aspects**
5) **covering nearly all aspects**

Consultation of the societal actors for information gathering in the research process

Was there science-practitioners interaction through one of the following modes

- Information gathering on context specific (local or global) features of the problem situation or the variables of the research framework
- Informing on the project and on outcomes and collect comments, for soliciting feedback from the societal actors

Likert scale

1) **not at all**
2) **on very little aspects of the produced knowledge**
3) **on a few key aspects**
4) **covering a substantial number of the aspects**
5) **covering nearly all aspects**

OUTCOME VARIABLE

Usable knowledge outputs

Did the project produce one of the following project outputs (if several outputs, then code the sum of the evaluation on the Likert scale of each of the output categories) ?

- New solutions (technical solutions, but also diagnosis, evaluation tools) used by societal actors during the project or within the 2 years that follow the project, beyond the interventions that were already planned in the research protocol at the beginning of the project
- Common action plans (for societal actors, government) with clear implementation plans accepted by the intended users and beneficiaries of the project
- New organisational mechanisms established (hierarchies/networks) established, during the project or within the 2 years that follow the project , beyond the interventions that were already planned in the research protocol at the beginning of the project

Likert scale

1) **Not at all**
2) **A small project outcome, for a limited part of of the intended users/beneficiaries**
3) **Moderate to significant project outcome, for a limited part of of the intended users/beneficiaries**
4) **Moderate to significant project outcome, for a large part of the intended users/beneficiaries**

Index

wicked problems x
Williamson, Oliver x