Complexity, ambiguity, and the boundaries of the future:
Toward a reflexive scenario practice in sustainability science

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Social and Ecological Sustainability

Waterloo, Ontario, Canada, 2023

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The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Anita Lazurko was the sole author of Chapters One and Five, which were written under the supervision of Dr. Derek Armitage and Dr. Vanessa Schweizer and were not written for publication. Anita Lazurko was the lead author of all three manuscripts in Chapters Two to Four. Chapter Two was solo authored. Chapter Three was co-authored with Dr. Vanessa Schweizer and Dr. Derek Armitage. Chapter Four was co-authored with Dr. Dan McCarthy, in addition to Dr. Jamila Haider, Dr. Tilman Hertz, and Dr. Simon West from the Stockholm Resilience Centre. As a lead author of these chapters, Lazurko was responsible for leading and conceptualizing the study design, carrying out data collection and analysis, and drafting and submitting manuscripts. The co-authors provided guidance during each step of the research and feedback on draft manuscripts. The co-authors at the Stockholm Resilience Centre also participated in collaborative dialogues that generated the manuscript. Bibliographic citations for Chapters Two to Four are as follows.

Chapter Two

Lazurko, A. (R&R). Boundaries of the Future: A framework for reflexive scenario practice in sustainability science. *One Earth.*

Chapter Three

Lazurko, A., Schweizer, V., Armitage, D. 2023. Exploring “big picture” scenarios for resilience in social-ecological systems: Transdisciplinary cross-impact balances modelling in the Red River Basin. Sustainability Science. https://doi.org/10.1007/s11625-023-01308-1

Chapter Four

Lazurko, A., Haider, J., Hertz, T., West, S., McCarthy, D. (Under Review). Operationalizing ambiguity in sustainability science: Addressing the elephant in the room. *Sustainability Science.*

Abstract

The future of humanity and the biosphere is complex and increasingly uncertain, complicating efforts to understand and address 21st century environmental crises like biodiversity loss and climate change. Transdisciplinary scenario practice offers a promising avenue to make sense of this complexity and uncertainty. Scenarios are often defined as coherent, internally consistent, and plausible descriptions of the potential future trajectories of a system, and transdisciplinarity is an integrative, problem-oriented, and societally embedded research paradigm that aims to generate knowledge about complex and contested problems. However, despite its promise, transdisciplinary scenario practice grapples with persistent ambiguity (i.e., the existence of multiple valid frames), which emerges from the plural values and perspectives of diverse actors involved in knowledge production, resistance to integration via any singular frame offered by an individual discipline, and the inherent complexity of sustainability challenges.

The lack of concepts, frameworks, and tools to operationalize ambiguity presents risks to the salience and legitimacy of transdisciplinary scenario practice. Ambiguity renders any scenario process as a partial framing of the future that focuses attention on what is most relevant and is contingent on how it was produced. Reflexivity (i.e., the process of examining how one's own beliefs, judgments, and practices influence the research) is cited as a crucial capacity for navigating such ambiguity, yet its role in sustainability science, and in scenario practice, remains unclear. Without reflexivity, those developing and using the scenarios are left without the means or motivation to critically reflect on how the scenarios are produced, their underlying assumptions, and their strengths and limitations for different modes of application. Further, the boundaries that delineate what future conditions and values are included *and excluded* from the scenarios are rendered invisible. This gap influences the salience and legitimacy of the scenarios to real-world sustainability challenges, particularly amid contemporary demands to enrich scenarios with the novel and potentially transformative conditions of the 21st century.

This dissertation explores two opportunities to operationalize ambiguity through reflexivity in transdisciplinary scenario practice. First, the field of operational research has a multi-decade history grappling with theoretical and practical aspects of ambiguity through critical systems thinking (CST), offering opportunities for sustainability science. Second, most scenario methods require implicit trade-offs that reduce or ignore aspects of complexity (and thus ambiguity), failing to get the "big

picture" roughly right. Semi-quantitative scenario methods like cross-impact balances (CIB) produce internally consistent scenarios by systematically and reflexively integrating diverse drivers of change, thereby reconciling some of these trade-offs and offering a promising yet underutilized scenario method for sustainability science.

Paper I aimed to contribute to reflexive scenario practice in sustainability science by making ambiguity explicit and operational using the lens of CST. This investigation generated the Boundaries of the Future framework, a novel synthesis of literatures that characterizes how key boundary judgments (i.e., choices that delineate what is included or excluded from a system) involved in the design of a scenario process influence the scope of future potential (i.e., future conditions and values) reflected in scenario outcomes, and proposes the degree to which this scope of future potential may reflect the dynamics of, and/or conditions for, social-ecological systems (SES) change (i.e., a dominant complexity-based lens that views high-level system behavior as emerging from social-ecological and cross-scale interactions and feedbacks). The most expansive choice under each of the ten boundary judgments in the framework enriches scenarios with the conditions for transformation (i.e., fundamental, systemic shifts away from existing systems; desirable or undesirable; navigated or unintended). The framework can be operationalized as an *ex ante* or *ex post* reflexive tool in sustainability research and practice by rendering each of the ten boundary judgments as an explicit site of critical reflection in a scenario process. Doing so can improve the salience and legitimacy of the scenarios, including by enriching scenarios with the potential for transformation.

Paper II aimed to explore the potential for semi-quantitative scenario methods to enrich scenario practice for a) the development of 'big picture' (i.e., integrative and holistic) scenarios in sustainability science and b) river basins attempting to build resilience to climate change. This objective was addressed through a case study transdisciplinary CIB modelling process in the Red River Basin, a transboundary river basin shared by the United States and Canada. The scenarios explore 'big picture' scenarios of a river basin under climate change by characterizing future change as emergent from interactions between diverse efforts to build resilience and a complex, cross-scale SES. The results surface significant complexities and ambiguities surrounding efforts to build resilience in river basins and affirm the potential for the CIB method to generate unique insights about the trajectory of SESs.

Reflections on the irreducible ambiguity that persisted through Papers I and II led to the development of Paper III, which aimed to explore how key concepts, frameworks, and lessons from CST may be adapted to help address the challenges presented by ambiguity in sustainability science (i.e., beyond scenario practice). The major contribution of this investigation is an operational definition of ambiguity focused on the subjectivity of system boundaries (i.e., *an emergent feature of the simultaneous and interacting boundary processes associated with being, knowing, and intervening in complex systems)* and two recommendations for sustainability scientists to operationalize ambiguity as a valuable means of addressing sustainability challenges: 1) adjust the theoretical orientation of sustainability science to consider the potential for and consequences of theoretical incommensurability and discordant pluralism, and 2) nurture the reflexive capacities of transdisciplinary researchers to navigate persistent ambiguity. CST literature and four case study reflections (including the transdisciplinary scenario process from Paper II) were used to develop the novel framework of Reflexive Boundary Critique to guide critical reflection on ambiguity at all stages of the research process.

In sum, this dissertation explored opportunities to operationalize ambiguity through reflexivity in transdisciplinary scenario practice, contributing to a rich and growing body of research that addresses the ambiguities inherent to research about complex sustainability challenges. My hope is that this contribution helps sustainability scientists give shape to and embrace ambiguity as a fundamental part of rigorous sustainability science.

Acknowledgements

I am grateful to everyone who was part of this research journey. Thank you to all those who contributed to the case study research in the Red River Basin. Thank you to Ted Preister and Dimple Roy, for co-conceptualizing and guiding the study from your positions of wisdom at the Red River Basin Commission and the International Institute for Sustainable Development. Rhian Brynjolson, your artwork helped make the study come alive. Most importantly, thank you to the study participants for generously sharing your knowledge.

I was lucky to spend five magical months visiting the Stockholm Resilience Centre in 2022. Thank you, Jamila Haider, for being a generous research host and providing a stimulating environment for me to deepen my research practice. Thank you to Simon West and Tilman Hertz for being thoughtful and encouraging collaborators, and Maja Schluter and the rest of the SESLINK group for inviting me into your discussions. Thank you Kajsa Sahlin, Anna Woodhead, and the many other researchers I met for the conversation and friendship. Thank you also to everyone I met on the island of Tranholmen, for making daily life in Sweden so life-giving and showing me how to take a proper summer holiday.

At the University of Waterloo, I benefited from the support of the leadership and administration at the School of Environment, Resources, and Sustainability (SERS), especially Jennifer Nicholson and Amanda Campbell. Thank you to my cohort of PhD students at SERS for the support, friendship, and especially for the zoom calls throughout the early days of the pandemic. Thank you also to the members of the Schweizer Research Group for the weekly discussions.

This research wouldn't have been possible without the support of the Social Sciences and Humanities Research Council of Canada, the Pierre Elliott Trudeau Foundation, and the Waterloo Institute for Complexity and Innovation. A special thank you to the PETF, for the programming and the opportunity to connect to the wisdom of your network. Thank you to the mentors and fellows, especially Eric Meslin, for helping give shape and substance to the possibilities ahead. Most importantly, thank you to my cohort of scholars: your intellect, humor, and passion is inspiring and humbling, and I am honored to call you friends.

To my supervisors Derek Armitage and Vanessa Schweizer, and to my committee members Dan McCarthy, Jeremy Pittman, and László Pintér. Thank you for supporting and challenging this dissertation to completion, for trusting my ideas, and giving me the freedom to make my own adventure while offering guiderails as needed. The contributions and learnings are shared with all of you.

Of course, thank you always to all my family and friends who have loved and supported me through the years - you know who you are. And little Archie, my best bud.

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"The first lesson of the universe is to never reason from only a single instance. Unless you only have one instance. In which case: find another."

Richard Powers, *Bewilderment*

Chapter 1
Introduction

1.1 Rationale and objectives

1.1.1 Complex and increasingly uncertain futures

The future of humanity and the biosphere is increasingly uncertain. The unprecedented scale of anthropogenic impact on the environment is pushing Earth systems past critical tipping points related to biodiversity loss and climate change, leading to nonlinear and irreversible changes (Rockström et al. 2009; Steffen et al. 2018). As a result, biophysical baselines are shifting in ways that can no longer be predicted using historical data; for example, river basins experience the impacts of climate change as climatic non-stationarity, resulting in more unpredictable precipitation regimes and an increased frequency and severity of extreme events (Milly et al. 2008; Marchau et al. 2019; IPCC 2021). Additionally, trade, financial, and communication systems are progressively more complex and hyperconnected yet homogenized across the globe, increasing the potential for novel risks and surprise events that are difficult to model (Young et al. 2006; Homer-Dixon et al. 2015; Keys et al. 2019; van der Leeuw 2020). For example, disruptions to food production in an agricultural river basin due to an extreme drought may cascade into global supply chains, impacting global food security (Rockström et al. 2014a; Ray et al. 2019; Ghadge et al. 2020; IPCC 2021). In such complex systems, the interactions between multiple social and ecological drivers, and across multiple scales (i.e., local to global), are more likely to produce emergent, transformative outcomes than individual drivers alone (Westley et al. 2011; Lade et al. 2013; Moore et al. 2014; Rocha et al. 2015). However, because not all drivers and interactions are measurable and testable, efforts to anticipate the future of these systems inevitably exclude important future conditions (Bell 1997; Carpenter et al. 2009; Elsawah et al. 2020).

These irreducible uncertainties are inherent properties of complex systems (Preiser et al. 2018), yet they complicate efforts to address the root cause of 21st century sustainability challenges. On the one hand, actors are responding directly to calls for deliberate transformation away from the unsustainability and injustice of the status quo (O'Brien 2011; United Nations 2015; McPhearson et al. 2021). Such transformations are motivated by profoundly different visions of the future in which new structures and processes address the root causes of persistent issues like biodiversity loss and climate change (Milkoreit 2016; Moore and Milkoreit 2020). While seemingly desirable, the pursuit of transformation is contested and messy as actors pursue novel innovations based on diverse and potentially divergent visions of the future (Leach et al. 2010). These innovations interact with broader system structures – which often resist such transformations – to produce emergent and difficult-to-predict outcomes (Moore et al. 2014).

On the other hand, actors are trying to build the resilience of existing systems to novel risks, thereby nurturing the capacity to develop under a changing environment (Folke 2016; UNFCCC 2019). In practice, such resilience building attempts to identify solutions that are adaptive to increasingly plausible yet more extreme future conditions, many of which are a direct result of the persistent environmental challenges that warrant transformation (Homer-Dixon et al. 2015; Helbing 2013; Keys et al. 2019). For example, efforts to build resilience to climate change in river basins range from conventional large-scale diversion schemes to mass wetland rehabilitation and restoration – two solutions that are rooted in divergent perspectives and interests in the existing system (Sendzimir et al. 2010; Mendez et al. 2012; Marshall and Alexandra 2016). Thus, seemingly contradictory efforts interact with one another and the larger systems within which they are a part, producing emergent outcomes that are difficult to imagine and nearly impossible to predict.

1.1.2 The promise of transdisciplinarity and scenarios

Sustainability science is tasked with the daunting challenge of trying to make sense of this complexity and uncertainty. The response to this challenge has contributed to two promising trends in the field. First, the ‘transdisciplinary turn’ of sustainability science emerged alongside other scientific paradigms like post-normal science (Funtowicz and Ravetz 1993) and mode 2 science (Nowotny et al. 2003) in response to the recognition that pluralist and societally embedded knowledge systems are required for science to contribute to the transformative changes required to address the root causes of 21st century environmental crisis (Cundill et al. 2005; Cornell et al. 2013; Caniglia et al. 2020). Transdisciplinarity grapples with complexity and uncertainty by bridging both disciplinary and science-society divides through reflexive, problem-oriented, and integrative research (Lang et al. 2012; Brandt et al. 2013). The intention of this paradigm is not only to generate broader system knowledge, but to mobilize knowledge in ways that promote meaningful learning for scientists and actors, including that which is required to contribute to the transformative agenda of sustainability science (Shrivastava et al. 2020).

Second, scenarios are increasingly popular tools for making sense of complexity and uncertainty in sustainability science (Peterson et al. 2003; Bai et al. 2016). Scenarios are often defined as coherent, internally consistent, and plausible descriptions of the potential future trajectories of a system (Heugens and van Oosterhout 2001). Scenarios have been developed through diverse methods at various scales (Oteros-Rozas et al. 2015a; Moallemi et al. 2021) and have been used to directly inform policy making or facilitate social learning (Börjeson et al. 2006; Miller 2007; Elsawah et al. 2020; Pereira et al. 2021). For example, explorative scenarios are used to identify solutions that are resilient or robust to multiple possible future climatic or socio-economic conditions (Lempert 2003), and normative scenarios are used to imagine and strategize pathways to desirable (e.g., more sustainable) futures (Börjeson et al. 2006). Scenarios have also been used to structure transdisciplinary research in which a model is co-produced through engagement with collaborators (McBride et al. 2017; Voinov et al. 2018; Moallemi et al. 2021). Recently, literature on the role of imagination in deliberate sustainability transformation has motivated the use of experimental scenario methods and creative media to build motivation and shared commitment for change (Galafassi et al. 2018; Hebinck et al. 2018a; Pereira et al. 2018a).

1.1.3 The importance of the social-ecological systems perspective

The union of transdisciplinarity and scenario practice is accompanied by a third important trend that further renders complexity and uncertainty explicit in sustainability science: the social-ecological systems (SES) perspective. The prevailing command-and-control mode of natural resource governance assumed ecosystems respond to human intervention in predictable, linear, and controllable ways (Dietz et al. 2003). In contrast, the SES perspective views linked human and natural systems as complex adaptive systems (Levin 1998; Levin et al. 2013). This view grapples explicitly with complexity by focusing on the social-ecological interactions and cross-scale feedbacks that produce high-level system behavior (Folke 2006; Reyers et al. 2018). Moreover, the SES perspective accepts uncertainty as irreducible and inherent to complex adaptive systems, which have unique properties that produce emergent and often surprising outcomes (Preiser et al. 2018). For example, complex SES dynamics allow the system to fluctuate within a single stable state or push it across thresholds into alternative states through regime shifts or social-ecological transformations that may be difficult or impossible to reverse (Walker et al. 2004; Folke et al. 2010; Rocha et al. 2015).

The SES perspective informs both transdisciplinarity research and scenario practice in sustainability science. In the case of transdisciplinarity, the SES perspective is often operationalized as an overarching framework to facilitate integration across disciplines (i.e., between the 'social' and the 'ecological') and perspectives in research about complex sustainability challenges (Angelstam et al. 2013; Benham and Daniell 2016; Cockburn 2022). This often occurs through the use and adaptation of seminal frameworks in the field (e.g., Ostrom 2009; Folke 2016). In the case of scenario practice, researchers applying the SES perspective have used scenarios as sense-making tools to characterize, adapt, and build resilience to the irreducible uncertainties of complex systems (Peterson et al. 2003; Verburg et al. 2016), with particular focus on place-based SESs (Oteros-Rozas et al. 2015a). Normative or target-seeking scenarios have also been suggested as essential tools in the early 'preparation' stage of social-ecological transformation (Moore et al. 2014).

1.1.4 Challenges: Persistent ambiguity and a lack of reflexivity

Clearly, the union of transdisciplinarity and scenario practice offers a promising avenue to make sense of complex and uncertain futures in sustainability science. This potential is furthered by the complexity-based lens offered by the SES perspective. However, while these trends enrich one another, they also present a major challenge. Namely, in their efforts to make sense of complexity and uncertainty, they each grapple with the ambiguity (i.e., the existence of multiple valid frames) that is inherent to complex sustainability challenges. Transdisciplinary research surfaces ambiguity through the plural values and perspectives of diverse actors involved in knowledge production. This ambiguity persists because transdisciplinarity resists integration via any singular frame offered by an individual discipline (Leach et al. 2010; Preiser et al. 2018; Dewulf et al. 2020; Turnhout et al. 2020). Ambiguity also permeates scenario literature under different names including future openness, which stems from a combination of uncertainty and ambiguity (Bell 1997; Elsawah et al. 2020); the subjectivity of plausibility judgments (Wiek et al. 2013; Schmidt-Scheele 2020); and critical futures literature, which directly challenges the predict-and-control origins of early scenario work (e.g., Inayatullah 1998a, b). The SES perspective highlights ambiguity as a persistent feature of the study of – and intervention in – complex adaptive systems (Levin et al. 2013; Preiser et al. 2018). For example, CASs are radically open, which makes it nearly impossible to decide which system components are inside and outside the system. Consequently, any system interpretation is partial, provisional, and contingent on subjective boundary choices (Juarrero 1999; Preiser et al. 2018).

While ambiguity is considered a feature of research about complex sustainability challenges, its role in sustainability science remains unclear. Myriad interpretations of ambiguity exist in uncertainty literature (Funtowicz and Ravetz 1990; Walker et al. 2003; Dewulf and Biesbroek 2018) and, of particular relevance to sustainability science, science and technology studies literature (Stirling 2006; West et al. 2014). The latter reveals how ambiguity implicates the intersection of epistemology (ways of knowing) and ontology (ways of being) – i.e., different frames emerge from and shape future action. While this conceptualization views ambiguity as inherent to complexity, it does not render ambiguity explicit and operational in ways that can be addressed in transdisciplinary scenario practice for sustainability science, and thus remains difficult to translate into policy and practice. Moreover, reflexivity (i.e., the process of examining how one's own beliefs, judgments, and practices influences the research) is often cited as a crucial capacity for navigating ambiguity and pluralism in both transdisciplinary research and scenario practice (Miller 2013; Miller et al. 2014; Popa et al. 2015; Haider et al. 2018). In other words, reflexivity can translate ambiguity from a slippery phenomenon 'out there' to a process that can be embedded in research. Yet, reflexivity in sustainability science, and for scenario practice, has been criticized for a lack of clarity and is not mainstream (Inayatullah 1998a; Jasanoff and Kim 2015; Popa et al. 2015; Scheele et al. 2018). Interestingly, the importance of capacities like reflexivity is not only discussed within academic literature: the Inner Development Goals are an emerging suite of policy and practice-oriented objectives that aim to identify and nurture the inner transformative skills required to achieve the Sustainable Development Goals (Inner Development Goals 2023).

The lack of concepts, frameworks, and tools to operationalize ambiguity through reflexivity in sustainability science is a crucial gap. Emerging frameworks and tools grapple with dimensions of ambiguity, such as by facilitating epistemological pluralism (Martin 2012; Tengö et al. 2014) or nurturing the unique capacities required of transdisciplinary researchers (Haider et al. 2018; Chambers et al. 2022). Research in sustainability science has also suggested the need to grapple with the subjectivity of system boundaries in research about complex SESs (Audouin et al. 2013). Yet, in the absence of holistic and operational modes of reflexivity, many sustainability scientists still operate from a middle space in which they embrace complexity and understand the need for pluralism broadly but struggle to overcome their tendency to evaluate knowledge against a singular 'unambiguous' frame. In such cases, ambiguity is not explicit yet persists, leaving research vulnerable to myriad risks and power dynamics associated with uncritical transdisciplinary collaboration. These risks include conflict and misunderstanding in collaboration across disciplines, paradigms, or sectors (Strang 2009), and the power dynamics that cast less dominant perspectives as political or subjective and more dominant perspectives as neutral and objective (Turnhout 2018; Turnhout et al. 2020).

The lack of concepts, frameworks, and tools to operationalize ambiguity through reflexivity is highly relevant to scenario practice. No scenario framework or method, even if applied in a transdisciplinary process, can reconcile the diverse domains, scales, values, drivers, and perspectives implicated in the future of complex sustainability challenges (Swart et al. 2004; Carpenter et al. 2009; Bai et al. 2016; Verburg et al. 2016). Therein lies the ambiguity: any scenario process produces a partial frame of the future that focuses attention on what is deemed most relevant and is contingent on how it is produced. Without reflexivity, scenario users are left without the means or motivation to critically reflect on the influence of subjective choices made in the design of a scenario development process (e.g., choice of framing or methods) and the strengths and limitations of these choices for their mode of application. Further, the boundaries that delineate the scope of future potential in the resulting scenarios (i.e., what future conditions and values are included *and excluded*) are rendered invisible. This gap influences the salience and legitimacy of the scenarios to real-world sustainability challenges; for example, by introducing the risk that scenarios are used in unintended or even inappropriate ways, or that scenarios are missing crucial conditions or values (i.e., more dominant frames of the future are reinforced, while those considering more novel or marginalized perspectives are cast aside). This latter risk is particularly relevant under contemporary demands to enrich scenarios beyond the status quo to reflect the unique conditions of the 21st century; for example, to motivate the pursuit of deliberate transformations to sustainability (Moore et al. 2014; Patterson et al. 2017), help actors build resilience to novel risks and disruption (Keys et al. 2019; Pereira et al. 2021) or assess the long-term implications of unsustainability, e.g., loss and damages (Mechler and Schinko 2016).

1.1.5 Opportunities: critical systems theory and semi-quantitative scenario analysis

This dissertation moves from the view that transdisciplinary scenario practice offers a promising avenue for making sense of complex and uncertain futures in sustainability science. Additionally, I view the social-ecological systems (SES) perspective as an important complexity-based lens for furthering this potential. However, these promising trends all grapple with persistent ambiguity, and the lack of concepts, frameworks, and tools to operationalize ambiguity through reflexivity presents risks to the salience and legitimacy of the outcomes of the research. The resulting research gap is broader than can be addressed in a single dissertation, so I focus on exploring two opportunities.

First, the field of operational research has a multi-decade history grappling with theoretical and practical aspects of ambiguity, offering opportunities for sustainability science. Critical systems thinking (CST) emerged from operational research to address divergence and conflict between first wave (i.e., positivist, hard systems) and second wave (i.e., interpretivist, soft systems) approaches (Midgley 1989; Flood and Jackson 1991; Jackson 2019). CST applies systems thinking, which is compatible with the social-ecological systems (SES) perspective. Yet, it does so through a pragmatist critique of the systems approach (Matthews 2006), moving from an epistemological ideal of critical awareness, emancipation, and pluralism (Flood and Ulrich 1990; Gao et al. 2003). In the process, CST grapples with conceptual challenges associated with ambiguity, such as theoretical and methodological pluralism (Midgley 1989, 1992; Ulrich 2003), in addition to practical frameworks that operationalize ambiguity through critical reflection on the subjectivity of system boundaries (Ulrich 1983; Midgley 2000). This lens complements the work of systems thinkers focused on the ethics and social impacts of systems thinking (Stroh 2015) and development psychologists concerned with the inner capacities required to break out of limited mindsets and embrace ambiguity (Kegan and Lahey 2016). Yet, CST is distinct in that it addresses ambiguity through a focus on system boundaries, presenting a unique opportunity to render ambiguity explicit and operational in scenario practice for sustainability science. Emerging research points to the promising lens offered by CST for sustainability research (e.g., Helfgott 2018; Rutting et al. 2022), yet the use of CST concepts and tools is still marginal.

Second, sustainability science lacks the integrative and holistic scenario methods required to 'open up' scenario practice to complexity and ambiguity. Instead, most scenario methods require implicit trade-offs (e.g., due to practical constraints) that reduce or side-step aspects of complexity, and thereby ignore the potential for alternative frames, i.e., ambiguity (e.g., see the Fallacy of Misplaced Concreteness, Whitehead (1967)). Such processes fail to "get the big picture roughly right", which is required to "peer through the mist of uncertainty" surrounding decisions about contemporary sustainability challenges (Polasky et al. 2020). For example, quantitative methods may be data-informed and reproducible but exclude drivers of change or perspectives that cannot be measured in quantitative terms (Gerst et al. 2014; Moallemi et al. 2021). Conversely, qualitative scenario methods consider a wider range of conditions, but, at times, lack the systematic approaches and analytical insights promoted by quantitative methods (Ramirez and Wilkinson 2014). Semi-quantitative scenario methods have been applied in energy and climate change research and are uniquely positioned to expose and reconcile some of these trade-offs. For example, the cross-impact balances (CIB) method applies systems theory to generate internally consistent narrative scenarios from a network of interacting qualitative *and* quantitative drivers of change (Weimer-Jehle 2006; Weimer-Jehle et al. 2016). The systematic approach required to build the components of a CIB model (see Section 1.3.2) makes all assumptions about the trajectory of these different drivers and their interactions explicit, facilitating a form of reflexivity that may surface unique complexities and ambiguities in the context of application (e.g., alternative frames of the same system). Moreover, the system-theoretical approach of CIB has unique compatibilities with the SES perspective that have yet to be explored. An opportunity exists to experiment with how such integrative and holistic (i.e., big picture) scenario methods can be used to structure transdisciplinary processes that take complexity and ambiguity seriously, thereby 'opening up' scenario practice to reflect a wider range of drivers and perspectives.

1.1.6 Dissertation purpose, objectives, and major contributions

The purpose of this dissertation is to explore these two opportunities (Section 1.1.5) in service of a more reflexive transdisciplinary scenario practice in sustainability science. This dissertation is manuscript-based, with each manuscript focusing on one objective.

- Paper I (Chapter 2): Boundaries of the future: A framework for reflexive scenario practice in sustainability science (Objective 1)
- Paper II (Chapter 3): Exploring big picture scenarios for resilience in social-ecological systems: Transdisciplinary scenario modelling in the Red River Basin (Objective 2)
- Paper III (Chapter 4): Operationalizing ambiguity in sustainability science: Addressing the elephant in the room (Objective 3)

Objective 1 (Paper I) aims to contribute to reflexive scenario practice in sustainability science by making ambiguity explicit and operational using the lens of CST. The major academic contribution from this investigation is the Boundaries of the Future framework. The framework is a novel synthesis of literatures that 1) characterizes how key boundary judgments (i.e., choices that delineate what is included or excluded from a system) involved in a scenario process influence the scope of future potential reflected in scenario outcomes, and 2) proposes the degree to which this scope of future potential may reflect the dynamics of, and/or conditions for, SES change. The most expansive choice under each boundary enriches scenarios with the conditions for transformative change (i.e., fundamental, systemic shifts away from existing systems; desirable or undesirable; navigated or unintended; see Chapter 2). The practical contribution of the investigation is the opportunity to use the Boundaries of the Future framework as an *ex-ante* or *ex post* reflexive tool, rendering each of the ten boundary judgments as an explicit site of critical reflection in a scenario process. Doing so can improve the salience and legitimacy of the scenario process, especially amid demands to enrich scenarios with the novel and potentially transformative conditions of the 21st century. The 72 social-ecological scenario case studies used to generate the framework exhibited a bias away from these more expansive choices, affirming the need to experiment with integrative and holistic scenario methods like CIB (Objective 2). Moreover, while the Boundaries of the Future framework aims to operationalize ambiguity through reflexivity, it is still a reflection of the onto-epistemological and methodological orientation of the study. This challenge of irreducible ambiguity motivated and informed the use of CST to operationalize ambiguity in sustainability science beyond scenarios (Objective 3).

Objective 2 (Paper II) aims to explore the potential for the CIB method to enrich scenario practice for a) the development of 'big picture' (i.e., integrative and holistic) scenarios in sustainability science and b) river basins attempting to build resilience to climate change. This objective was addressed through a case study transdisciplinary scenario modelling process in the Red River Basin, a transboundary river basin shared by the United States and Canada, in partnership with the Red River Basin Commission and the International Institute for Sustainable Development. The scenarios explore 'big picture' (i.e., integrative and holistic) scenarios of a river basin under climate change by characterizing future change as emergent from interactions between diverse efforts to build resilience and a complex, cross-scale SES. The results surface significant complexities and ambiguities surrounding efforts to build resilience in river basins and affirm the potential for the CIB method to generate unique insights about the trajectory of SESs. Reflection upon the process revealed how the CIB method contributed to 'opening up' boundary judgments (i.e., to consider the dynamics of, and conditions for, SES change) that were underexplored in the case studies used to generate the Boundaries of the Future framework (Objective 1). However, ambiguity persisted through the modelling process due to process-oriented constraints and underlying onto-epistemological tensions.

This reflection motivated and informed efforts to operationalize ambiguity in sustainability science more broadly (Objective 3).

Finally, through investigation of Objectives 1 and 2, a broader objective emerged. **Objective 3 (Paper III) aimed to explore how key concepts, frameworks, and lessons from CST may be adapted to help address the challenges presented by ambiguity in sustainability science (i.e., including and beyond scenario practice).** More specifically, it aimed to establish 1) a holistic conceptualization of ambiguity and 2) recommendations for how sustainability scientists can operationalize this conceptualization of ambiguity as a valuable means of addressing sustainability challenges. The major contribution of this investigation is an operational definition of ambiguity focused on the subjectivity of system boundaries (i.e., *an emergent feature of the simultaneous and interacting boundary processes associated with being, knowing, and intervening in complex systems)* and two recommendations for sustainability scientists to operationalize ambiguity: 1) to adjust the theoretical orientation of sustainability science to consider the potential for and consequences of theoretical incommensurability and discordant pluralism, and 2) to nurture the reflexive capacities of transdisciplinary researchers to navigate persistent ambiguity. CST literature and four case study reflections, including the transdisciplinary scenario process from Objective 2, were used to develop the novel framework of Reflexive Boundary Critique to guide critical reflection on ambiguity at all stages of the research process. The findings of this objective can help sustainability scientists give shape to and embrace ambiguity as a fundamental part of rigorous sustainability science.

1.2 Literature and theoretical framing

The dominant bodies of literature informing the dissertation are depicted in Figure 1-1, under categories of theoretical lens, research practice, and application area. Each body of literature is summarized in Sections 1.2.1 to 1.2.3. The three bodies of literature that comprise the theoretical lens (i.e., SES theory, transformation theory, and CST) are granted the most attention, and are further elaborated as required for specific aspects of the dissertation in Papers I, II, and III. The bodies of literature associated with the research practice and the application area are not discussed in full but are rather summarized to situate the contributions of the dissertation.

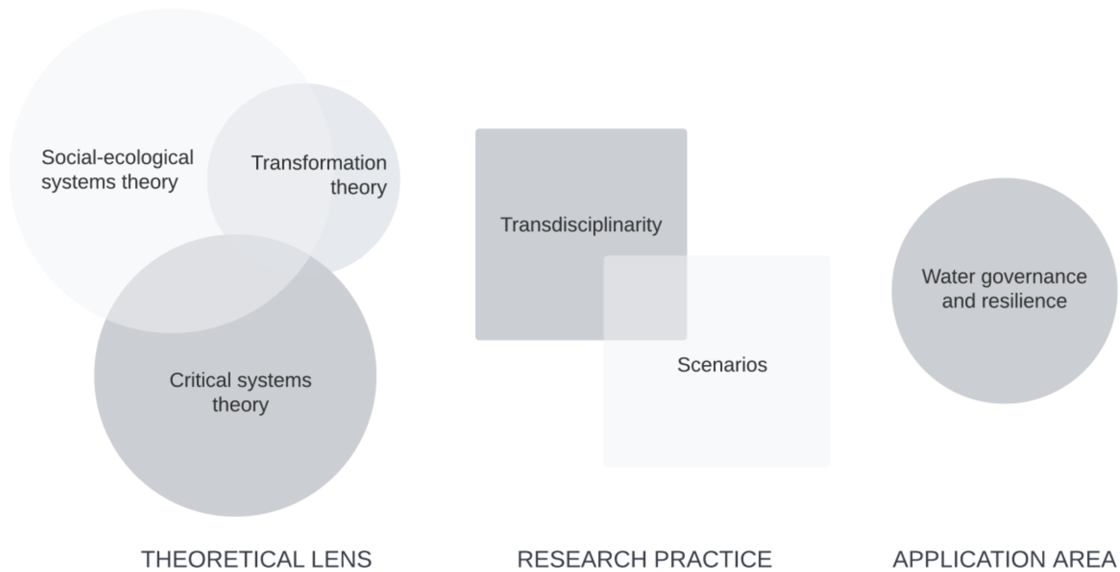

Figure 1-1: Dominant literatures for the dissertation

1.2.1 Theoretical lens

1.2.1.1 Social-ecological systems theory

SES theory addresses the complexity of the future by characterizing linked human and natural systems as complex adaptive systems (Levin 1998; Preiser et al. 2018). This theory directly informs Papers I and II and is discussed in Paper III. From an SES view, high-level system behavior emerges from low-level processes of self-organization involving social-ecological interactions and feedbacks between multiple drivers across scales (Folke 2006; Reyers et al. 2018). SESs can experience significant changes as they fluctuate within a single stable state or move across thresholds into alternative states through regime shifts (Müller et al. 2014; Rocha et al. 2015), or as actors pursue deliberate social-ecological transformations (Walker et al. 2004; Folke et al. 2010). The unique characteristics of social-ecological transformation are discussed alongside other transformation theories in Section 1.2.1.2.

The SES perspective characterizes the interplay of stability and change through social-ecological resilience or 'resilience thinking'. Resilience evolved from roots in ecology (Holling 1973; Berkes et al. 2003) to become a forward-looking approach focused on the unique capacities of SESs to persist, adapt, and transform in the face of unexpected and surprising change (Folke 2016). While persistence, adaptation, and transformation may intuitively appear to act in tension, their interdependencies manifest through social-ecological interactions across spatial and temporal scales. For example, the heuristics of the adaptive cycle and panarchy, which characterize the continuous cycles of growth, conservation, destruction, and reorganization across scales that characterize change in SESs (Holling 2001), reveal how cycles of change at smaller scales can revolt and change larger cycles and how the accumulated memory at larger scales can affect smaller scales (Walker et al. 2004; Filbee-Dexter et al. 2017). An emerging frontier of SES research focuses on detailing the capacities required for adaptation and transformation, including system reflexivity (Moore et al. 2018; Folke et al. 2021). Through this dynamic lens, resilience thinking helps characterize how and why efforts to build resilience to novel risks, for example in river basins dealing with climate change, interact with – and often encompass – efforts to transform away from the status quo.

The SES perspective also highlights the unique characteristics of complex adaptive systems that introduce ambiguity to the study of – and intervention in – complex sustainability challenges (Levin et al. 2013; Preiser et al. 2018). For example, SESs are radically open as information, energy, and matter are constantly exchanged across a permeable boundary between the system and its environment (Preiser et al. 2018, 2021). They are also constituted relationally, meaning a system’s behavior is determined more by the nature of its interactions than individual components, and these interactions connect systems in nested hierarchies across spatial and temporal scales (Gunderson and Holling 2003; Cash et al. 2006; Preiser et al. 2018). These features render the external boundary conditions as integral to system behavior as the system structure and make it nearly impossible to decide which system components are inside and outside the system (Juarrero 1999; Preiser et al. 2018). Thus, these boundary conditions are dependent on the choices of the observer, who is also part of the system they seek to understand (Cilliers 2001; Preiser et al. 2018).

In response to critiques of more mechanistic applications of the SES perspective (e.g., Leach 2008; Cretney 2014), sustainability science increasingly draws from diverse domains of social science. This move to social sciences deepens knowledge about the ‘social’ component of SESs, for example by centering the role of agency (Brown 2014; Cretney 2014), the link between landscapes and culture (Masterson et al. 2017; Sterling et al. 2017), or the power and politics that influence efforts to understand and address environmental crises (Brien 2012; Turnhout 2018). Emerging social science research focuses on various dimensions of ambiguity; for example, novel frameworks are weaving together diverse knowledge systems for an enriched picture of SES change (Tengö et al. 2014; Rathwell et al. 2015). These efforts recognize the insights offered by transdisciplinary knowledge production, while acknowledging the risks of cooption, reduction, and instrumentalization of marginalized knowledge systems in uncritical processes of integration (Kates et al. 2012; Rathwell et al. 2015).

1.2.1.2 Transformation theory

Several approaches have emerged to characterize the dynamics of, and conditions for, transformative change, as a response to calls for deliberate "transformations to sustainability" (Patterson et al. 2017). Transformation theory, and in particular SES transformation, is most prominent in Papers I and II, as it directly informed the development of the Boundaries of the Future framework in Paper I and the social-ecological scenario framework that underpinned the transdisciplinary scenario modelling process in Paper II. Transformation theory is less prominent in Paper III, though it is compatible with the critical-emancipatory perspective of CST.

Transformation approaches can be broadly categorized as structural, systemic, and enabling (Scoones et al. 2020). Structural approaches offer descriptive, historical accounts of socially organized ideological change (e.g., the French revolution). Systemic approaches, including the SES perspective, address change in complex systems by analyzing how transformations emerge from relationships between actors, institutions, and ecological or technical variables (Smith et al. 2005; Moore et al. 2014). Enabling approaches, such as sustainability pathways, directly address the human values, agencies, capacities, and framings held by actors that influence transformation (Leach et al. 2010). These three approaches provide distinct but complementary views on transformation.

According to the SES perspective (i.e., a systemic approach), transformation occurs when major changes to social or ecological variables have cross-scale impacts and/or alter the dominant feedbacks that govern the system (Moore et al. 2014). This type of transformation proceeds through three phases: preparing for change, navigating the transformation, and building resilience of the new trajectory (Olsson et al. 2004a; Moore et al. 2014). Through these phases, transformation emerges through shifting interactions between individual actor agency (i.e., bottom-up) and system structure (i.e., top-down) (Westley et al. 2013; Moore et al. 2014, 2018) and requires an enabling environment including institutional structures and capacities for experimentation, integration of diverse knowledge types (Gelcich et al. 2010; Sendzimir et al. 2010), strong multi-level social networks (Moore and

Westley 2011), and availability of local resources (Olsson et al. 2006). Other systemic transformation approaches offer complementary insights to the SES perspective. In particular, the field of sustainability transitions studies hosts an evolving body of literature on governance of sustainability transitions from a socio-technical systems perspective (Rotmans et al. 2001; Rotmans and Loorbach 2009), and mirrors aspects of SES transformation theory. For example, multilevel perspective theory characterizes socio-technical transitions as emerging as niche innovations (i.e., actor agency) as entering the incumbent regime (i.e., system structure) due to changing selection pressures in the regime (Geels 2002; Patterson et al. 2017).

Critiques of systemic approaches to transformation reflect those of the SES perspective more generally (Section 1.2.1.1). These critiques center ambiguity by questioning who governs transformation, whose framings of transformation count, and how wins and losses in transformation are distributed among actors (Smith and Stirling 2008; Leach et al. 2010; Blythe et al. 2018). From this view, transformation is not a universally desired endpoint or process but is contested, value-laden, and subjective to a particular perspective. The STEPS pathways approach directly addresses this view by characterizing transformation as emergent from the interactions that occur within this plural and political space (Stirling 2014). Emerging research in sustainability science draws from this more critical view on transformations while maintaining the SES perspective. For example, Pereira et al. (2018b, 2020) use experimental multimedia scenario methods to create ‘transformative spaces’, which are collaborative spaces in which actors invested in sustainability transformation can experiment with novel ideas and practices to motivate and inform action.

1.2.1.3 Critical systems theory

Operational researchers have a multi-decade history grappling with both theoretical and practical aspects of ambiguity through CST. CST is a key theoretical lens underpinning the Boundaries of the Future framework from Paper I and the operationalization of ambiguity in Paper III. Just as systems approaches are used to understand complex SESs (and SES transformation) in sustainability science, operational research uses systems models to aid in complex implementation problems. The first wave of OR used hard systems models underpinned by expert-driven positivism, which was followed by a second wave of soft systems approaches underpinned by an interpretivist perspective (Midgley 1989; Flood and Jackson 1991; Jackson 2019). Divergence and conflict between first and second wave approaches, in addition to ambiguity surrounding the boundaries of stakeholder engagement, led to the observation that understandings of a problem and what constitutes as 'improvement' may change significantly when system boundaries are altered (Churchman 1970). Thus, Churchman's pragmatist critique of the systems approach (Matthews 2006) launched a third critical-emancipatory wave called critical systems thinking (CST) underpinned by tenets of critical awareness, emancipation, and pluralism (Flood and Ulrich 1990; Gao et al. 2003). Thus, the systems perspective is compatible with SES theory (Section 1.2.1.1), and the critical-emancipatory lens is compatible with transformation theory (Section 1.2.1.2).

CST explicitly grappled with the conceptual challenges associated with ambiguity, including theoretical and methodological pluralism and paradigm incommensurability (Midgley 1989, 1992; Ulrich 2003). Theoretical and methodological pluralism attempted to reconcile debates between first and second wave system approaches by recognizing that methodologies derived from different or contradictory paradigms (e.g., positivist versus interpretivist) offer valid but partial and contextual framings of a system. While desirable in theory, "atheoretical pragmatism" surfaced as individuals picked and chose methodologies without knowledge of their theoretical origins (Midgley 1992; Bowers 2019). This was perceived as a threat to the field, so critical system theorists sought an appropriate meta-framework to guide systemists who were operationalizing pluralism in systems practice (Bowers 2011). The system of systems methodology (SOSM) is the first of such attempts, guiding which type of methodologies are appropriate for the type of system (i.e., simple, complex) and the relationship between participants (i.e., unitary, pluralist, coercive) (Jackson and Keys 1984; Jackson 2019). This effort toward integration via a meta-framework was criticized for several reasons, including for its rigidity and its assumption of theoretical commensurability, which risks masking ambiguity (Gregory 1996).

CST also addressed the need for practical frameworks to operationalize ambiguity through reflection on the partial, provisional, and observer-dependent nature of system boundaries (Ulrich 1983; Midgley 2000). According to Churchman, boundaries are social and personal constructs that determine the limits of knowledge that are considered pertinent for an analysis (Churchman 1970). The framework of Critical Systems Heuristics was proposed to guide reflection upon boundaries through 'boundary critique' (Ulrich 1983; Ulrich and Reynolds 2010). According to CSH, any claim about a system depends on a reference system, which is made up of 'boundary judgments' that generate the dominant view of which facts and values are relevant, thereby indicating empirical and normative selectivity (Ulrich 1983). CSH includes a list of questions designed to facilitate boundary critique by revealing sources of motivation (e.g., what is/ought to be the purpose?), sources of power (e.g., who is/ought to be the decision maker?), sources of knowledge (e.g., what expertise is/ought to be consulted?), and sources of legitimation (e.g., what worldview is/ought to be determining?). Midgley's process philosophy (2000) is a philosophy of knowledge for CST inspired by the process philosophy pioneered by Whitehead (1978). This form of process philosophy proposes a shift from the *content* of knowledge to the *process* of bringing knowledge into being, in particular the *process of making boundary judgments* (see Section 1.3.1).

1.2.2 Research practice

1.2.2.1 Transdisciplinarity

Transdisciplinarity is a research principle that emerged in response to the need for more open, pluralist, and integrative knowledge production to address complex sustainability challenges (Cundill et al. 2005; Cornell et al. 2013; Caniglia et al. 2020). The challenges presented by ambiguity in transdisciplinary research motivated the contributions of Papers I and III, and key principles of the ideal-typical transdisciplinary research process directly informed the methodology of the scenario modelling case study in Paper II (see Section 3.2 for a description of the ideal-typical research process).

The unique characteristics of transdisciplinarity hold promise for addressing complexity and uncertainty (see Section 1.1.2), yet they also contribute to surfacing ambiguity and thus demand reflexivity. Transdisciplinarity is defined as an integrative, reflexive, and method-driven research principle with three key requirements: 1) focusing on societally relevant problems, 2) enabling learning processes among researchers from different disciplines and with actors outside of academia, and 3) creating knowledge that is solution-oriented and socially robust (Lang et al. 2012; Brandt et al. 2013). This paradigm is differentiated from multi- and interdisciplinarity, in which disciplines work together from within or between their individual paradigms, as it aims to "transcend" disciplinary boundaries using collaborative approaches, shared conceptual frameworks, and novel methodologies (Castán Broto et al. 2009; Kemp and Nurius 2015). This high degree of integration, collaboration, and novelty is important for highlighting the complexity of sustainability challenges, yet it surfaces ambiguity through the diverse values and perspectives of scientific and diverse actors involved in knowledge production. This ambiguity often manifests as challenges establishing the reliability, validity, and "social robustness" of the transdisciplinary research outcomes (Lang et al. 2012; Cornell et al. 2013). Addressing these challenges demands highly reflexive integration processes, yet the power dynamics between different forms of knowledge (e.g., scientific over local knowledge, or natural sciences over social sciences) can make such reflexivity practically and ethically challenging (Turnhout et al. 2019).

1.2.2.2 Scenarios

Scenarios have become popular tools for anticipating and navigating change in sustainability science (Peterson et al. 2003; Bai et al. 2016). Scenarios are also used across the science-policy interface; for example, scenarios feature prominently in global environmental assessments like the Shared Socioeconomic Pathways for climate research (Riahi 2016), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Pereira et al. 2020b), and the United Nations Global Environment Outlook (e.g., UN Environment 2019). The Boundaries of the Future framework in Paper I focuses on scenario practice in sustainability science generally, while the transdisciplinary scenario modelling process in Paper II generated novel scenarios using the CIB approach in a case study. As introduced in Section 1.1.2, scenarios are often defined as coherent, internally consistent, and plausible descriptions of the potential future trajectories of a system (Heugens and van Oosterhout 2001). Scenarios were popularized in the latter 20th century through work on scenario planning driven by the US Army and RAND Corporation, alongside qualitative narrative scenario development by Peter Schwartz and colleagues in the Global Business Network (Schwartz 1991). Various typologies of scenarios exist (van Notten et al. 2003a; Mahmoud et al. 2009; Sharpe et al. 2016), with one popular typology differentiating between predictive (i.e., what will happen), explorative (i.e., what could happen), and normative (i.e., what we want to happen) scenarios (Börjeson et al. 2006). The use of scenarios in sustainability science ranges across these scenario types, which are developed through diverse methods including both quantitative models and qualitative participatory processes conducted at various spatial and temporal scales (Oteros-Rozas et al. 2015a; Moallemi et al. 2021). Scenarios are used to directly inform policy and decision making, facilitate social learning, and structure transdisciplinary research processes (Börjeson et al. 2006; Miller 2007; Lang et al. 2012; Elsawah et al. 2020; Pereira et al. 2021). As discussed in Section 1.1.2, scenarios have been used to structure transdisciplinary research in which a model is co-produced through engagement with collaborators (McBride et al. 2017; Voinov et al. 2018; Moallemi et al. 2021).

Amid their rising popularity, scenario research and futures studies have been criticized for a lack of reflexivity connecting a scenario process to its outcomes and impact in the present (e.g., Inayatullah 1998; Jasanoff and Kim 2015; Scheele et al. 2018). Moreover, the use of scenarios has been criticized by scholars who believe that scenarios sometimes lack evidence, downplay uncertainty, do not adequately consider different timelines or perspectives, and lack transparency (Dong et al. 2013; Reed et al. 2013). While discussed only briefly in the contribution of Paper I, the field of anticipatory governance is beginning to address some of these critiques from a governance perspective. Anticipatory governance aims to conceptualize and facilitate processes of "governing in the present to shape uncertain futures" (Muiderman et al. 2020). Anticipatory governance literature offers a critical perspective on these processes – including and beyond scenarios – for example by critiquing the present political implications of anticipatory processes (Boyd et al. 2015; Hebinck et al. 2018b; Vervoort and Gupta 2018; Gupta et al. 2020) and generating novel methods for imagining and navigating a wide range of futures in service of sustainability transformation (Vervoort et al. 2015; Mangnus et al. 2019, 2022). This literature also focuses on reflexivity through the concept of futures literacy (Mangnus et al. 2021), defined as the "capacity to design and implement processes that make use of anticipation" (Miller 2007).

1.2.3 Application area

1.2.3.1 Water governance and resilience

The case study application of CIB in a transdisciplinary scenario modelling process in Paper II is applied to the area of water governance and resilience. A shift in water governance is required to address the novel uncertainties and complexities introduced by climate change at a river basin scale. Water governance is defined broadly as the social functions that regulate and coordinate water development (Jiménez et al. 2020). The dominant 19th and 20th century paradigm of water governance enabled rapid economic development but was limited by silo thinking, reactive management of externalities, and rigid control of variability (Pahl-Wostl 2007; Baird and Plummer 2021). For example, large-scale channels and dams enabled agricultural and energy production but were optimized for historical climate variability and may be brittle to climate change (Altinbilek 2002; McCartney 2009; Giuliani et al. 2016). In recent decades, various paradigms surfaced to deal with these challenges, such as Integrated Water Resources Management (Biswas 2008), the water-energy-food-nexus (Benson et al. 2015), and adaptive governance (Folke et al. 2005; Huitema et al. 2009).

Most recently, the resilience paradigm (Walker et al. 2004; Folke et al. 2010) has been applied to enable effective water governance under climate change (Baird and Plummer 2021). From this view, river basins are complex SESs that evolve with and adapt to environmental change, and outcomes emerge from social-ecological interactions and feedbacks across scales (Rockström et al. 2014a; Walker 2020; Chester et al. 2021). Various definitions of resilience exist, but resilience here is drawn from the SES perspective (Sections 1.1.3 and 1.2.1.1) and involves "the capacity to adapt or transform in the face of change… particularly unexpected change, in ways that continue to support human wellbeing" (Folke et al. 2016; Baird and Plummer 2021). For example, water managers may adopt adaptive rather than static management plans and processes, optimize infrastructure for multiple climate scenarios rather than one, or use ecosystems for their natural capacity to buffer variability alongside traditional infrastructure (Pahl-Wostl and Knieper 2014; Faivre et al. 2017; Marchau et al. 2019).

While a resilience paradigm may be effective for dealing with climate change, efforts to build resilience in practice are complex and contested. Novel approaches may be viewed as risky (Jeffrey and Gearey 2006) and must contend with the institutional inertia of conventional approaches (Sendzimir et al. 2010; Mendez et al. 2012; Marshall and Alexandra 2016). For example, infrastructure financing mechanisms may be biased away from valuing the long-term, systemic impacts of resilient solutions (Lazurko and Pintér 2022). Additionally, despite a shared language of resilience, efforts to build resilience hold hidden tensions and trade-offs rooted in divergent perspectives and interests in the future (Leach 2008; Helfgott 2018a). For example, questions of resilience to what and for whom surface assumptions about what constitutes a desirable resilient future, and the costs (financial and non-financial) and degree of system transformation required to achieve it. These challenges are particularly pronounced in contexts where building resilience may require transformative changes that shift pathways toward a profoundly new system (Folke et al. 2016; Pereira et al. 2021).

1.3 Research design

The dissertation is situated within the paradigm of transdisciplinarity (Lang et al. 2012; Brandt et al. 2013) as discussed in Section 1.1.2 and 1.2.2.1, which surfaces unique considerations regarding salience, credibility, and legitimacy across disciplinary and science-society boundaries (Cash et al. 2005; Hansson and Polk 2018). Consequently, this dissertation is guided by efforts to achieve the balance of epistemological agility and methodological groundedness required for rigorous transdisciplinary sustainability science (Haider et al. 2018). Epistemological agility here is defined as "an understanding of different ontological and epistemological standpoints and views across multiple disciplines" and is discussed in Section 1.3.1 (philosophical foundations). Methodological groundedness is defined as "the deep understanding and skillful handling of at least one specific methodological approach for data gathering, modeling, and/or analysis" and is discussed in Section 1.3.2 (research methods).

1.3.1 Philosophical foundations

The philosophical foundations summarized in Table 1-1 drew on the approach by Haider (2017) and were guided by work by Moon and Blackman (2014) and Moon et al. (2021). Broadly, the dissertation is rooted in a *complexity worldview*. Complexity emerged from the systems approach and has been studied from various perspectives (Bateson 1979; Prigogine and Stengers 1984; Rosen 1991; Cilliers 1998; Levin 1999). A recent epistemological break moved away from the restricted complexity of this systems approach (i.e., studying specific types of systems called "complex") toward general complexity (i.e., a complexity worldview, where any system is complex), drawing attention to the relationship between the whole system and its parts (Morin 2008; Preiser et al. 2018). The dissertation addresses complexity from the latter view, primarily through the dominant social-ecological systems (SES) perspective (see Section 1.2.1.1).

The ontological foundations of the dissertation span from *bounded relativism* to *critical realism* (Moon and Blackman 2014). Bounded relativism (i.e., multiple realities exist for different social groups based on experiences and culture) opens up discussions about ambiguity and reflexivity in Papers I and III to both epistemological and ontological pluralism, encompassing a broad range of onto-epistemological and theoretical commitments that may influence ambiguity in sustainability science. In contrast, critical realism (i.e., one reality exists but is unknowable in full, so all knowledge is limited (Bhaskar and Hartwig 2016; Cockburn 2022)) offers grounds to validate the integrated scenario framework and scenario model developed in Papers I and II, respectively, while acknowledging the presence of multiple interpretations of (unknowable) reality.

The epistemological foundations of the dissertation were broadly *constructionist*, in which meaning is generated through an interplay between the subject and object of knowledge, i.e., in the interaction between the observer and the observed (Moon and Blackman 2014). Papers I and III adopt this orientation in their application *to change/liberate* (Moon et al. 2021) the field of sustainability science by exploring opportunities to operationalize ambiguity through reflexivity. More specifically, Papers I and III adopt the critical-emancipatory lens of *process philosophy* from critical systems theory (Section 1.2.1.3), which emerged from a pragmatist critique of the systems approach (Matthews 2006). Process philosophy shifts focus from the *content* of knowledge to the *process* of bringing knowledge into being, in particular the *process of making boundary judgments* (Midgley 2000). This lens connects the observer and the observed through the same lens (i.e., the process of making boundary judgments), which is appropriate for a complexity worldview that views knowledge as partial and provisional (i.e., due to the dynamics of complex adaptive systems) and situates observers as part of the complexity they seek to understand. Moreover, process philosophy allows for methods derived from different paradigms (e.g., positivist versus interpretivist) to co-exist without contradiction (Midgley 2000; Jackson 2019).

Paper II adopts a *constructionist* orientation in its application to simultaneously *understand* the future of the Red River Basin, and also to *change/liberate* (Moon et al. 2021) by 'opening up' the future to diverse perspectives and drivers through the use of a particular method. In spanning these two motivations for acquiring knowledge, Paper II adopts a broadly *pragmatist* lens, which takes seriously the idea that it is "impossible to apprehend (non-contextually) the whole system" (Churchman 1970; Matthews 2006), so all necessary approaches are required to address a research problem (Moon and Blackman 2014). This stance allowed for a combination of methods (e.g., semi-structured interviews, literature validation, workshops, etc., see Section 1.3.2) to be used in the transdisciplinary scenario modelling process.

Table 1-1: Summary of philosophical foundations of the dissertation

	Worldview: Complexity		
Chapter	Paper I	Paper II	Paper III
	'Boundaries of the future'	*'Exploring big picture scenarios'*	*'Operationalizing ambiguity'*
Ontology	Bounded relativism ←→	Critical realism ←→	Bounded relativism

Epistemology	Constructionism		
Application	Critical-emancipatory ←→ Pragmatism ←→ Critical-emancipatory		
Methodology	Abductive		
Methods	Process of abductive inquiry in literature	Transdisciplinary scenario modelling in the Red River Basin	Dialogue among co-authors

1.3.2 Research methods

This dissertation is underpinned by an abductive mode of inquiry. Abduction is defined as "inference to the best explanation" and tends to be used at the stage of hypothesis formulation and testing and theory development (Walton 2005). Abduction was appropriate because the dissertation was exploratory and involved navigating between inductive and deductive modes of inquiry as required, both within each chapter (e.g., Paper I) and across the dissertation. The research design included three components corresponding to Papers I, II, and III. These components are described in full in each of the respective chapters.

1.3.2.1 'Boundaries of the future' from a process of abductive inquiry

Objective 1 was addressed through a process of abductive inquiry in literature (Chapter 2, Paper I). This process began with a high-level assumption that emerged through reading widely in relevant literatures: critical systems theory offers an appropriate theoretical lens for reflexive scenario practice in sustainability science through its focus on boundary judgments. Following this proposition, a search protocol generated a) a body of seminal literature in sustainability science (i.e., the dynamics of, and conditions for SES change and transformation) and scenario practice, and b) a list of 72 social-ecological scenario case studies. An inductive review of the seminal literature generated twelve provisional boundary judgments in an initial framework. To be included in the framework, the boundary judgment must (1) directly connect to (implicit or explicit) choices in the design of a scenario process, (2) apply to nearly every scenario process to justify inclusion in an integrative guiding framework (i.e., noting that critical systems theory highlights how additional, context-specific boundary judgments will also be required in each unique case), and (3) delimit the scope of future potential in a way that may reflect the dynamics of, and/or conditions for, SES change (including transformation). Then, these twelve provisional boundary judgments were used as themes for deductive coding of 72 social-ecological scenario case studies. The boundary judgments in the framework were refined and validated using the coding of the case studies. An additional step beyond the framework development applied descriptive statistics to the case study coding to indicate common Boundaries of the Future in scenario case studies to date.

1.3.2.2 'Big picture futures' from transdisciplinary scenario modelling in the Red River Basin

Objective 2 was addressed through a transdisciplinary scenario modelling process in the RRB, in partnership with the Red River Basin Commission and the International Institute for Sustainable Development (Chapter 3, Paper II). The RRB is part of the Hudson Bay drainage system, covering parts of Minnesota, South Dakota, and North Dakota, before meandering northward for approximately 480 km into Lake Winnipeg in Manitoba (Red River Basin Commission 2005; Leitch and Krenz 2013). Climate change is expected to exacerbate existing climatic variability and its implications in the region (Prairie Climate Centre 2013; Rasmussen 2016; Bertrand and Mcpherson 2018; Shrestha et al. 2020).

The CIB scenario method was used to structure the scenario modelling process. CIB projects internally consistent scenarios from a network of interacting qualitative or quantitative drivers of change (Weimer-Jehle 2006; Kosow and Gaßner 2008). The CIB modelling process begins with determining a set of *descriptors*, which are the most important and uncertain drivers of change influencing the future of a system. The uncertainty of each descriptor is represented by a small number (i.e., 1 to 4) of *variants*, or mutually exclusive outcomes. In CIB, a scenario is made up of the selection of one variant for each descriptor. The systemic interactions between descriptors are determined by considering *influence judgments* between variants. These judgments are the direct influences of the selection of a variant from one descriptor on the selection of a variant from another. A software like ScenarioWizard (Weimer-Jehle 2021) is used to calculate the impact balances for each possible scenario to determine which scenarios are internally consistent (i.e., self-reinforcing and stable) or internally inconsistent (i.e., transient or unstable). Scenarios that are internally consistent are considered plausible by many CIB analysts (Schmidt-Scheele 2020).

The scenario modelling process followed the steps of an ideal-typical transdisciplinary study, which moves through collaborative problem framing, knowledge co-creation, and (re)integration of the knowledge (Lang et al. 2012). Prior to CIB modelling, consultation with partners helped frame the purpose of the scenarios, which was to address the issue of resilience to floods and droughts to the year 2050. The scenario modelling process was guided by an SES framework, which caters to the structure of CIB by depicting the future of an SES as emerging from social-ecological interactions across scales (i.e., river basin and global) and between the system structure and actor agency (Walker et al. 2006; Scholes et al. 2013; Reyers et al. 2018). Efforts were made to ensure the framework prompted consideration of more transformative outcomes where possible. Development of the scenarios began with a round of semi-structured interviews with experts and opinion leaders in the RRB (n=34), which were inductively coded multiple times to generate the model descriptors and variants, and to indicate potential influence judgments. A second round of interviews (n=11) confirmed these judgments. Significant uncertainty and ambiguity in the influence judgments was addressed through literature validation and sensitivity analysis, which followed a similar protocol to Schweizer and Kriegler (2012). The resulting scenario analysis produced eight scenarios that were robust (i.e., to uncertainty in the model assumptions) and internally consistent (i.e., self-reinforcing and stable configurations of the system). Three near-term strategies were tested for their systemic influence on scenario outcomes. The results of the process were translated into narratives and visual art, which were presented and discussed with participants in a debrief workshop.

1.3.2.3 'Operationalizing ambiguity' from dialogue among co-authors

Objective 3 was developed alongside a group of co-authors assembled during a research visit at the Stockholm Resilience Centre (Chapter 4, Paper III). A proposition emerged through reflection during the development of Papers I and II and the associated review of key literature in CST and sustainability science (i.e., transdisciplinarity, social-ecological systems change, and transformation). Namely, that key concepts, frameworks, and tools from CST may be applicable beyond the use of scenarios to help operationalize ambiguity in sustainability science. This proposition was brought to the group of co-authors for a series of dialogues that iteratively and reflexively drew from researchers' individual knowledge and experiences and additional relevant literature. The first dialogue oriented all co-authors to key literature and clarified the process moving forward. The insights and recommended literature from the first dialogue were synthesized into three areas of sustainability science that influence, or are influenced by, ambiguity: 1) framings produced by diverse research paradigms in transdisciplinary research, 2) framings held by actors within a research context, and 3) the onto-epistemological and ethical framing held by an individual researcher. Each co-author was asked to read one or two key papers and bring reflections to the next dialogue.

The second dialogue followed a structured discussion about these three areas of interest. First, co-authors explored the three areas of sustainability science that influence, and are influenced by, ambiguity from the first dialogue, which helped to identify a common stance among co-authors, clarify key tensions and identify missing areas of literature. Then, each co-author shared their reflections on the assigned readings. Finally, each co-author reflected on a past or current case study, guided by frameworks from CST (e.g., boundary critique, boundary marginalization). The results of the second dialogue were synthesized into a provisional conceptualization of ambiguity, and several key insights from CST that may help operationalize ambiguity in sustainability science. This was shared with co-authors to launch a third dialogue, which focused on identifying unresolved tensions in the contribution to date. These unresolved tensions were placed in a discussion document where co-authors contributed their written thoughts. All contributions were then synthesized into the first draft of a manuscript. This draft manuscript was discussed in a fourth dialogue and refined through subsequent meetings and asynchronous communication among co-authors until completion.

1.3.3 Ethics and positionality

The fieldwork for the transdisciplinary scenario modelling study in Paper II was reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee, study no. 43193, which included informed participant consent. In addition to the protections offered by these ethical formalities, my own motivation and positionality have ethical implications that should be acknowledged.

This dissertation was motivated by a normative stance: that the existing global trajectory is deeply unsustainable and unjust, and enriching the way we engage with the future (and ambiguity therein) can and should make a difference. While this normativity may be obvious for a PhD in Social & Ecological Sustainability and a problem-orientation is routine in transdisciplinary research, the choice to engage with certain problems and not others, and to put faith in impact through academic institutions (which have a strong colonial legacy), can be ethically fraught.

My positionality as a white, woman, settler Canadian, engineer-turned-transdisciplinary sustainability scientist situates my role in the contribution of this dissertation and in academia more broadly. My strength as a researcher lies in my bridging role, which is fluent in the dominant disciplinary language and perspective of my early training while caring deeply about and gesturing toward the marginalized. Yet, to approach ‘the future’ from this place of relative privilege carries an ethical responsibility to recognize and address the historical pitfalls of well-intentioned researchers who inadvertently reinforce status quo injustices by nature of their presence (Snow 2018; McGuire-Adams 2021) - i.e., transdisciplinarity situates me, the researcher, as not only analyzing but intervening in systems. I cannot claim to have navigated these tensions perfectly, but I learned a lot and attempted to address this omnipresent ‘elephant in the room’ in Paper III. I hope this and other demonstrations of reflexivity in doctoral research for sustainability (e.g., Haider 2017; Macdonald 2019; González García-Mon 2022) inspire others to reflect upon and lean into the irreducible ambiguity inherent to research about complex sustainability challenges.

1.4 Organization of the dissertation

This dissertation is comprised of five chapters and is manuscript-based. Chapter 1 is the ‘Introduction’ that introduces the rationale, purpose and objectives, literature and theoretical background methods, and major contributions of the dissertation. Chapter 2 is Paper I, titled ‘Boundaries of the future: A framework for reflexive scenario practice in sustainability science’. The manuscript develops and validates a reflexive framework for scenario practice in sustainability science. Chapter 3 is Paper II and is titled ‘Exploring big picture scenarios for resilience in social-ecological systems: Transdisciplinary cross-impact balances modelling in the Red River Basin’. The manuscript explores ‘big picture’ (i.e., integrative and holistic) scenarios of the Red River Basin under climate change through a transdisciplinary scenario modelling process and explores the potential for the CIB method to surface diverse perspectives and drivers of change. Chapter 4 is Paper III and is titled ‘Operationalizing ambiguity in sustainability science: Addressing the elephant in the room’. The manuscript explores how key concepts and frameworks from CST may be adapted to conceptualize and operationalize ambiguity in sustainability science. Finally, Chapter 5 synthesizes the significant and original contributions to knowledge made in this dissertation. This includes a review of the purpose and objectives, a summary of key research findings, and reflections on the strengths and limitations of the research.

Chapter 2

Boundaries of the future: A framework for reflexive scenario practice in sustainability science

2.1 Introduction

Scenarios are increasingly popular tools for anticipating and navigating change in sustainability science (Peterson et al. 2003; Bai et al. 2016). Scenarios are often defined as coherent, internally consistent, and plausible descriptions of the potential future trajectories of a system (Heugens and van Oosterhout 2001). The use of scenarios in sustainability science ranges from explorative (i.e., possible futures) to normative (i.e., desirable futures), and can be used to directly inform policymaking or facilitate social learning (Börjeson et al. 2006; Miller 2007; Elsawah et al. 2020; Pereira et al. 2021). Scenarios are developed through diverse methods, including both quantitative models and qualitative participatory processes conducted at various spatial and temporal scales (Oteros-Rozas et al. 2015a; Moallemi et al. 2021). They are also used as sensemaking tools to facilitate transdisciplinary (i.e., problem-oriented and integrative) research (Lang et al. 2012). Emerging applications also help participants imagine and experiment with novelty to build commitment and motivation for deliberate transformation (Butler et al. 2016; Sharpe et al. 2016; Moore and Milkoreit 2020).

Amid their rising popularity, scenario practice in sustainability science grapples with the ambiguity (i.e., existence of multiple valid interpretations) inherent to the future of complex sustainability challenges. This ambiguity can be understood through the social-ecological systems (SES) perspective, which has become a dominant lens of inquiry in sustainability science. The SES perspective views the future of linked human and natural systems as emergent from complex and cross-scale social-ecological interactions (Folke et al. 2010; Preiser et al. 2018). From this lens, ambiguity stems from the complexity of SESs (i.e., "we cannot know complex things completely" (Midgley 2000; Cilliers 2002)) and their high degree of future openness (i.e., important conditions are not all measurable and testable, producing both uncertainty and ambiguity (Bell 1997; Carpenter et al. 2009; Elsawah et al. 2020)). This ambiguity persists amid the diverse perspectives and value conflicts of scientists and actors attempting to understand and intervene in these systems (Funtowicz and Ravetz 1993; Rathwell et al. 2015; Haider et al. 2018).

Scenario practice for sustainability science currently lacks the frameworks and tools required to effectively expose and address this ambiguity. In particular, scenario research and futures studies have been criticized for a lack of reflexivity, e.g., critical reflection regarding how the design of a scenario process influences the scenario outcomes (Inayatullah 1998a; Jasanoff and Kim 2015; Scheele et al. 2018). Anticipatory governance literature responds to this critique in part by conceptualizing and facilitating processes of "governing in the present to shape uncertain futures" (Muiderman et al. 2020). This research often focuses on the political implications of anticipation and how to use the future to make better decisions in the present (Boyd et al. 2015; Hebinck et al. 2018b; Vervoort and Gupta 2018; Gupta et al. 2020). It also addresses the need to develop futures literacy, i.e., the capacity to effectively utilize processes of anticipation (Miller 2007; Gugerli 2010), which includes "reflexivity regarding different attitudes toward the future" (Mangnus et al. 2021). Yet, it does not yet offer practical and holistic frameworks that can be operationalized to guide more reflexive scenario practice in sustainability science.

The lack of practical and holistic frameworks to operationalize ambiguity through reflexivity presents risks to the salience and legitimacy of scenario practice in sustainability science. No single model or method can reconcile the diverse domains, scales, and perspectives implicated in complex sustainability challenges (Swart et al. 2004; Carpenter et al. 2009; Bai et al. 2016; Verburg et al. 2016). Consequently, any scenario process offers a partial framing of the future that focuses attention on what is most relevant and is contingent on how the scenarios were produced (Turnhout et al. 2019). For example, scenarios used in global environmental assessments (Riahi 2016; UN Environment 2019; Pereira et al. 2020b) are adopted across research communities as useful narratives of the global future (O'Neill et al. 2020; Bakkes et al. 2022; Kuiper et al. 2022). Yet in all cases, the research communities developing the scenarios acknowledge they have limitations and are working to enrich them with a broader and more inclusive set of future conditions and values (Rothman et al. 2009; O'Neill et al. 2020; Pereira et al. 2021; van Ruijven et al. 2022). Without reflexivity, scenario users are left without the means or motivation to critically reflect on the influence of subjective choices made in the design of a scenario development process (e.g., choice of framing or methods) and the strengths and limitations of these choices for their mode of application. Further, the boundaries that delineate the scope of future potential in the resulting scenarios (i.e., what future conditions and values are included *and excluded*) are rendered invisible. This gap may limit the potential impact of the scenario process on real-world sustainability challenges (e.g., if scenarios are missing important conditions (Scheele et al. 2018)) and leaves scenario processes vulnerable to the power dynamics between frames (e.g., more dominant frames of the future are considered neutral and objective, while novel or marginal frames are cast as political and subjective (Turnhout 2018; Turnhout et al. 2020)).

Efforts to enrich scenario practice beyond dominant frames of the future are particularly crucial for navigating novel and disruptive SES change in the 21st century. The unprecedented scale of anthropogenic impact on the environment is increasing the potential for nonlinear, irreversible, and disruptive SES change (Rockström et al. 2009; Steffen et al. 2015; Keys et al. 2019). Biophysical baselines are shifting in ways that can no longer be predicted using historical data (Milly et al. 2008; Polasky et al. 2011; Marchau et al. 2019; IPCC 2021). Moreover, global trade, financial, and communication systems are progressively more complex and hyperconnected yet homogenized, increasing the potential for novel risks and surprise events (Young et al. 2006; Liu et al. 2013; Homer-Dixon et al. 2015; Keys et al. 2019). These and other conditions challenge traditional methods and metrics for understanding the future (Bai et al. 2016; Verburg et al. 2016). Further, actors are responding directly to calls for deliberate transformations away from the unsustainability and injustice of the status quo (O'Brien 2011; United Nations 2015; McPhearson et al. 2021). Imagining and navigating deliberate transformation is thought to demand more pluralist and imaginative scenario processes than are currently mainstream (Pereira et al. 2019, 2021; Moore and Milkoreit 2020). A lack of reflexivity presents the risk that these transformative changes, both desirable and undesirable, are excluded from scenario processes, reducing their salience for addressing 21st century sustainability challenges.

Critical systems thinking (CST) offers a unique epistemological lens to make ambiguity explicit and operational through reflexivity (Vervoort et al. 2015; Helfgott 2018b; Rutting et al. 2022). CST emerged from the field of operational research upon the recognition that understandings of a system and recommendations for improvement may change when boundaries are altered (Churchman 1970). These observations led to the development of a philosophy of knowledge that advocates for critical awareness (i.e., reflection on the limitations of one's own perspective), pluralism (i.e., embracing diverse perspectives), and emancipation (i.e., elevating marginalized or less powerful perspectives) (Flood and Ulrich 1990; Gao et al. 2003; Jackson 2019). This ideal reflects a pragmatist critique of early systems approaches (i.e., that assumed knowledge could be objective and comprehensive) with the view that knowledge is inevitably contextual, partial, and contingent (Matthews 2006). In practice, CST focuses attention on boundary judgments that delineate what is included or excluded from a system, generating a dominant view of which facts or values are considered relevant (Ulrich 1983; Midgley 2000; Ulrich and Reynolds 2010). Process philosophy takes this perspective further, viewing reality and knowledge as produced through this continuous process (Midgley 2000).

This study aims to contribute to reflexive scenario practice in sustainability science by developing a framework to make ambiguity explicit and operational using the lens of CST. The first objective is to develop a reflexive framework (i.e., 'Boundaries of the Future') that 1) characterizes how key boundary judgments involved in a scenario process influence the scope of future potential (i.e., future conditions and values) reflected in scenario outcomes, and 2) proposes the degree to which this scope of future potential may reflect the dynamics of, and/or conditions for, SES change. Importantly, the latter proposition is based on existing theoretical literature in sustainability science, *not* on empirical studies that evaluate a scenario process for its ability to anticipate real-world SES change or produce real-world impacts (e.g., to motivate sustainability transformation). Moreover, the framework is normative in that the most expansive choice under each boundary judgment may enrich the scenario process in ways that reflect the dynamics of, and conditions for, transformation. Here, transformation is defined as fundamental, systemic shifts away from existing systems that are desirable or undesirable and navigated or unintended (Chapin III et al. 2010; Moore et al. 2014). The second objective is to apply the framework by analyzing social-ecological scenario case studies against the boundary judgments in the framework. This process validated the boundary judgments in the framework and revealed common Boundaries of the Future in case studies to date, offering reflections for future research.

2.2 Methods

The framework was developed, applied, and validated through a process of abductive inquiry. Abductive inquiry is defined as "inference to the best explanation" and tends to be used at the stage of hypothesis formulation and testing and theory development (Walton 2005). A process of abductive inquiry was appropriate because developing and validating the framework required reflexively navigating back-and-forth between inductive (i.e., from specific observations to general conclusions) and deductive (i.e., from general information to specific conclusions) modes of reasoning. Further, a process of abductive inquiry enabled the iterative methodology required to a) integrate a range of disparate literatures into an operational framework (i.e., synthesize both theoretical and case study literature that is too dispersed for a highly systematic, purely inductive approach), b) structure this synthesis in a way that exposes the underlying yet often unacknowledged boundary choices that influence scenario practice for sustainability science (i.e., through the lens of boundary judgments from CST), and c) offer a normative stance on how boundary judgments can better reflect the future conditions relevant for sustainability science (i.e., to propose the degree to which different judgments reflect the dynamics of, and conditions for, SES change and transformation). While such an abductive process introduces the potential for researcher subjectivity, it was necessary for the research objectives and was conducted with reflexivity and efforts to reduce researcher bias.

The abductive process (Figure 2-1) began with a high-level conceptual assumption, which was that critical systems theory offers an appropriate theoretical lens for reflexive scenario practice in sustainability science through its focus on boundary judgments (Section 2.2.1). These boundary judgments were considered active sites of judgment required in a scenario process that delimit the scope of future potential in the resulting scenarios. The framework was then developed through several steps (Section 2.2.2 to 2.2.5), guided by the conceptual assumption. (1) A search protocol generated a) a body of seminal literature in scenario practice and sustainability science, and b) a list of 72 social-ecological scenario case studies. (2) An inductive review of seminal literature in scenario practice and sustainability science generated the boundary judgments in the initial framework. (3) This initial framework was applied through deductive coding of 72 social-ecological scenario case studies using these initial boundary judgments as coding themes. (4) The boundary judgments in the framework were refined and validated using the coding of the case studies from (3). (5) An additional step beyond the framework development (Section 2.2.6) applied descriptive statistics to the case study coding from (3) to indicate common Boundaries of the Future in scenario case studies to date.

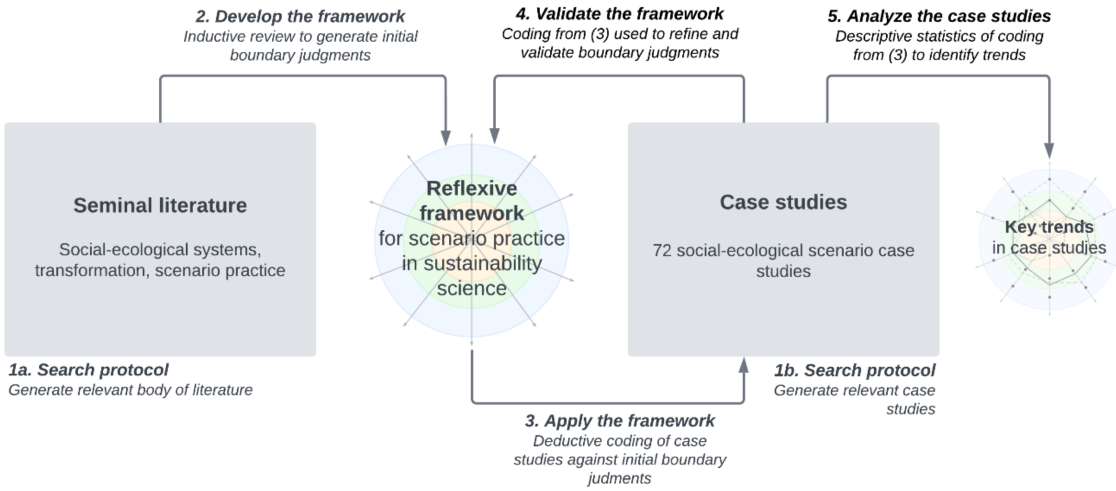

Figure 2-1: Process of abductive inquiry used to generate the reflexive framework for scenario practice in sustainability science

2.2.1 Critical systems theory and the 'boundaries of the future'

The process of abductive inquiry was underpinned by a critical systems lens. In particular, 'boundary critique' is an application of process philosophy, viewing reality and knowledge as produced through the process of making boundary judgments (Midgley 2000). Thus, the conceptual assumption that informed the development of the framework (i.e., that critical systems theory offers an appropriate theoretical lens for reflexive scenario practice in sustainability science through its focus on boundary judgments) is depicted as 'Boundaries of the Future' (Figure 2-2), or an adapted version of the popular futures cone (Voros 2017). According to this view, scenarios are developed in the present. The scenario process involves boundary judgments that delimit the scope of future potential reflected in the resulting scenarios. These boundary judgments are active sites of judgment that implicitly or explicitly determine what is included and excluded from the analysis and generate a dominant view of which facts or values are considered relevant. Future potential beyond these boundaries is marginalized or unknown. The development of the framework considered both first-order judgments (i.e., about the 'observed'), and second-order judgments, which are the content that gives rise to these judgments (i.e., about the 'observer') (Midgley 2000), without differentiation to ensure both were represented.

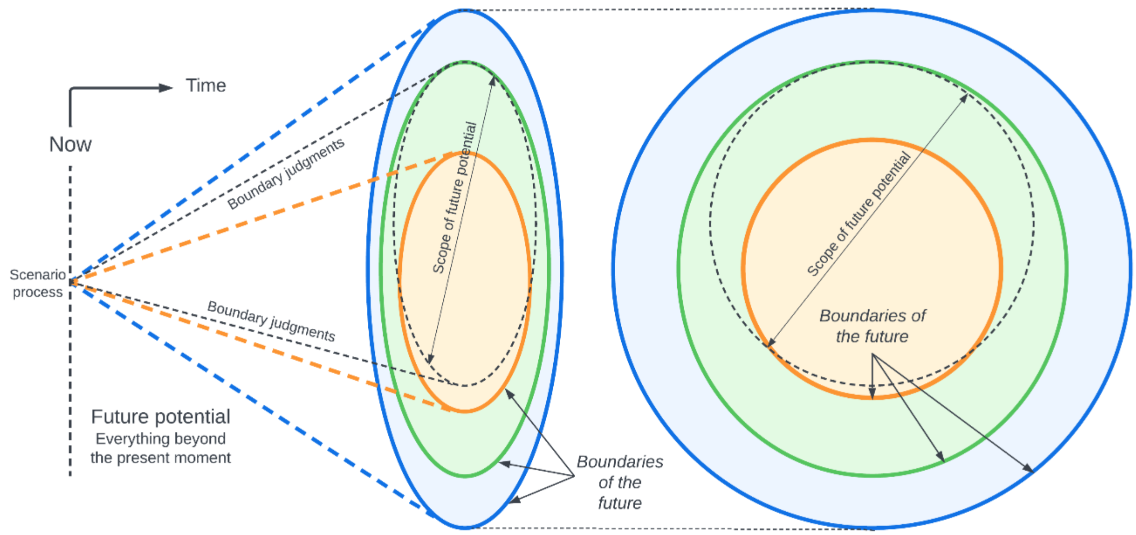

Figure 2-2: Conceptual assumption that guided the development of the reflexive framework for scenario practice. Boundaries of the future are generated by boundary judgments made through the scenario process, which create the scope of future potential reflected in the scenarios. The dotted black line offers an example.

2.2.2 Literature search protocols

A two-part search protocol generated a long list of seminal literature in scenario practice (Group A) and sustainability science (Group B) for the inductive review. Group A literature was retrieved from Scopus and Google Scholar prior to December 2021 in the English language only. The primary search terms were *scenario** OR *foresight* OR *futures* OR *anticipatory governance* AND *sustainability* (OR *sustainability science* OR *sustainability research*). Upon an initial search, the databases returned a highly disparate and wide-ranging set of literature that mentioned the term "scenario" but did not adequately focus on the use of scenarios as a research practice. Thus, the search protocol was adapted to return more targeted and relevant literature for scenario practice by combining the original terms in different ways, adding additional keywords to the initial search (e.g., *scenario develop** OR *scenario analys** OR *scenario plan**), and by scanning the reference list of review papers that were already selected. This led to a more iterative search protocol than would be required for a systematic review but was appropriate to find the relevant literature. Each search was sorted by 'Relevance' and 'Citation (high to low)', and the title and abstract of the first 100 hits of each search were reviewed. The inclusion criteria were a) the paper focuses on the use of scenarios as a research practice, either theoretically or methodologically, and b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case). The search continued until the list of literature was as close to saturation as would be feasible for the review. A more comprehensive description of the search protocol and a list of literature can be found in Appendix A.

Group B literature was retrieved through four distinct categories of searches on Scopus and Web of Science prior to December 2021 in the English language only. Category 1 retrieved general literature that addresses the dynamics of change in SESs and was found simply using the term *social-ecological system**. Category 2 retrieved literature that addresses transformation from an SES perspective using the terms (*social-ecological system** AND *transformat**). Category 3 was included because the SES approach is one of multiple approaches to transformation (Scoones et al. 2020) and may be missing important components relevant to social dimensions of transformation and ambiguity (e.g., diverse perspectives of actors in transformation) (Stirling 2014; Blythe et al. 2018). This literature was retrieved from the results of Category 2 searches, and by conducting additional searches including (*transformat** AND (*sustainability* OR "*social-ecological system**")) AND *critique* OR *politic** OR *emancipat**). Finally, Category 4 addresses unintended transformations in SESs beyond those covered in Category 1 and was found using the search combinations ("*social-ecological system*"* AND *Anthropocene*; *social-ecological system*"* AND *"regime shift"*; "*social-ecological system**" AND "*tipping point*"; *Anthropocene* AND *risk*; *complexity* AND *risk*). The results of each search were sorted in order of 'Cited by (Highest)' (i.e., to retrieve seminal literature) and the title and abstract of the first 100 results were reviewed. The inclusion criteria were a) the paper focuses on the dynamics of, and conditions for, SES change (and/or transformation) and b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case). A more comprehensive description of the search protocol and a full list of literature can be found in Appendix A.

An additional search protocol generated a list of case studies used to validate the framework. The protocol involved a search protocol using Scopus, Web of Science, Google Scholar, and Science Direct to gather a wide range of inter- and transdisciplinary cases. An initial search query generated literature with the following terms in their title, abstract, or keywords: *scenario**" AND "*social-ecological*" OR "*socio-ecological*" OR "*human-natural*" OR "*human-environment*" OR "*socio-environmental*" OR "*human and natural*" from the year 2000 to the time of the search (August 2021) in the English language. A second search further refined terms in an attempt to catch scenario-specific case studies that might have been missed in the initial search; this search included the terms *"future scenario*" OR "scenario analy*" OR "scenario develop*" OR "scenario plan*" OR "scenario" AND "social-ecological" OR "socio-ecological" OR "human-natural" OR "human-environment" OR "socio-environmental" OR "human and natural."* The Biosphere Futures portal was used as an additional source of case studies, as it aims to build "a global collection of social-ecological scenario case studies to support the emerging community of practice" (Stockholm Resilience Centre 2020). The abstract and title of the first 100 results sorted from both "Relevance" and "Date of Publication" were evaluated using three inclusion criteria: 1) the case study must be the primary focus of the paper (conceptually and methodologically), 2) the scenarios must contain both social and ecological elements, and 3) the study must be in an inter-, multi-, or trans- disciplinarity journal (i.e., to avoid studies representing a single discipline). Most case studies were journal articles, but a handful of case studies from the Biosphere Futures portal in grey literature were also included. The list of 72 case studies that resulted from this search is included in Appendix B.

2.2.3 Inductive review to generate boundary judgments

An inductive review of the literature identified boundary judgments, i.e., choices that delineate what is included or excluded from the scenarios. The review began with inductive coding of the literature on scenario practice (Group A); i.e., the list of codes (i.e., boundary judgments) emerged from and evolved through the coding process. This review of Group A literature generated a tentative list of codes, which was then used as a starting point for a review of literature on SES change (Group B) through which the codes (i.e., boundary judgments) continued to evolve. To be included in the framework, the boundary judgment must (1) directly connect to (implicit or explicit) choices in the design of a scenario process, (2) apply to nearly every scenario process to justify inclusion in an integrative guiding framework (i.e., noting that critical systems theory highlights how additional, context-specific boundary judgments will also be required in each unique case), and (3) delimit the scope of future potential in a way that may reflect the dynamics of, and/or conditions for, SES change (including transformation). This review developed a provisional framework of twelve boundary judgments.

2.2.4 Deductive coding of case studies to validate the boundary judgments

The 72 social-ecological scenario case studies were deductively coded using the boundary judgments generated from the inductive review in Section 2.2.3 as themes. The coding was conducted in NVivo in two rounds. First, each study was coded according to the 12 boundary judgments on the provisional framework. This coding informed a revision of the provisional framework by 1) excluding judgments that were not relevant to all cases and 2) adjusting judgments that did not reflect the full scope of dimensions along the axis of the judgment. The discarded judgments included the type of *baseline* scenario (historical; novel) and the degree of *social-ecological interdependency* (separate; linked; co-evolving). The former was discarded because few studies mentioned any baseline at all, and the latter was discarded because it overlapped too significantly with the *social-ecological complexity* judgment.

The case studies were coded a second time against the ten judgments in the final framework and the codes for each judgment were then revisited to validate the placement of each choice along the axis. For some judgments, this step involved returning to literature (and in isolated cases, retrieving additional literature; see Appendix A) to further validate this placement. Additionally, many studies did not explicitly state all 10 boundaries but could be interpreted. For example, if a study did not state an *epistemological lens* but synthesized qualitative and quantitative data into one common set of scenarios, it was considered 'critical realist'. While efforts were made to remove subjectivity in these interpretations, there may be small margins for alternative interpretations.

2.2.5 Descriptive statistics

The final coding of the 72 case studies was used to identify key trends in scenario case studies to date (i.e., common boundaries of the future). To do so, each boundary judgment was translated into a categorical variable, with the multiple choices under each judgment. Each choice was represented by 1, 2, or 3 depending on its location on the framework (i.e., most expansive choices reflecting transformation were given a '3'). The average for each boundary judgment across the case studies was determined to reveal trends.

2.3 Results

2.3.1 Framework for reflexive scenario practice in sustainability science

The final framework is depicted in Figure 2-3. The ten boundary judgments are clustered under three categories 1) framing, 2) methodology, and 3) system characterization. These three categories and the ten boundary judgments are active sites of judgment in a scenario process, delimiting the scope of future potential in ways that may reflect the dynamics of, and/or conditions for, SES change. Each boundary judgment is depicted as an axis on the radar chart, with the outermost choice as reflecting the dynamics of, and conditions for, transformation (blue). The boundary judgments are each discussed in detail in Section 2.3.2, and suggestions for how the framework can be operationalized to facilitate reflexive scenario practice in sustainability science is discussed in Section 2.3.3.

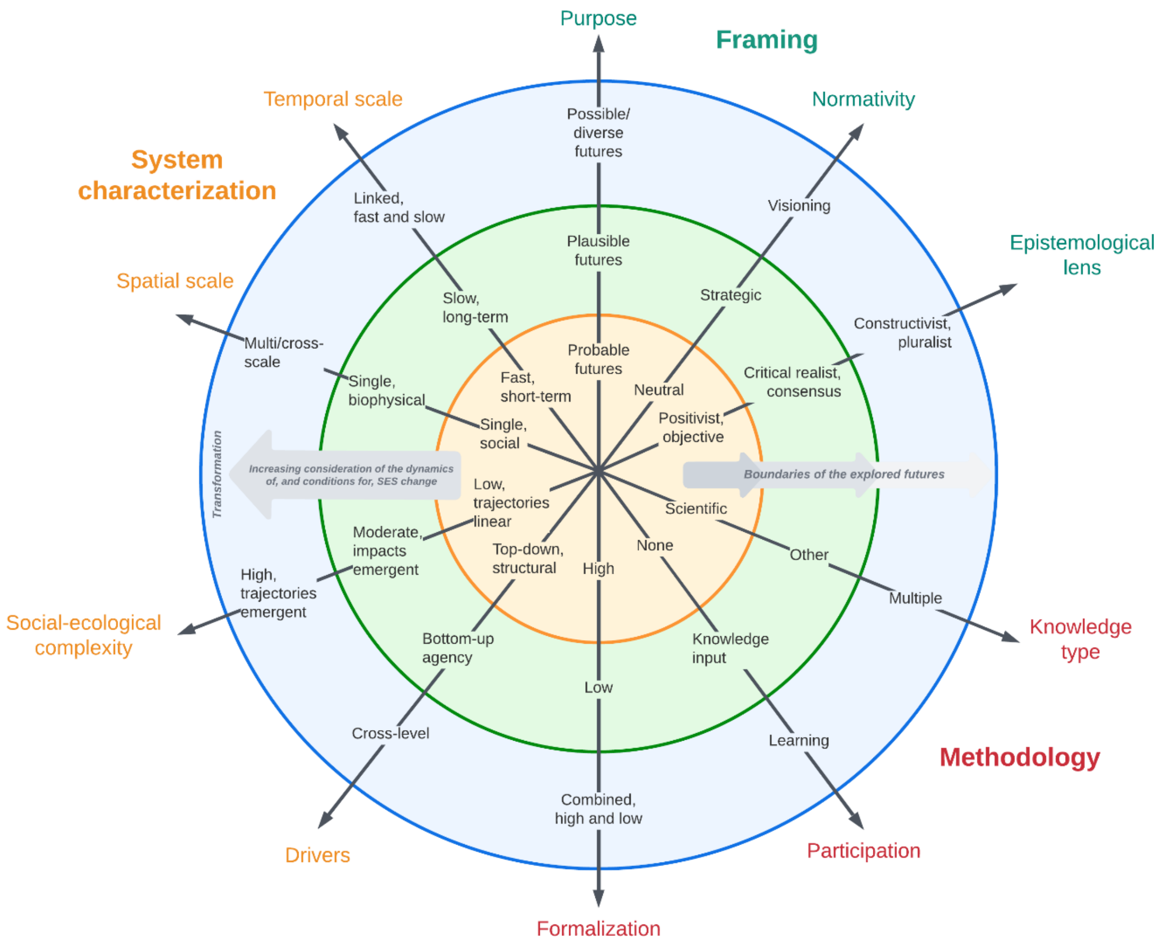

Figure 2-3: Boundaries of the Future; the final reflexive framework for scenario practice in sustainability science. Each axis on the radar chart is a boundary judgment. Choices moving outward from the center of the framework are proposed to have the potential for increasing consideration of the dynamics of, and conditions for, SES change. The outermost selection has the potential to reflect that of transformation.

2.3.2 Boundary judgments

A description of each boundary judgment follows. This description includes the justification for and implications of each choice along the axis of each judgment (i.e., in the proposed order of increasing consideration of the dynamics of, and conditions for, SES change). The description also includes the number of case studies coded to each choice under each judgment. Appendix C includes a table that offers a comprehensive summary of this section with more citations, and Appendix D includes the full case study coding for each boundary judgment.

2.3.2.1 Category 1 – Framing

2.3.2.1.1 Purpose

The *purpose* of a scenario process is its overarching objective. The purpose can vary widely and is highly context-specific, but it broadly determines the most important criterion for evaluating which scenarios are included in the analysis. These include exploring 1) *probable futures*, 2) *plausible futures*, and 3) *possible/diverse futures*. Scenarios framed to assess probable futures (i.e., likely to happen, based on current trends (Voros 2017)) are often used for formal planning and strategy development and to analyze or mitigate risks (Muiderman et al. 2020). These scenarios are viewed as scientifically credible, as probability judgments are usually based on historical data or expert judgment and are compatible with a range of quantitative decision tools (Rounsevell and Metzger 2010). However, such scenarios exclude future conditions that are non-verifiable according to these traditional scientific metrics (Pereira et al. 2007; Wiek et al. 2013). For example, these scenarios would exclude novel or surprising conditions for which historical data is unavailable or science is uncertain, such as the novel SES dynamics experienced as Earth systems are pushed past critical tipping points (Rocha et al. 2015; Keys et al. 2019) or the innovative practices, ideas, and perspectives that contribute to transformative change (Biggs et al. 2010; Bennett et al. 2016). Thus, scenarios framed around probability metrics at least partially reflect the view of 20th-century natural resource management in which ecosystem responses to human intervention can be predicted and controlled (Dietz et al. 2003; Westley et al. 2011). Only two of the 72 case studies reflected this purpose. For example, Song et al. (2021) use land use change predictions derived from a spatial-temporal evaluation model to inform adaptation and transformation planning in South Korea.

Scenario processes framed to explore plausible futures (i.e., could happen based on existing knowledge (Voros 2017)) are often used to build up societal preparedness and capacities to navigate uncertainty (Peterson et al. 2003; Muiderman et al. 2020). The scenarios maintain scientific credibility through evaluations of plausibility via internal consistency or expert judgment, thereby including a wider scope of complexity and uncertainty and novel drivers of change (Schweizer and Kriegler 2012; Bhave et al. 2018). These broader metrics of plausibility includes conditions for which probability judgments may be unavailable but can still be evaluated as "occurable" (Pereira et al. 2007; Wiek et al. 2013), thus potentially opening up scenarios to greater novelty in SESs. Still, plausibility is a contested and undertheorized term (Schmidt-Scheele 2020) and subjective plausibility judgments may exclude novel or counterintuitive phenomena. Sixty-two of 72 case studies reflected this purpose. For example, four qualitative trajectories to 2070 in the Yamaha watershed in Wisconsin, USA were combined with quantitative time series to assess changes to ecosystem services under different social-ecological conditions (Carpenter et al. 2015).

Scenario processes framed to explore possible/diverse futures (i.e., might happen based on future knowledge (Voros 2017)) are often used to evaluate robustness to a wide scope of uncertainty (Lord et al. 2016) and to mobilize actors to co-create new futures (Bourgeois et al. 2017; Moore and Milkoreit 2020; Pereira et al. 2020a). By rejecting metrics of probability and plausibility and instead focusing on scenario possibility and diversity, these scenarios may reflect the widest range of potential SES change including transformations that diverge significantly from the present. For example, they may consider the outcomes of more experimental, creative techniques for modelling or imagining the future (Vervoort et al. 2015; Bendor et al. 2017; Merrie et al. 2018). While such processes broaden the scope of future potential, there may be trade-offs in reproducibility and perceived credibility and compatibility with other scientific processes. Eight of 72 case studies reflected this purpose. For example, Pereira et al. (2018a) use creative participatory futuring and art to imagine radical, but desirable futures in southern Africa.

2.3.2.1.2 Normativity

The *normativity* in a scenario process is the degree to which the desirability of the scenarios is considered, including 1) *neutral*, 2) *strategic*, or 3) *imaginative*. Framing scenarios as neutral explores a range of futures without considering their desirability. Such scenarios can be used to identify robust options (Brown et al. 2016) or discuss whether planned strategies are enabled or constrained by scenario outcomes (Bohensky et al. 2011). This approach may be appropriate for many scenario studies, but the normative aspects of the resulting scenarios may be underrepresented or underdeveloped. Forty of the 72 case studies were not explicitly normative. For example, Plieninger et al. (2013) use scenarios to assess the impact of possible drivers of cultural landscape change on ecosystem services in a biosphere in southern Germany, with little consideration of desirability.

Strategic scenarios can enrich the scope of normative conditions. Such processes either identify desirable objectives and strategic pathways to achieve them or evaluate the implications of strategic options (Robinson 2003; IPBES 2016). While such scenarios are policy-relevant and actionable, they may favor incremental or adaptive actions, excluding the longer-term, more radical conditions that may reflect or motivate transformative change (Iwaniec et al. 2020). Twenty-two of 72 case studies reflected this scope of normativity. For example, Palacios-Agundez et al. (2013) downscale the Millennium Ecosystem Assessment scenarios to develop plausible futures for ecosystem services and wellbeing in Biscay, Spain, followed by a backcasting process to identify management options.

Visioning scenarios can enrich the scope of normative conditions further. These scenarios are less concerned with a clear connection to near-term strategy, focusing instead on imagination and creativity (Wiek and Iwaniec 2014; Pereira et al. 2018a). Such processes are rooted in the view that imagination (e.g., Milkoreit 2016; Galafassi et al. 2018; Moore and Milkoreit 2020) and visions of a "good life" can be important leverage points for sustainability transformation (Chan et al. 2020), though this link has yet to be clearly established empirically. Still, the potential of visioning is informing the development of a range of new theories and methods that focus on scenario creativity and desirability over scientific reproducibility, with the aim to inspire and motivate the scientists and actors involved in scenario development (Bennett et al. 2016; Iwaniec et al. 2020; Moore and Milkoreit 2020). Ten of 72 case studies reflected this scope of normativity. For example, the Seeds of Good Anthropocene (SOGA) method was used to imagine desirable futures in which promising seeds of potential in the present become mainstream in southern Africa and northern Europe (Pereira et al. 2018a; Raudsepp-Hearne et al. 2020).

2.3.2.1.3 Epistemological lens

The *epistemological lens* is the theory of knowledge that distinguishes what constitutes a valid belief, and thus determines how multiple perspectives are integrated in the scenario process. Diverse epistemological perspectives are relevant in sustainability science (Moon and Blackman 2014; Moon et al. 2021), but can broadly range across 1) *positivism*, 2) *critical realism* to 3) *constructivism*. Scenario processes framed with a positivist epistemological lens are expert-informed and model-driven, and the scenarios attempt to reflect an objective reality (Vervoort et al. 2015; Carlsen et al. 2017). These scenarios reflect the view of those advocating for more neutral and transparent approaches to scenario development (Carlsen et al. 2017) and align with sustainability science's roots in natural sciences (Holling 2001). Such scenario processes avoid integration and/or discard any perspectives that are incommensurate with the more dominant view (Turnhout et al. 2020); for example, local and Indigenous knowledge is considered important for understanding long-term change in SESs (Armitage et al. 2011; Lam et al. 2020a) but would be rejected as "unscientific" (Martin 2012). A positivist lens may also oversimplify the social components of SESs and undervalue the role of pluralism (Leach et al. 2010; Brown 2014), potentially perpetuating top-down, command-and-control views of transformation (Stirling 2014; Blythe et al. 2018). Thirteen of 72 case studies reflected this epistemological lens. For example, Le et al. (2010) use a Land Use Dynamics Simulator to evaluate the implications of policy interventions in a mountain watershed in central Vietnam.

While not always explicit in scenario processes, critical realism is emerging as an appropriate underlying epistemology for sustainability science (Preiser et al. 2022; Cockburn 2022). Scenario processes framed with a critical realist lens integrate multiple perspectives to gain an enriched understanding of the future (Cockburn 2022). This integration is possible because critical realism views all knowledge as eternally incomplete, but approximations of truth are required for decisive action (Groff 2004; West et al. 2014; Preiser et al. 2022). This stance aligns with calls for integrated knowledge systems to address complex, socially relevant problems (Cundill et al. 2005; Cornell et al. 2013; Caniglia et al. 2020). For example, the Story-and-Simulation approach uses qualitative narrative scenarios as inputs into quantitative models (Alcamo 2008), implicitly assuming that both qualitative and quantitative models contribute to an enriched picture of reality. This lens enriches scenarios with multiple perspectives and interests in SES change and transformation (Preiser et al. 2018; Cockburn 2022). However, it may exclude highly novel or discordant understandings of SES change and a truly critical-emancipatory lens on transformation, because the "integration imperative" of critical realism does not directly address the power imbalance between different perspectives (Klenk and Meehan 2015; Cockburn 2022). Thus, critical realism does not address the risk of co-optation, reduction, and instrumentalization of marginalized perspectives through integration with more dominant perspectives (Inoue and Moreira 2016; Mazzocchi 2018; Turnhout et al. 2020). Forty-eight of 72 case studies reflected this epistemological lens.

A scenario process underpinned by a constructivist, pluralist epistemological lens views knowledge as subjective and constructed through experience (Moon and Blackman 2014). A constructivist lens not only accommodates multiple perspectives but can embrace discordant views that cannot be reconciled (Gregory 1996; Vervoort et al. 2015). These scenario processes evaluate each source of knowledge according to the criteria of its own knowledge system (e.g., Tengö et al. 2014), and may avoid integration entirely to emphasize pluralism and discordance (Vervoort et al. 2015). Such processes may generate transformative scenarios that would be rejected under more strict evaluations of objectivity and consensus, such as those developed using novel experimental methods (Mangnus et al. 2019; Pereira et al. 2021). Further, by enabling a more critical-emancipatory lens on scenarios (Inayatullah 1998a; Scheele et al. 2018); i.e., "the future cannot be a source of freedom without a critique of dominant narratives" (Gugerli 2010), this lens may enable a more critical-emancipatory view on transformation (Stirling 2014) and allow for deliberation and learning as multiple framings are exposed and negotiated through processes of transformation (Pereira et al. 2018b, 2020a). For example, the reflexive-interventionist scenario typology highlights the importance of engaging with multiple epistemologies in multi-actor scenario development (Wilkinson and Eidinow 2008), and the exploratory framework of 'worldmaking' offers a pluralist lens for scenario analysis, explicitly building out scenarios as alternative worlds rather than different narratives of the same world, thereby avoiding attempts at consensus through ontological agency (Vervoort et al. 2015). Eleven of 72 case studies reflected this epistemological lens.

2.3.2.2 Category 2 – Methodology

2.3.2.2.1 Knowledge type

The *knowledge type* is broadly defined as the dominant form of knowledge that is included in the scenario process. This judgment differs from the *epistemological lens*, which defines the criteria by which these knowledge inputs are evaluated and how multiple perspectives (within or across knowledge types) are integrated. The knowledge type can include 1) *scientific*, 2) *other* (e.g., experiential, Indigenous, local, practitioner, etc.) and 3) *multiple.* The choice to inform the scenario process exclusively with scientific knowledge is common and holds legitimacy in many disciplinary academic and policy contexts (Verburg et al. 2016). These scenarios can include a wide range of future SES conditions that can be scientifically studied and modelled, particularly as sustainability science becomes increasingly systemic and integrative (Cash et al. 2003; Clark and Harley 2020). However, scientific knowledge has a legacy of reductionism that deals with complexity by breaking it down into understandable parts (Holling et al. 2000). This tendency is limiting when trying to address complex SES dynamics that implicate interdependencies across scales and disciplines (Swart et al. 2004; Miller et al. 2008; Tàbara and Chabay 2013; Cornell et al. 2013). Moreover, scenarios that favor scientific knowledge over other knowledge systems risk reinforcing dominant narratives of the future, masking an enriched understanding of complex SES change and the plural framings and interests involved in deliberate transformation (Blythe et al. 2018). Twenty-two of the 72 case studies were developed with scientific knowledge only. For example, the Land Use Dynamics Simulator developed by Le et al. (2010) draws exclusively from scientific knowledge.

Alternatively, scenario processes can draw exclusively from other types of knowledge. Such processes broaden dominant, science-based narratives of the future with alternative understandings of SES change; for example, with Indigenous knowledge that developed through experimentation and adaptation over long periods (Armitage et al. 2011; Tengö et al. 2014; Rathwell et al. 2015) and experiential practitioner or local knowledge that is derived from integrative real-world experience (Cundill et al. 2005; Reed and Abernethy 2018). These knowledge types are often marginalized from research and policy processes, introducing challenges associated with perceived legitimacy and risks of cooption or further marginalization by more dominant forms of knowledge. Yet, they also offer unique perspectives regarding SES change, including transformation (Ocholla 2007; Bohensky and Maru 2011; Lam et al. 2020a). Further, such scenario processes may better address the subjective and normative aspects that produce divergent framings and interests in deliberate transformation (Leach et al. 2010). Twelve of 72 case studies include local, practitioner, or Indigenous knowledge exclusively. For example, researchers co-produced scenarios with Indigenous Arctic communities to explore divergent pathways toward a desirable future in the face of socio-environmental change (Falardeau et al. 2019).

Finally, scenarios can be purposefully and systematically informed by both scientific and other forms of knowledge, aligning with the transdisciplinary turn of sustainability science (Tàbara and Chabay 2013; Cornell et al. 2013). Doing so enriches the scenario process with the benefits of both scientific and other knowledge types (Miller et al. 2008; Tengö et al. 2014). The resulting scenarios may offer an enriched understanding of SES change, as new insights surface through the process of exposing complementarities and dissonances between knowledge types (Peterson et al. 2003; Bennett and Zurek 2006; Rathwell et al. 2015; Lam et al. 2020a) and the plural framings and interests of diverse knowledge holders implicated in transformation (Stirling 2006; Leach et al. 2010). However, such scenario processes introduce important consideration and risks associated with knowledge integration; see the *epistemological lens* boundary judgment. Thirty-eight of 72 case studies included multiple knowledge types of knowledge (i.e., scientific and other).

2.3.2.2.2 Participation

The *participation* boundary judgment indicates the nature and purpose of the inclusion of non-expert participants in the scenario process, which can range across 1) *none*, 2) for *knowledge input*, and 3) for *engagement and learning*. The choice to exclude any non-expert participants can be pertinent for some scenario processes that serve an important purpose in sustainability science. However, the results are limited to the scope of future conditions understood and deemed relevant by experts, excluding the knowledge, interests, and values held by more diverse participants (Fazey et al. 2020). These scenarios may exclude SES changes not easily represented in expert-driven processes; see *knowledge type* and *epistemological lens* judgments for examples. In such process, actors remain without any role in the development of scenarios that may be relevant to them (Arnstein 2019). Fifteen of 72 case studies did not include participation. For example, Shoyama et al. (2019) map land use change scenarios to assess changes to biodiversity and ecosystem services in Japan.

Alternatively, many scenario processes include non-expert participants to input knowledge into an expert-driven process (Moallemi et al. 2021). This form of participation can enrich scenarios with diverse understandings of and experiences with SES change, surfacing feedbacks and surprises not easily represented in data-intensive models (Bennett et al. 2003; van Vuuren et al. 2012; Lord et al. 2016; Verburg et al. 2016). However, participants are not included in the ongoing reflection, iteration, and learning that occurs through the research process, so the scope of future conditions and values are still limited to those considered relevant by experts (Reed et al. 2013; Moallemi et al. 2021). Moreover, simply consulting actors may result in tokenism or instrumentalization of their perspective for the gain of experts (Arnstein 2019) and participant selection can reinforce power dynamics if done uncritically (Morgan 2014). Further, the transformative potential that occurs through participant learning is limited (Pahl-Wostl et al. 2013; Pereira et al. 2018b). Thirty of 72 case studies included participation for knowledge input. For example, Baggio et al. (2016) use surveys to collect inputs for a network model that projects scenarios of changing resource abundance and shifting cultural practices.

Scenario processes can involve higher degrees of participation as non-experts are embedded through the research process, enabling scenario co-production and learning (Robinson 2003; Wilkinson and Eidinow 2008). This form of participation not only enriches scenarios with diverse understandings of and experiences with SES change, but it can also facilitate the learning and experimentation required to help actors manage complex SES behavior (Armitage et al. 2009; Biggs et al. 2012) and contribute to transformative learning by challenging participants to question existing assumptions and paradigms about the future (Pahl-Wostl et al. 2013; Pereira et al. 2018b, 2020a). These processes also delegate more power to participants through greater ownership and partnership in the scenario process (Arnstein 2019). Twenty-seven of the 72 case studies involved non-experts for participant learning. For example, Bohensky et al. (2011) co-produced exploratory scenarios for the ecotourism industry in Milne Bay, Papua New Guinea, measuring changes in perception before and after the scenario process to demonstrate participant learning.

2.3.2.2.3 Formalization

The *formalization* judgment is the degree to which input assumptions are quantified or codified into a formal structure or model in the scenario process. This judgment ranges across 1) *high*, 2) *low*, and 3) *combined*. A high degree of formalization implies a quantitative scenario process, usually in the form of a model. Highly formalized scenarios provide transparency and analytical rigor to the assumptions underlying the scenarios, and the ability to reproduce and validate system behaviour improves (Moallemi et al. 2021). Such scenarios offer a high level of granularity and may surface the emergent and non-intuitive outcomes of social-ecological interactions and feedbacks that can be codified by the chosen method. However, quantitative models can become specialized and difficult to reconcile across other models and epistemologies (Gerst et al. 2014; Verburg et al. 2016). Further, they exclude any future conditions that are incompatible with the chosen method, and for which appropriate theory and data are unknown. Consequently, the results may be biased toward computable, measurable, and testable aspects of a system, excluding wildcard or “surprise” events (Carpenter et al. 2009) and the messy, emergent properties of transformation (Sharpe et al. 2016; Pereira et al. 2018b). Moreover, the quantification processes may exclude important social, technological, cultural, and economic drivers of change that are difficult to quantify yet are expected to dominate 21st-century change (Gerst et al. 2014). Twelve of the 72 case studies were highly formalized. For example, Norman et al. (2012) evaluate possible land use change scenarios using a spatially explicit model.

The choice to develop scenarios with a lower level of formalization usually implies the use of qualitative narrative methods. Such scenarios include any future conditions that can be conceptualized qualitatively, potentially including some conditions that are excluded from highly formalized models; for example, difficult-to-measure social or cultural drivers (Gerst et al. 2014). Qualitative scenarios may also enable consideration of more diverse perspectives and transformative future conditions that surface through creative methods. For example, scenario processes using integrative media and art are used to imagine transformation and facilitate transformative learning (Galafassi et al. 2018); see *participation* judgment. However, these processes rely on broad conceptualizations and assumptions about system behavior and human agency, so they may be associated with higher uncertainty and lower granularity (Berkhout et al. 2002; Swart et al. 2004; Carpenter et al. 2009; Moallemi et al. 2021). Moreover, qualitative scenarios rely on human intuition to select critical uncertainties, which may be fallible and thus exclude counter-intuitive and emergent conditions of complex SESs (Peterson et al. 2003; Ramirez and Wilkinson 2014; Bai et al. 2016). Thirty-six of 72 case studies had low formalization. For example, many scenario processes used the Intuitive Logics method to define and combine key uncertainties and predetermined elements into narrative scenarios (Schwartz 1991; Kosow and Gaßner 2008).

The choice to combine high and low levels of formalization (i.e., qualitative and quantitative) enriches scenarios with future conditions that are better understood using both qualitative and quantitative methods (Verburg et al. 2016; Moallemi et al. 2021; Pereira et al. 2021). For example, the popular Story-and-Simulation approach uses qualitative narrative scenarios as inputs to expert-driven integrated assessment models (Kok et al. 2006; Alcamo 2008). Alternatively, emerging semi-quantitative scenario methods like morphological analysis (Zwicky 1969; Ritchey 2006; Lord et al. 2016) and cross-impact balances (Weimer-Jehle 2006) develop consistent scenarios from diverse qualitative and quantitative drivers of change. Twenty-four of 72 case studies linked high and low levels of formalization.

2.3.2.3 Category 3 – Characterization

2.3.2.3.1 Drivers

The *drivers* are the dominant part of the system from which change is assumed to occur in the scenario process. These include 1) *top down* (structural), 2) *bottom-up* (agency), and 3) *cross-level*. Many scenario processes focus on structural drivers, which are outside of direct human control (Schwartz 1991; Lempert 2003). Such scenarios characterize the top-down drivers that influence SES change, such as critical uncertainties that inform efforts to build resilience in SESs (Peterson et al. 2003) or the structural conditions that can enable (e.g., social networks and experimentation) or constrain (e.g., rigidity) deliberate transformation (Olsson et al. 2006; Gelcich et al. 2010; Sendzimir et al. 2010). However, these scenarios exclude the bottom-up processes that produce emergent outcomes in SESs (Levin 1998; Reyers et al. 2018). Further, they exclude the conditions for deliberate transformation, which emerges from the interaction between the system structure and bottom-up actor agency (Westley et al. 2011; Moore and Westley 2011). Moreover, a focus on top-down change may generate scenarios that are not rooted in the local realities for which they are meant to be applied (Pereira et al. 2021). Thirty-one of 72 case studies focused on top-down, structural drivers. For example, Ruiz-Mallen et al. (2015) define climate, policy, and socio-economic horizons in various countries to the year 2030 to frame discussions about local adaptation options.

Alternatively, scenarios can emphasize bottom-up change and drivers that actors have agency to control. This choice characterizes the low-level interactions that influence SES change, reflecting the view that high-level SES behavior emerges from bottom-up interconnectivity and self-organization (Levin et al. 2013; Reyers et al. 2018). Consequently, such processes may characterize the dynamics of deliberate and unintended transformation, such as when underlying, low-level drivers reach tipping points and flip an SES into a new system state (Moore et al. 2014; Rocha et al. 2015; Bennett et al. 2016; Filbee-Dexter et al. 2017). Further, the focus on human agency reflects the important social dimensions of transformation (Moore and Westley 2011; Westley et al. 2013; Lam et al. 2020b) and may enable a more critical-emancipatory view on transformation, such as by highlighting the plural and contested nature of transformation (Leach et al. 2010; Blythe et al. 2018) and generating scenarios that are rooted in local realities and practical action (Pereira et al. 2021). However, the lack of constraining influence of top-down (structural) conditions (e.g., social-ecological traps; see Carpenter and Brock 2008; Chapin III et al. 2010) may not reflect real-world

SES behaviour. For example, the RESORTES board game facilitates discussions that forecast land use and agro-forestry planning by focusing on individual land-use decisions and collaboration (Andreotti et al. 2020), and the SOGA scenario method facilitates a participatory process in which actors envision futures in which small-scale seeds are in their mature state (Pereira et al. 2021).

Considering both top-down and bottom-up drivers enriches the scope of future potential. This choice reflects the understanding that future change in SESs involves interacting drivers and feedbacks across various domains and levels (Swart et al. 2004), including resistance from the existing system structure (Carpenter and Brock 2008; Sendzimir et al. 2010). Further, it reflects how deliberate transformation emerges from the interplay of structure and agency (Westley et al. 2011; Moore and Westley 2011). Twenty-five of 72 case studies linked bottom-up and top-down drivers. For example, Kebede et al. (2018) explore cross-level interactions by combining a global climate change scenario and shared socio-economic pathways (i.e., top-down drivers) with four adaptation policy trajectories (i.e., bottom-up drivers).

2.3.2.3.2 Social-ecological complexity

The *social-ecological complexity* is the degree of complexity (e.g., unpredictability, and emergence) that is assumed to influence change within the scenario process. This judgment ranges across 1) *low*, 2) *moderate*, or 3) *high complexity*. A low level of complexity assumes scenario trajectories and their outcomes are predictable and linear, reflecting the view of 20th-century natural resource management in which ecosystems exist in one stable state and respond to human intervention in linear and controllable ways (Dietz et al. 2003; Westley et al. 2011; Reyers et al. 2018). These scenarios thus assume that environmental change can be governed without reference to broader systemic connectivity or biophysical limits (Rockström et al. 2009; Renn et al. 2011a; Westley et al. 2011; Helbing 2013). Consequently, scenarios generated from this characterization exclude the complex, emergent, and more unpredictable dynamics of SESs. For example, they cannot consider the intertwined social-ecological interactions and feedback effects that produce often counterintuitive outcomes (Helbing 2013; Moore et al. 2014; Bauch et al. 2016; Reyers et al. 2018). Further, the assumption that a system has one single equilibrium excludes potential for transformation into new system equilibria (Crépin et al. 2012; Moore et al. 2014; Rocha et al. 2015; Biggs et al. 2018; Tàbara et al. 2018). Twelve of 72 case studies reflect this perspective. For example, four scenarios were developed by considering two drivers of change – appropriate institutions and collaborative action – to explore the future of water in Bangalore, India (Poonacha and Kodugant 2018).

A moderate degree of complexity assumes scenario trajectories are considered linear, but their outcomes and impacts are considered emergent and unpredictable. Thus, the scenarios set the context in which complex SES behavior can be explored. This approach partially enriches scenarios with the complex dynamics of SESs, because although scenario trajectories are linear and predictable, the social-ecological and cross-scale interactions that occur within or as a result of those trajectories are addressed (Levin et al. 2013; Folke et al. 2016; Biggs et al. 2022). Forty-two of 72 case studies reflect this perspective. For example, Gourguet et al. (2021) evaluate the systemic response of shellfish aquaculture in the Normand-Breton Gulf in France to relatively straightforward perturbation scenarios of environmental change.

Finally, a high degree of complexity characterizes the scenario trajectories themselves as emergent and unpredictable. Such processes engage directly with intertwined social-ecological elements and feedbacks that produce change in SESs (Levin et al. 2013; Preiser et al. 2018; Biggs et al. 2022). For example, they may consider potentially transformative changes that are more likely to emerge in the presence of multiple interacting social and ecological drivers than individual drivers alone (Westley et al. 2011; Lade et al. 2013; Moore et al. 2014; Rocha et al. 2015). Eighteen of 72 case studies reflect this view. For example, Hanspach et al. (2014) show how SES trajectories are "(1) shaped by their specific historical contexts, (2) influenced by external drivers, and (3) modified by internal dynamics" by evaluating how development trajectories may change in the future based on a combination of changing SES dynamics, social conditions, and natural capital bundles.

2.3.2.3.3 Spatial scale

The *spatial scale* is the type of spatial dimension used to measure and study phenomena in the scenario process (Gibson et al. 2000; Cash et al. 2006). Spatial scale selection can be 1) *single, social scale*, 2) *single, biophysical scale*, or 2) *multi- or cross-scale*. The selection of spatial scale is complex and subjective, as spatial scales can be defined and organized in several ways (Cumming et al. 2006; Biggs et al. 2007; Audouin et al. 2013). Scenario processes conducted at a single scale allow for a focused analysis. In particular, single scales that are compatible with the mode of social organization (e.g., governance; local or federal) include conditions compatible with the governance context but may exclude ecological dynamics that fall out of the administrative boundary (Epstein et al. 2015). Thus, in contexts with a scale mismatch (i.e., when scale of environmental change and social organization are not aligned), a single-scale boundary can mean that important components of the SES are lost (Cumming et al. 2006; Folke et al. 2007). Twenty-six of 72 case studies use a single scale reflecting the modes of social organization. For example, Henriques et al. (2015) selected a national scale to analyze water management challenges in England and Wales.

Alternatively, aligning a single scale to the biophysical scale (e.g., river catchment, mountain range) enriches scenarios with a wider scope of ecological dynamics (Epstein et al. 2015), which may be more compatible for capturing SES change. This choice is predominant in many sectors such as water, which advocates for a watershed- or catchment-scale management approach (Cohen and Davidson 2011; Falkenmark et al. 2019a). However, if the biophysical boundary is not compatible with a governance context (i.e., a scale mismatch; Cumming et al. (2006)), scenarios may be disconnected from policy processes and difficult to link to action (Epstein et al. 2015). Twenty-five of 72 case studies use a single, biophysical scale. For example, Franklin et al. (2019) develop a holistic model to study social-ecological drivers of change in the Kenai River fisheries.

Scenarios that move beyond a single scale to link multiple spatial scales enrich the scope of future potential (e.g., local to national; watershed to global). Multi-scale assessments focus on two or more scales without systematically linking them, while cross-scale assessments foreground the interactions between them (Scholes et al. 2013). This classification has also been described as “loosely” or tightly” linked multi-scale scenarios (Biggs et al. 2007). Such multi- and cross-scale scenarios reflect the knowledge that SESs are highly influenced by complex cross-scale dynamics; for example, the panarchy heuristic shows how transformation at lower scales may maintain resilience at higher scales in the face of exogenous stress or shock (Holling 2001; Gelcich et al. 2010). They also acknowledge that SESs are increasingly globally networked and tele-connected across scales (Liu et al. 2013; Verburg et al. 2016; Keys et al. 2019). However, multi- and cross-scale scenarios encounter challenges including mismatches between socio-economic and biophysical scales, difficulty reconciling scenario drivers, loss of validity at alternative scales, and ambiguity regarding how scales are delineated (Cash et al. 2006; Biggs et al. 2007; Schweizer and Kurniawan 2016). Twenty-one of the 72 case studies are multi- or cross-scale. For example, Allan et al. (2022) link global Shared Socioeconomic Pathways to local-scale drivers as part of an assessment of ecosystem services and livelihoods in coastal Bangladesh.

2.3.2.3.4 Temporal scale

The *temporal scale* is the length of the temporal duration used to measure and study phenomena in the scenario process. This ranges across 1) *fast*, 2) *slow*, or 3) *linked*. Short to medium time scales (i.e., a few years to two decades) highlight fast cycles of change. These scenarios align with political and management time scales, potentially facilitating a link to action (Elsawah et al. 2020). Further they allow for a higher temporal resolution that could include short-term innovations and experimentation that may contribute to transformation (Holling 2001; Westley et al. 2013). However, they exclude slower, longer cycles of change in SESs and time-lagged ecosystem responses (Adrian et al. 2012), thus masking the slow variables and feedbacks that influence SES behaviour (Biggs et al. 2012). This presents the risk that scenario users may attribute the impacts of slow-changing, underlying drivers of SES change to faster-changing proximate drivers (Filbee-Dexter et al. 2017). Twenty-three of 72 case studies use a short to medium time scale. For example, Martinez-Sastre et al. (2017) use a time scale of 2030 to evaluate how land use change scenarios affect cultural ecosystem services relied upon by Mediterranean communities.

Under longer temporal scales (i.e., two decades or more), future conditions have more time to diverge from the present. For example, scenarios may consider the long-term preparation phase that precedes a sudden transformation triggered by a crisis (Olsson et al. 2004b; Elsawah et al. 2020) or slow-changing ecological drivers that may trigger regime shifts (Dakos et al. 2015; Ellis 2015; Döll and Romero-Lankao 2016; Filbee-Dexter et al. 2017). However, these processes offer a lower temporal resolution and may underemphasize the role of short-term novelty and experimentation in transformation. Twenty-seven of 72 case studies use a longer-term, multi-decade time horizon. For example, Merrie et al. (2018) use science fiction prototyping to develop radical ocean futures over time scales from 2050 to 2070.

Linking fast and slow temporal scales can focus on discrete scales (i.e., loosely linked) or systemic interactions across scales (i.e., tightly linked) (Scholes et al. 2013). Doing so enriches scenarios to consider the complexity of SES change, including cross-scale interactions (Holling 2001; Falkenmark et al. 2019b). Tightly linked temporal scales in particular reflect SES dynamics, such as how fast cycles of change in the panarchy framework can revolt and influence slower cycles, and how the accumulated memory of slower scales can enable or inhibit these faster scales (Holling 2001; Allen et al. 2014). However, linking scales is challenging due to incomparable data and results at different scales and the potential loss of scientific credibility when translating one scale to another

(Döll et al. 2002; Biggs et al. 2007). Six of 72 case studies link fast and slow temporal scales. For example, Iwaniec et al. (2020) combine short-term (5 years), medium-term (20 years), and long-term (2060) strategic scenarios to develop desirable future pathways at the Central Arizona-Phoenix Long-term Ecological Research Urban site.

2.3.3 Operationalizing the framework

The Boundaries of the Future framework can facilitate a reflexive scenario practice in sustainability science by making each of the ten boundary judgments an explicit site of critical reflection throughout the design and implementation of a scenario process. This critical reflection should consider which choice under each boundary judgment is most suitable for the desired outcomes while acknowledging practical opportunities and constraints. Table 2-1 summarizes the ten boundary judgments and key questions that can be asked to facilitate this critical reflection. These questions are written in both the "is" and "ought" modes, as per CST (Ulrich 1983): the "is" mode reflects the current state of the system or process, and the "ought" mode reflects a desired or improved state (i.e., the ethical stance from which the "is" judgment is made). The difference between the two reveals contested value judgments between stakeholders or unresolved boundary judgments (Jackson 2019). These questions should be considered throughout a scenario process (i.e., before, during, and after) to surface emerging considerations and facilitate reflexive learning.

Table 2-1: Guiding framework for operationalizing the Boundaries of the Future framework to facilitate reflexive scenario practice in sustainability science; more detailed explanations of each judgment can be found in Appendix C.

	Boundary		*Judgments (innermost to outermost)*		
Framing	**Purpose** *Overarching objective that determines the most important criterion for scenario evaluation*	What is (ought to be) the objective of the scenario process, and criterion for scenario evaluation?	***Probable futures*** Scenario probability as a key criterion (i.e., likely to happen, based on current trends)	***Plausible futures*** Scenario plausibility as a key criterion (i.e., could happen based on existing knowledge)	***Possible/diverse futures*** Scenario possibility and diversity as key criteria (i.e., might happen based on future knowledge)

	Boundary		*Judgments (innermost to outermost)*		
	Normativity *The degree to which the desirability of scenarios is considered*	What degree of normativity (desirability) is (ought to be) considered in the scenario process?	***Neutral*** Scenario process explores range of futures without considering desirability	***Strategic*** Scenarios consider desirable futures that are strategic; strong connection to near-term action	***Visioning*** Scenarios consider desirable futures that are primarily visions; not necessarily connected to near-term strategy (e.g., imaginative)
	Epistemological lens *The theory of knowledge that distinguishes what constitutes a valid belief and how multiple perspectives are integrated in the scenario process*	What epistemological lens is (ought to) underpin the scenario development process?	***Positivist*** Objectivity; expert-informed and model driven; scenarios attempt to reflect an objective reality	***Critical realist*** Consensus; integrative; scenarios incorporate multiple perspectives to gain an enriched understanding of the future	***Constructivist, pluralist*** Discordant; knowledge about the future is subjective and constructed through experience; emphasis on pluralism and difference
Methodology	**Knowledge type** *The dominant form of knowledge included in the scenario process*	What is (ought to be) the dominant knowledge type included in the scenario process?	***Scientific only*** Scenario methodology only draws from formal, scientific knowledge (i.e., experts, models)	***Other*** Scenario methodology only draws from other forms of knowledge (i.e., local, practitioner, experiential, Indigenous, traditional, etc.)	***Multiple*** Scenarios are purposefully, systematically informed by both scientific and other forms of knowledge
	Participation *The nature and purpose of the inclusion of non-expert participants in the scenario process*	What degree of participation is (ought to be) used in the scenario process?	***None*** Only experts are included (no participation)	***Knowledge input*** Non-expert participants are included to input knowledge into an expert-driven process	***Engagement and learning*** Higher degrees of participation as non-experts are embedded through the research process through scenario co-production and learning

	Boundary		*Judgments (innermost to outermost)*		
	Formalization *The degree to which input assumptions are quantified or codified into a formal structure or model in the scenario process*	What degree of formalization is (ought to be) used for the scenarios?	***High*** Scenarios are highly formalized, meaning they are quantitative (i.e., usually in a model)	***Low*** Scenarios have a lower level of formalization, meaning they are qualitative (i.e., usually in narrative form)	***Combined*** Scenarios combine both high and low levels of formalization, meaning they are hybrid and combine qualitative and quantitative
System characterization	**Drivers** *The dominant part of the system from which change is assumed to occur in the scenario process*	What type of drivers of change are (ought to be) reflected in the scenarios?	***Top-down (structural)*** Scenarios characterize the future according to top-down drivers of change, which are outside of direct human control	***Bottom-up (agency)*** Scenarios characterize the future according to bottom-up change and drivers that actors do have agency to control	***Cross-level*** Scenarios characterize the future according to both top-down (structural) and bottom-up (agency) change
	Social-ecological complexity *The degree of complexity (e.g., unpredictability, and emergence) that is assumed to influence change within the scenario process*	What degree of social-ecological complexity is (ought to be) reflected in the scenarios?	***Low*** Scenarios reflect the view that scenario trajectories and their social-ecological outcomes/impacts are linear and predictable	***Moderate*** Scenarios reflect the view that scenario trajectories are linear, but their outcomes/impacts are emergent and difficult to predict; i.e., scenarios set the context in which complex SES behavior can be explored	***High*** Scenarios reflect the view that scenario trajectories are emergent and difficult to predict; i.e., the scenarios themselves represent complex SES behaviour
	Spatial scale *The type of spatial dimension used to measure and study phenomena in the scenario process*	What spatial scale is (ought to be) used for the scenario process?	***Single, social/governance*** Scenarios consider a single spatial scale that is compatible with the mode of social organization (i.e., governance scale, e.g., local or federal administration)	***Single, biophysical*** Scenarios consider a single spatial scale that is compatible with the biophysical landscape (e.g., ecotone, river catchment, mountain range, etc.)	***Multi- or cross-scale*** Scenarios explicitly link multiple spatial scales (e.g., local to national; watershed to global, etc.)

	Boundary		Judgments (innermost to outermost)		
	Temporal scale *The length of the temporal duration used to measure and study phenomena in the scenario process*	What temporal scale is (ought to be) used for the scenario process?	***Fast*** Short-medium time scale (i.e., a few years to two decades)	***Slow*** Long time scale (i.e., two decades or more)	***Linked*** Linking fast and slow time scales

2.3.4 Common 'boundaries of the future' in case studies

The number of case studies coded to each judgment is summarized in Figure 2-4. These synthesized results show that most studies were framed as exploring plausible futures (86 percent), were not explicitly focused on normative or desirable futures (56 percent) and adopted a critical realist epistemological lens (67 percent). Many scenarios were qualitative (50 percent) and involved participants for knowledge input (42 percent) over explicit efforts to facilitate participant learning (38 percent). Interestingly, most studies drew from multiple types of knowledge (53 percent). The scenario studies characterized the system primarily using top-down, structural drivers (43 percent) and a majority viewed scenarios as linear but their outcomes as complex (58 percent). Spatial scale selection did not favor any boundary judgment, while temporal scale selection favored a single scale (41 and 48 percent) over multiple scales (11 percent). Sixteen studies did not indicate a temporal scale and could not be interpreted. The case study coding can be found in Appendix D.

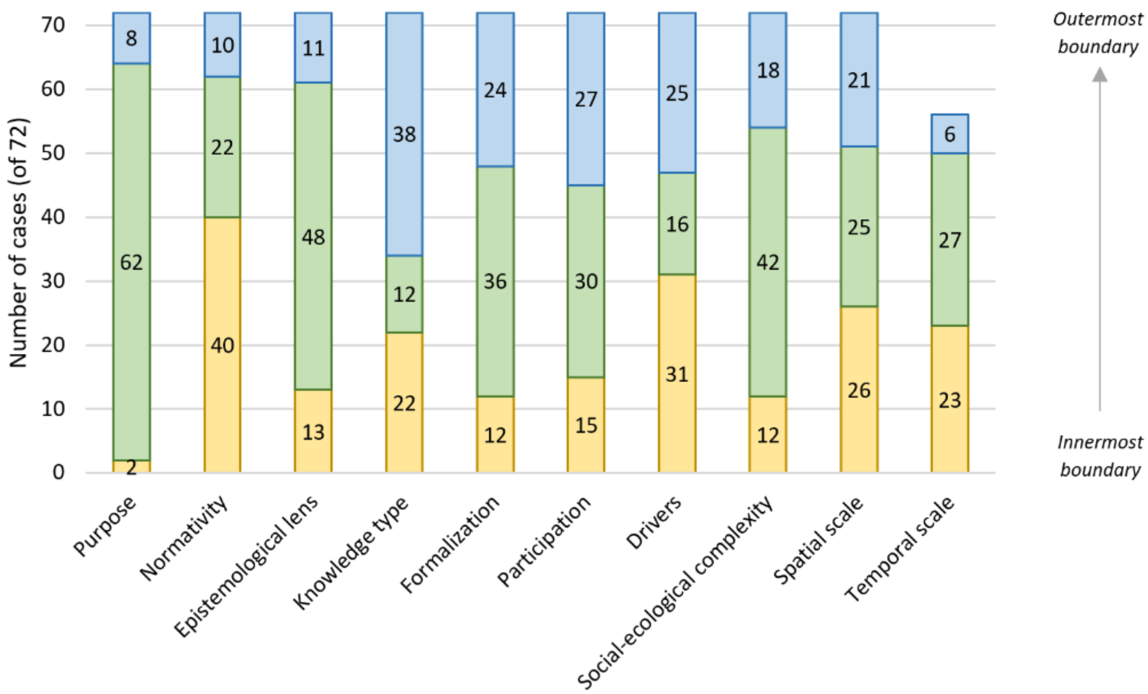

Figure 2-4: The number of case studies coded to each choice for each boundary judgment. Each column of the bar chart is an axis on the framework. Data in yellow, green, and blue correspond to the yellow, green, and blue boundaries on the framework respectively, moving from the innermost to the outermost choice. Sixteen studies did not indicate a temporal scale and could not be interpreted.

The same data in Figure 2-4 is depicted as averages on the Boundaries of the Future radar chart in Figure 2-5, revealing common Boundaries of the Future in case studies. The solid black line depicts the average selection for each judgment across all 72 case studies (solid line). Because the scenario purpose is a consequential boundary judgment, the averages for studies reflecting each different 'purpose' boundary judgment are also depicted (see legend). The average boundary overall appears to include a moderate scope of future potential (i.e., middle-of-the-road for most judgments). Scenarios framed to explore probable futures tend toward a positivist epistemological lens and scientific knowledge, operationalized with highly formalized methods and little participation. A significant proportion of studies aimed to explore plausible futures (86 percent), so these studies closely follow the average. Studies framed to explore possible/diverse futures tend toward a critical realist or pluralist epistemological lens, involve multiple types of knowledge and adopt a wider scope of imaginative normative potential. Interestingly, the selection of purpose does not appear to have a differentiating influence on the way the system is characterized, though scenarios framed to assess probable futures tend to focus on top-down structural drivers, and scenarios framed to explore possible/diverse futures reflect longer or linked temporal scales.

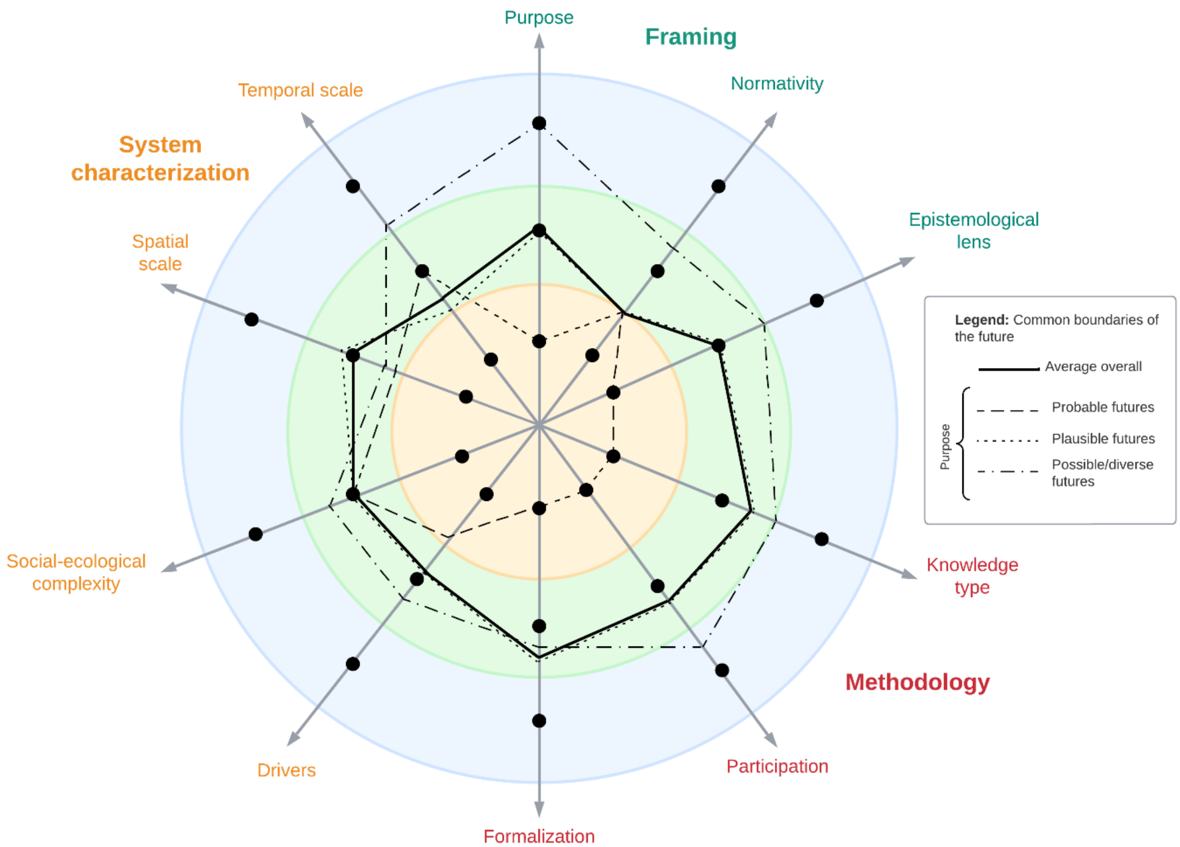

Figure 2-5: Boundaries of the future on average overall and on average for each 'purpose' boundary judgment. See the legend for which line corresponds to which subset of case studies and Figure 2-3 for placement along each axis.

2.4 Discussion

The key findings can be summarized as four takeaways. First, the Boundaries of the Future framework offers a framework that makes ambiguity in scenario practice explicit and operational and may be used as a reflective tool to facilitate reflexive scenario practice in sustainability science. Second, the framework and case study analysis together chart an important future research agenda in sustainability science. Third, reflections upon the challenges encountered during the study revealed a lack of reflexivity in scenario case studies to date, affirming the need for such a framework. Finally, the framework has limitations and should be adopted with consideration. These takeaways are each discussed in turn.

The practical contribution of this study is a framework that can be operationalized to facilitate reflexive scenario practice in sustainability science. This study demonstrated the framework as an *ex-post* reflective tool and proposes its use as an *ex-ante* reflexive tool before, during, and after a scenario process. Reflexivity is often cited as a crucial capacity for navigating ambiguity and pluralism in sustainability research (Miller 2013; Miller et al. 2014; Popa et al. 2015). Numerous scenario typologies help organize scenario practice (e.g., van Notten et al. 2003; Börjeson et al. 2006; Muiderman et al. 2020) and synthesis papers point to the unique opportunities and challenges in the use of scenarios for sustainability research (e.g., Elsawah et al. 2020; Muiderman et al. 2020; Pereira et al. 2021). However, these literatures do not offer a clear and granular strategy for reflexively linking the design of a scenario process to scenario outcomes. In contrast, the Boundaries of the Future framework fills a strategic operational gap by guiding researchers through ten key boundary judgments involved in designing a scenario process under categories of framing, methodology, and system characterization. Each judgment is an active site of choice that delimits the scope of future potential in the resulting scenarios. The boundary judgments are depicted as axes on a radar chart, in the proposed order of increasing consideration of the dynamics of, and conditions for, SES change, and the outermost choice may enrich scenarios to reflect the potential for transformation (desirable or undesirable). Thus, the framework reveals the influence of subjective choices made in the design of a scenario process and what the resulting scenarios may include *and exclude*, thereby helping enrich scenarios to reflect the novel and potentially transformative conditions of the 21st century.

The framework and case study analysis together point to important avenues for future research. The average Boundaries of the Future shown in Figure 2-5 show a bias away from judgments that open up scenarios toward the dynamics of, and conditions for, SES change and transformation. For example, few studies adopt a pluralist epistemological lens or assume scenarios are emergent from the interactions between system structure (top-down drivers) and actor agency (bottom-up drivers). The case study analysis also exposes how suites of boundary judgments tend to co-occur (e.g., purpose, epistemological lens, participation, formalization) and how framing choices (i.e., purpose, epistemological lens) do not seem to have a strong influence on the way the system is characterized. Sustainability scientists may use these results to investigate linkages and trade-offs between boundary judgments and guide the development of, and experimentation with, scenario processes that are designed to address yet underexplored parts of the framework. Most importantly, these findings affirm the need to embed the Boundaries of the Future framework into scenario development processes. For example, global environmental assessments like the Shared Socioeconomic Pathways for climate research (Riahi 2016), the United Nations Global Environment Outlook (e.g., UN Environment 2019) and the Nature Futures Framework from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Pereira et al. 2020b) may use the framework to reflect upon and enrich the use of scenarios in their assessments. Doing so may, for example, offer transparency to scenario users regarding the strengths and limitations of the scenarios for different modes of application.

Challenges encountered through the process of developing and applying the framework validated the need for greater reflexivity in scenario practice. In the case studies, many boundary judgments were opaque and had to be inferred from the way the study was introduced or the results are presented, indicating that authors may not have been reflexive about their boundary judgments or were unaware of the choices available to them. Moreover, some case studies framed their scenario process according to an enriched scope of future potential (e.g., participant learning, sensemaking about complexity), but did not choose commensurate boundary judgments under the categories of methodology or characterization. Additionally, despite the obvious temporal dimension of scenarios, sixteen of 72 studies did not provide enough information to infer a temporal scale. Such limitations present risks to the salience and legitimacy of a scenario study, demanding a framework like the Boundaries of the Future framework to structure and facilitate critical reflection about these choices.

While the ten boundary judgments offer a holistic view of the Boundaries of the Future, the framework has limitations. The framework enables reflexivity within a complexity worldview (e.g., as per the SES perspective), but it excludes more dynamic understandings of change that reject the need for boundary-making (Hertz et al. 2020; West et al. 2020); for example, the focus on linear time and system boundaries overlooks different conceptualizations of time (e.g. cyclical) and diverging beliefs about the ability of human agency to change future trajectories (Inayatullah 1998a; Jimmy et al. 2019; Hunfeld 2022). Similarly, while efforts were made to reduce researcher subjectivity through the process of abductive inquiry used in the study, the final framework is a product of a specific approach, which was influenced by the desired audience for the framework and the positionality of the researcher. Moreover, the framework is based on a synthesis of theoretical literature about SES change; significant research is required to empirically test and validate the theoretical assumptions informing the placement of each choice along each axis of the framework, Finally, the framework is provisional, as it was developed at a specific moment in time. The framework should be updated, and case studies revisited, as the understanding of SES change and the use of scenarios in sustainability science continues to evolve.

2.5 Conclusion

This study aimed to contribute to reflexive scenario practice in sustainability science by making ambiguity explicit and operational using the lens of CST. To do so, the first objective was to develop a reflexive framework that 1) characterizes how key boundary judgments involved in a scenario process influence the scope of future potential reflected in scenario outcomes, and 2) proposes the degree to which this scope of future potential may reflect the dynamics of, and/or conditions for, SES change. The intention was to offer a practical tool that facilitates more reflexive and transparent boundary choices in scenario practice. This objective was achieved through a process of abductive inquiry in seminal literature related to scenario practice and sustainability science, underpinned by a critical systems lens. The ten boundary judgments in the final framework highlight three categories of judgment in a scenario process: scenario framing, methodology, and system characterization. The framework is operationalized through a series of ten questions that can be used as an *ex-ante* reflexive tool *and/or* for *ex-post* evaluation of a scenario process. Moreover, the framework shows how scenario practitioners who wish to enrich their scenario practice with the conditions of SES change, and in particular transformation, can push their judgments closer to the outside of the framework.

The second objective was to apply the framework by analyzing social-ecological scenario case studies against the framework. This objective was addressed through an analysis of 72 cases, which was embedded in the process of abductive inquiry used to generate the framework. Thus, the case study analysis served to validate the final framework, demonstrate its practical application, and reveal common boundaries of the future in case studies to date. Together, this process offered important considerations for future research in the use of scenarios for sustainability science.

Chapter 3

Exploring “big picture” scenarios for resilience in social-ecological systems: Transdisciplinary cross-impact balances modelling in the Red River Basin

3.1 Introduction

Global climate change is expected to increase the frequency and severity of extreme events and shift the climatic regime in river basins around the world (IPCC 2021). This hydroclimatic intensification is significant and deeply uncertain (Milly et al. 2008; Marchau et al. 2019), exacerbating the risk of flood and drought damages, disruptions to food production and ecosystem services, and harms to human health (Rockström et al. 2014a; Ray et al. 2019; IPCC 2021). The capacity of society to prepare for and cope with these risks depends upon several uncertain social and economic factors (Gallopín 2006; Engle and Lemos 2010), which are both made vulnerable by climate change and may further degrade natural river basin functions, such as through land use change (Lambin and Meyfroidt 2010). Resilient water systems also play a critical role in society’s capacity to deal with stresses and shocks more broadly (Falkenmark et al. 2019b).

A shift in water governance is required to address the novel uncertainties and complexities introduced by climate change at a river basin scale. Water governance is defined broadly as the social functions that regulate and coordinate water development (Jiménez et al. 2020). The dominant 19th and 20th century paradigm of water governance enabled rapid economic development but was limited by silo thinking, reactive management of externalities, and rigid control of variability (Pahl-Wostl 2007; Baird and Plummer 2021). For example, large-scale channels and dams enabled agricultural and energy production but were optimized for historical climate variability and may be brittle to climate change (Altinbilek 2002; McCartney 2009; Giuliani et al. 2016). In recent decades, various paradigms surfaced to deal with these challenges, such as Integrated Water Resources Management (Biswas 2008), the water-energy-food-nexus (Benson et al. 2015), and adaptive governance (Folke et al. 2005; Huitema et al. 2009).

Most recently, the resilience paradigm (Walker et al. 2004; Folke et al. 2010) has been applied to enable effective water governance under climate change (Baird and Plummer 2021). From this view, river basins are complex social-ecological systems (SESs) that evolve with and adapt to environmental change, and outcomes emerge from social-ecological interactions and feedbacks across scales (Rockström et al. 2014a; Walker 2020; Chester et al. 2021). Resilience here is "the capacity to adapt or transform in the face of change… particularly unexpected change, in ways that continue to support human wellbeing" (Folke et al. 2016, p. 41). For example, water managers may develop adaptive rather than static management plans, optimize infrastructure for multiple climate scenarios rather than one, or use ecosystems for their natural capacity to buffer variability alongside traditional infrastructure (Pahl-Wostl and Knieper 2014; Faivre et al. 2017; Marchau et al. 2019).

While a resilience paradigm may in theory be effective for dealing with climate change, efforts to build resilience in practice are complex and contested. Novel approaches may be viewed as risky (Jeffrey and Gearey 2006) and must contend with the institutional inertia of conventional approaches (Sendzimir et al. 2010; Mendez et al. 2012; Marshall and Alexandra 2016). For example, infrastructure financing mechanisms may be biased away from valuing the long-term, systemic impacts of resilient solutions (Lazurko and Pintér 2022). Additionally, despite a shared language of resilience, efforts to build resilience hold hidden tensions and trade-offs rooted in divergent perspectives and interests in the future (Leach 2008; Helfgott 2018a). For example, questions of resilience to what and for whom surface assumptions about what constitutes a desirable resilient future, and the degree of transformation required to achieve it. Most actors lack the tools and frameworks to anticipate and navigate the future in a manner that reconciles such diverse framings, scales, and drivers of change (Bai et al. 2016; Verburg et al. 2016). These challenges are particularly pronounced in contexts where building resilience may require transformative changes that shift pathways toward a profoundly new system (Folke et al. 2016; Pereira et al. 2021).

Scenarios are promising tools for explicitly engaging with complex and uncertain futures (Peterson et al. 2003; Miller et al. 2014; Bai et al. 2016). Scenarios are coherent, internally consistent, and plausible descriptions of the potential future trajectories of a system (Heugens and van Oosterhout 2001). Explorative scenarios (i.e., what could happen) have been used in river basin contexts to project how climatic and socio-economic change may impact water supply and demand, and normative scenarios (i.e., what we want to happen) are often used to develop investment strategies (Varis et al. 2004; Dong et al. 2013; Elsawah et al. 2020). Emerging studies combine explorative and normative scenarios through participatory methods to collaboratively envision and strategize pathways toward sustainable or resilient river basin systems amid top-down pressures (Schneider and Rist 2014; Carpenter et al. 2015; Hirpa et al. 2018), and a handful of studies focus explicitly on scenarios related to resilience (e.g., Helfgott 2018).

Semi-quantitative scenario methods like the cross-impact balances (CIB) method are uniquely positioned to model integrative and holistic scenarios that "get the big picture roughly right" (Polasky et al. 2020). CIB applies systems theory to generate internally consistent narrative scenarios from a network of interacting drivers of change (Weimer-Jehle 2006; Weimer-Jehle et al. 2016). CIB has been applied in energy transitions and climate change research (Schweizer 2020; Weimer-Jehle et al. 2020), and applications of CIB are expanding toward a wider range of policy processes (Stankov et al. 2021; Kosow et al. 2022). However, this relatively new method has evolved within its own community of practice and has yet cross over into SES research, despite its compatibility with SES theory. CIB is compatible with an SES perspective because it takes complexity seriously, modelling scenarios as emergent outcomes of systemic interactions and feedbacks (Kosow and Gaßner 2008), including across scales (Schweizer and Kurniawan 2016; Kemp-Benedict et al. 2019). This lies in contrast to the more popular Intuitive Logics (IL) method that develops four narrative scenarios by exploring the systemic consequences of the intersection of two drivers of change (Ramirez and Wilkinson 2014).

Additionally, while popular Story-and-Simulation approaches translate qualitative scenarios into inputs for quantitative models (Alcamo 2008; Elsawah et al. 2020), CIB integrates qualitative alongside quantitative drivers within the scenario model. Thus, CIB reconciles trade-offs between qualitative and quantitative methods that make 'big picture' scenario modelling challenging; quantitative methods may be data-informed and reproducible but exclude drivers of change or perspectives that are not measured in quantitative terms (Gerst et al. 2014; Moallemi et al. 2021), and qualitative scenario methods consider a wider range of future conditions, but, at times, lack the systematic analysis and analytical insights (e.g., model sensitivity analysis) promoted by quantitative methods (Ramirez and Wilkinson 2014).

Transdisciplinary scenario processes offer further opportunities to explore diverse perspectives and interests in the future of river basins. Transdisciplinary research caters to the problem-oriented and integrative nature of sustainability science by bringing together diverse actors to generate knowledge (Lang et al. 2012; Brandt et al. 2013). Participatory scenario models can be used to structure transdisciplinary research processes, in which a model is co-produced through engagement with collaborators (McBride et al. 2017; Voinov et al. 2018; Moallemi et al. 2021). The goal of such processes is not only to structure models and produce outputs, but to mobilize knowledge in a way that facilitates societal impact and promotes meaningful learning for both scientists and participants.

The CIB method is often used to develop authoritative models through expert-driven scenario development processes. However, emerging applications of CIB aim to facilitate stakeholder engagement and collaborative learning, opening up the method to a wider range of non-expert participants (e.g., Stankov et al. 2021; Sun 2021).

To our knowledge, few or no studies have applied the CIB method to model river basin scenarios under climate change, no studies have used CIB to explicitly model scenarios as emergent from complex social-ecological dynamics, and while CIB has been used in a participatory manner, it has not been used to explicitly structure transdisciplinary research. In this study, we aimed to explore 'big picture' scenarios of a river basin under climate change by characterizing future change as emergent from interactions between diverse efforts to build resilience and a complex, cross-scale SES. We also aimed to explore the potential for the CIB method to surface diverse perspectives and drivers of change in SESs through a transdisciplinary scenario modelling process.

3.2 Methods

The phases of an ideal-typical transdisciplinary research process guided the study (Lang et al. 2012), including a) case study formulation and collaborative problem framing, b) co-creating knowledge, and c) (re)integrating the knowledge.

3.2.1 Case study formation and collaborative problem framing

The participatory scenario modelling process was situated in the Red River Basin (RRB). The RRB is part of the Hudson Bay drainage system, covering parts of Minnesota, South Dakota, and North Dakota, before meandering northward for approximately 480 km into Lake Winnipeg in Manitoba (Red River Basin Commission 2005; Leitch and Krenz 2013). The RRB is governed by a complex arrangement of institutions from community to federal and transboundary level (Hearne 2007), and is the homeland of diverse First Nations, Métis, and Tribal communities including Cree, Ojibway, Anishinaabee, and Dakota communities. Climate change is expected to exacerbate existing climatic variability and its implications (Prairie Climate Centre 2013; Rasmussen 2016; Bertrand and Mcpherson 2018; Shrestha et al. 2020). Additional pressing issues include eutrophication of downstream water bodies (Schindler et al. 2012) and soil erosion (Liu et al. 2015). A history of forced relocation and colonization of Indigenous lands in addition to contemporary socio-economic trends such as agricultural technology and urbanization introduce significant complexity to decision-making.

Additionally, actors are attempting to build a more resilient system, such as by rehabilitating ecosystems and shifting toward regenerative agriculture, as discussed at the Annual RRB Land and Water Conference in January 2021.

The Red River Basin Commission and the International Institute for Sustainable Development were chosen as collaborators due to their active role in networks driving resilience building efforts. Through consultation with these partners, the transdisciplinary scenario process was framed around the issue of resilience to ongoing floods and droughts. The year 2050 was chosen as the single temporal scale. This was chosen to situate the scenarios far enough in the future to ensure divergence from the present and to focus on linking across spatial scales, i.e., by simplifying the temporal scales (Scholes et al. 2013). A case study advisory committee of four individuals from various institutions in the basin were consulted throughout the research process.

3.2.2 Co-creating knowledge through participatory scenario modelling

3.2.2.1 Cross-impact balances scenario method

The CIB method projects internally consistent scenarios from a network of interacting drivers of change or critical uncertainties (Weimer-Jehle 2006; Kosow and Gaßner 2008). A CIB modelling process begins with determining a set of *descriptors*, which are the most important and uncertain drivers of change influencing the future of a system. The uncertainty of each descriptor is represented by a small number (i.e., 1 to 4) of *variants*, or mutually exclusive outcomes. In CIB, a scenario is made up of the selection of one variant for each descriptor. The systemic interactions between descriptors are determined by considering *influence judgments* between variants. These judgments are the direct influences of the selection of a variant from one descriptor on the selection of a variant from another. Influence judgments are captured in a judgment section, as depicted in Table 3-1, in which variants in the row are promoting (+) or inhibiting (-) variants in the column, on a scale of weak (1), moderate (2), or strong (3). Interactions with no direct influence are given an influence judgment of zero. According to best practice, each row in a judgment section should sum to zero (i.e., as depicted in Table 3-1) to satisfy the principle that the direct influence of the variant in the row is a source of selectivity between mutually exclusive variants in the column. The influence judgments for the whole system are captured in a *cross-impact matrix*.

Table 3-1: Example of a judgment section in a CIB matrix

		Descriptor 1		
		Variant a	Variant b	Variant c
Descriptor 2	Variant x	+1	+2	-3
	Variant y	-2	-1	+3
	Variant z	-1	0	+1

Internally consistent scenarios are the stable or self-reinforcing configurations of the model, in which each descriptor exists in one of its variants. A software like ScenarioWizard (Weimer-Jehle 2021) is used to calculate the impact balances for each possible scenario to determine which scenarios are internally consistent (i.e., self-reinforcing and stable) or internally inconsistent (i.e., transient or unstable). Scenarios that are internally consistent are considered plausible by many CIB analysts (Schmidt-Scheele 2020). A full description of the mathematics of impact balances and internally consistent scenarios can be found in Weimer-Jehle (2006).

3.2.2.2 Social-ecological scenario framework

A social-ecological scenario framework was developed to characterize future change as emergent from efforts to build resilience and a complex, cross-scale SES. The framework depicted in Figure 3-1 brings together existing knowledge about the dynamics of SES change and the structure of the CIB method.

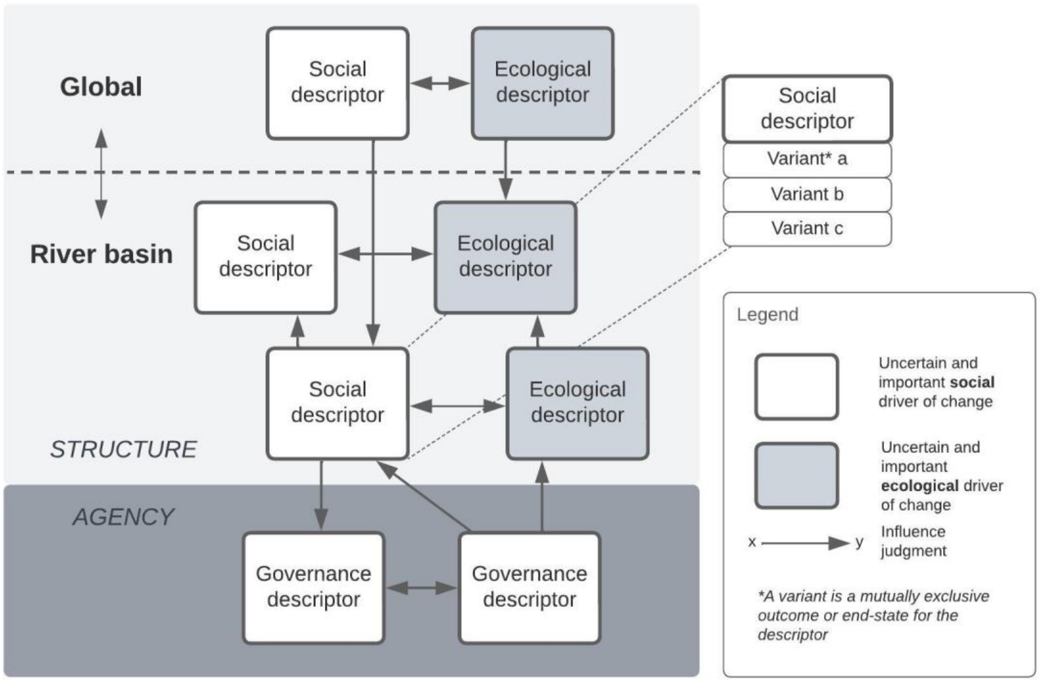

Figure 3-1: Social-ecological scenario framework

The framework depicts the future of an SES as emerging from social-ecological interactions across scales (i.e., river basin and global) and between the system structure and actor agency. Cross-scale dynamics are depicted as the influence of global change on the river basin scale (Walker et al. 2006; Scholes et al. 2013; Reyers et al. 2018). More specifically, social and ecological subsystems (i.e., social and ecological descriptors, variants, and their interactions at the river basin scale) are influenced by broader social, economic, and political settings and related ecosystems (i.e., social and ecological descriptors, variants, and their interactions at the global scale), as per the seminal framework for analyzing the sustainability of SES (Ostrom 2009; McGinnis and Ostrom 2014).

While the CIB method evaluates the plausibility of scenarios (i.e., as internal consistency), balancing scenario plausibility with diversity is important to capture the potential for social-ecological transformation. According to SES theory, transformative change emerges from the interplay of top-down structural change with bottom-up actor agency (Moore and Westley 2011; Westley et al. 2013). Thus, actor agency is represented in governance descriptors, which interact with structural social-ecological descriptors. In addition, seeds (i.e., small-scale yet promising innovations in the present assumed to be mainstream in the future) were introduced as variants to the governance descriptors to reflect the view that transformation emerges when these marginal innovations interact with top-down structures to scale in higher level systems (Geels 2002; Moore et al. 2014; Bennett et al. 2016).

A key characteristic of complex SESs is emergent outcomes (Reyers et al. 2018; Schlüter et al. 2019). In the framework, interactions between efforts to build resilience and the social-ecological context implicate social-ecological, cross-scale, and structure-agency interactions, producing emergent internally consistent scenarios. Thus, the cross-impact matrix that details these interactions defines a stability landscape for the SES, and the internally consistent scenarios are the stability domains or basins of attraction (Walker et al. 2004; Folke et al. 2010). Changes to the influence judgments in the cross-impact matrix alter the stability domain, shifting the internal consistency of scenarios and thus generating new or altered basins of attraction.

3.2.2.3 Participatory scenario modelling

A summary of the 6-step participatory scenario modelling process is depicted in Figure 3-2.

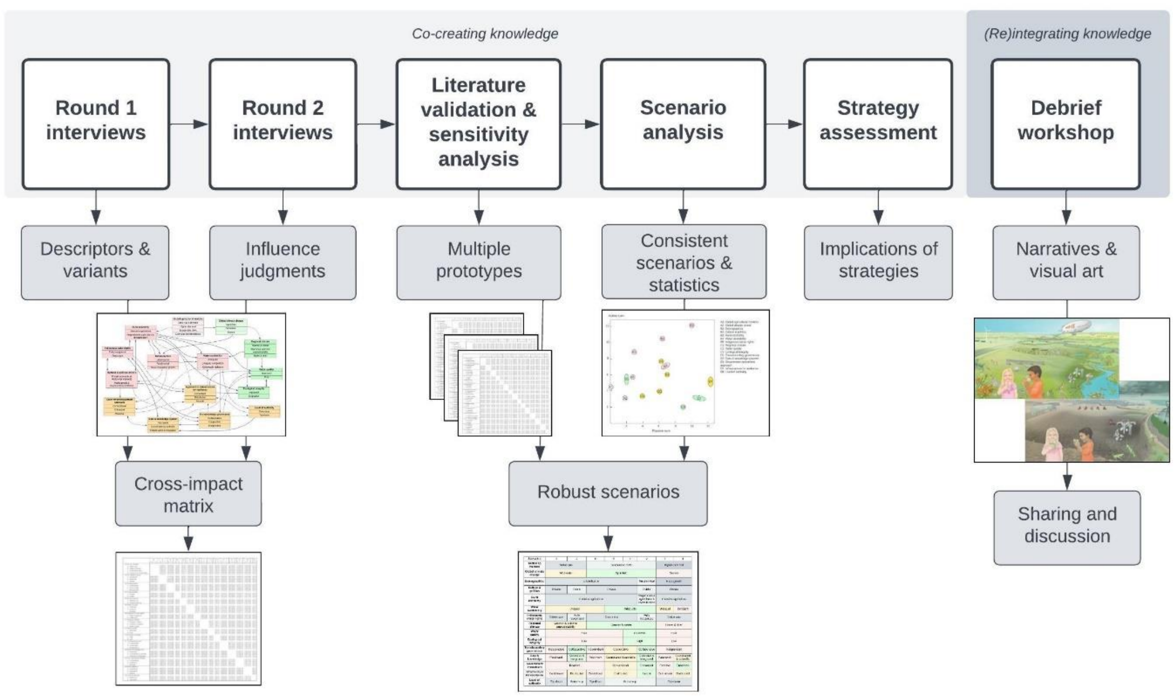

Figure 3-2: Six-step transdisciplinary scenario modelling process

3.2.2.3.1 Round 1 interviews

Semi-structured interviews with 34 experts and opinion leaders in the RRB elicited critical social and ecological drivers of change influencing resilience to climate variability and change, visions of a desirable resilient future, and current practices or projects contributing to that future. Prior to the interviews, a scan of academic and grey literature generated a preliminary list of descriptors. The documents were gathered from case study partners and relevant keyword searches on Web of Science, Scopus, and Google Scholar, and broad themes were translated into descriptors for each category in the social-ecological scenario framework.

Consultation with study partners generated an initial list of interviewees. Snowball sampling determined additional interviewees until reaching an approximate saturation point. The 34 interviewees were recruited to represent various levels of governance and areas of expertise, with some interviewees representing multiple perspectives. The levels of governance represented include transboundary (10), federal (8), provincial or state (11), municipal or watershed (7), Indigenous organization or governance (5), and general experts (9). Interviewees were experts or opinion leaders (i.e., a mixture of academics and practitioners) on at least one of the following: agriculture (8), climate (11), environment and ecology (15), governance (12), water management and infrastructure (17), and Indigenous governance (6). Indigenous perspectives were included through experts on Indigenous governance rather than Elders due to concerns regarding the ethics of coding Indigenous knowledge. Efforts were made to get participants from both the US and Canada, but a majority (22) of the interviewees were Canadian. Participation challenges were exacerbated by the availability of interviewees, particularly as the study was conducted during the COVID-19 pandemic.

Interviews were conducted virtually with a Miro board following the interview protocol in Appendix E. The preliminary descriptors from the document scan were used as examples to prompt discussion, but participants were encouraged to generate additional descriptors. The interviews were audio recorded and transcripts were coded in NVivo in three rounds. In the first round, interviewee responses were coded into general themes that roughly fit as descriptors in the main categories social-ecological scenario framework. Interviewee responses to questions regarding current practices or projects contributing to resilience were coded as potential seeds. In the second round, the text under each category of the model framework was coded with the structure of CIB in mind to generate a provisional set of descriptors and variants, introducing seeds as variants where appropriate. Attempts to draft a description for each descriptor and variant alongside a third round of coding refined the list to 15 descriptors, each with 1 to 4 variants. While effective, the process of coding interviews inevitably introduced subjectivity due to the interpretation required to translate interviewee knowledge into the structure of a CIB model. These descriptors and variants were discussed with the case study advisory committee and circulated to all participants for feedback, resulting in some minor adjustments.

3.2.2.3.2 Round 2 interviews

A second round of semi-structured interviews with 11 experts and opinion leaders elicited the influence judgments to complete the cross-impact matrix (i.e., the stability landscape of the SES). Before the interviews, the transcripts from round 1 interviews were coded a fourth time to identify relationships between descriptors. Interviewee statements that clearly indicated the direction and approximate strength of the interaction were translated into provisional influence judgments and depicted in a network diagram. Uncertain judgment sections were highlighted to prioritize the discussions during round 2 interviews.

Round 2 interviewees were topical experts selected in consultation with partners. Ten of these interviewees had participated in round 1 interviews and all were selected due to specific expertise in at least two descriptors in the model associated with uncertain influence judgments. These interviews continued until all uncertain judgment sections were discussed. Again, interviews were conducted virtually with a Miro board following the interview protocol in Appendix E. The interviews were targeted to the most uncertain influences in the model and the expertise of the interviewee. Interviewees who found the language and structure of CIB intuitive were asked directly for influence judgments, while others were asked to describe interactions qualitatively. These descriptions were later translated into influence judgments. At this stage, several judgment sections were still uncertain due to a wide range of ontological (i.e., inherent system variability) and epistemic uncertainties (i.e., lack of knowledge), in addition to ambiguity (i.e., divergent framings) (Dewulf and Biesbroek 2018).

3.2.2.3.3 Literature validation and sensitivity analysis

A review of targeted literature triangulated interview data and addressed remaining uncertain judgment sections. Because the range of topics addressed in the CIB model was broad, literature was generated by a) revisiting documents from the document scan informing round 1 interviews and b) searching Google Scholar, Scopus, and Web of Science for keywords relevant to the topics for each judgment section. A scan of the title and abstract of the results determined which results were read in detail to find supporting evidence for various influence judgments. Literature from the RRB context was used where possible, but other regional or global literature was used when appropriate.

Because most interviewees were experts on the river basin scale, literature on the shared socio-economic pathways (SSPs) was the sole data source for characterizing influence judgments between descriptors at the global scale. The SSPs depict plausible socio-economic futures at the global scale for use in climate change research (Nakicenovic et al. 2014; van Vuuren et al. 2017). Several studies characterize the implications of different SSPs on the regional scale (e.g., high, middle, low-income countries) in a manner that links global descriptors, such as agricultural markets, to river basin scale descriptors, such as the state of the rural economy (e.g., Calvin et al. 2017; Graham et al. 2018). The SSPs also indicate how different socio-economic descriptors like global agricultural markets may contribute to greenhouse gas emissions. Thus, the SSPs were also used to link global descriptors with global climate change. The rationale for these judgment sections is detailed alongside all other judgment sections in Appendix F.

The sensitivity analysis of the remaining uncertain influence judgments followed the protocol described by Schweizer and Kriegler (2012). The sensitivity analysis atypical, because it was not used to assess the existing quality of data but rather to generate new data that helped identify scenarios that are 'robust' to model uncertainty (i.e., to find scenarios that emerge as internally consistent regardless of the 'sensitivities' in the model data). The protocol designates a baseline model void of uncertain influence judgments and then identifies each uncertain influence judgment as a type I (i.e., new influences from baseline), type II (i.e., adjusted relationships from baseline), or type III (i.e., combinations of influences) sensitivity analysis. The numerous sensitivities of these three types were configured into six independent prototypes of the model that represented the maximally diverse range of uncertainty in the model. Appendix F describes the type of sensitivity for each uncertain judgment section, and Appendix G elaborates the sensitivity analysis protocol.

3.2.2.3.4 Scenario analysis

ScenarioWizard was used to generate internally consistent scenarios (i.e., basins of attraction of the SES) for each prototype. The scenario analysis focused on determining which internally consistent scenarios were common across model prototypes and are thus robust to model uncertainty (i.e., valid regardless of 'sensitivities' in the model data). The frequency statistics, bias statistics, and the active-passive diagrams for the different prototypes generated further insights. Bias statistics are used to check the quality of influence judgments by revealing systemic bias away from consistent scenarios containing a specific variant (Weimer-Jehle 2021). A bias statistic of less than 10 percent was considered an indication of significant bias in the model. An active-passive diagram depicts the role of descriptors within the system. The active sum (y-axis) represents the degree to which the descriptor is an impact source (i.e., exerts influences on other descriptors). The passive sum (x-axis) represents the degree to which the descriptor is an impact sink (i.e., receives influences from other descriptors).

3.2.2.3.5 Strategy assessment

In addition to the scenario analysis, the implications of three water governance strategies were tested in the model. These strategies were discussed by many interviewees as potentially influential shifts in the system but were not characterized in the model structure. Assumptions were made about how select influence judgments may change, generating a new model prototype for each strategy (i.e., transformations in the stability landscape of the SES, generating new basins of attraction). These new prototypes were then modelled in ScenarioWizard. The results were compared to the original six prototypes, focusing on internally consistent scenarios, frequency statistics, and bias statistics.

3.2.3 Knowledge (re)integration

The final phase of knowledge (re)integration first required translating model outputs into formats that could be shared to stimulate discussion among participants. Five of the most divergent scenarios were selected from the eight robust scenarios to offer a manageable number for participants to discuss. The lead author translated the outputs from ScenarioWizard into narratives. The narratives describe the RRB under the chosen combination of variants, highlighting key influences that contribute to the internal consistency of the scenario. A local artist depicted these scenarios as visual art.

3.2.3.1 Debrief workshop

A virtual workshop aimed to facilitate deeper engagement with the results. While the initial intention of the workshop was to ‘reintegrate’ knowledge as per the ideal-typical research process (Lang et al. 2012), time and format constraints led to a more traditional knowledge sharing workshop. Twenty-two participants were recruited from interviewees and the board of the RRBC. Nineteen of the 22 participants had participated in at least one round of interviews. As in the interviews, participants represented various levels of governance (with some representing multiple), including transboundary (9), federal (5), provincial or state (12), municipal or watershed (6), Indigenous organization or governance (4), and general experts (5). Interviewees were experts or opinion leaders on at least one of the following topics: agriculture (3), climate change (7), environment and ecology (8), governance (7), water management and infrastructure (17), and Indigenous governance (5).

The workshop began with a presentation of the rationale, methodology, and results, using the narratives and visual art to communicate the scenarios. Participants were then split into breakout rooms where they worked together to 1) rank scenarios from most to least desirable, 2) rank scenarios from most to least plausible, and 3) discuss how existing initiatives are promoting or inhibiting different scenarios. In a final debrief, participants were asked whether the scenario process changed the way they thought about the future of the RRB. This question served as a simple evaluation in the absence of more robust pre- and post-workshop surveys. The full workshop protocol is included in Appendix I.

The workshop transcripts were analyzed using a simple thematic content analysis. The analysis focused on statements that surfaced potentially divergent assumptions about scenario desirability and plausibility, in addition to statements linking existing initiatives to the scenarios. Participant responses to the debrief questions were analyzed to provide a broad indication of the extent to which the CIB method effectively helped actors explore diverse perspectives and drivers of change in an SES.

3.2.4 Researcher positionality

Researcher positionality is important for transdisciplinary research in contexts with diverse perspectives and interests like the RRB. The lead author who conducted fieldwork and interpreted the data is a western-trained scientist and Canadian settler. While efforts were made to avoid scientific subjectivity and bias, this positionality may have influenced access to study participants, the information participants felt comfortable to share, and how different perspectives (e.g., scientific versus local or practitioner knowledge) were interpreted and integrated into the scenario model. These biases may have also been influenced by the virtual format of the study, which allowed for the use of novel tools (e.g., Miro boards during interviews and workshops) while limiting participants to those who were comfortable with and available for online engagement during the COVID-19 pandemic.

3.3 Results and Discussion

This section summarizes the study results and the significance of the findings for the phases of co-creating knowledge (Section 3.3.1) and sharing and (re)integrating knowledge (Section 3.3.2).

3.3.1 Co-creating knowledge: Participatory scenario modelling

3.3.1.1 Descriptors and variants

The 34 round one interviews generated fifteen descriptors, which are the important and uncertain drivers of change relevant to resilience to climate variability and change in the RRB. Social and ecological drivers of change at river basin and global scales make up the structure of the cross-scale SES, and governance descriptors characterize efforts to build resilience, introducing the influence of actor agency. Multiple variants for each descriptor cover a range of mutually exclusive outcomes. Several seeds were included as variants (e.g., “collaborative governance” under the transboundary governance descriptor), broadening the scope of outcomes to include the potential for transformation. Detailed descriptions of these variants are summarized in Table 3-2.

Table 3-2: Descriptors and variants according to categories in the social-ecological scenario framework, including scale, structure (S) and agency (A), and type (social or ecological)

Scale	*S/A*	*Type*	*Descriptor*	*Variants*	*Details*
GLOBAL	STRUCTURE	SOCIAL	**Global agricultural markets** Direct influences of changing global agricultural market demand on the RRB	**Status quo**	Stable demand for conventional agricultural exports. (In a world in which social, economic, and technological trends do not shift significantly from historical patterns, demand for agricultural exports remains stable.)
				Increasing demand	Higher demand for conventional agricultural exports. (In a high-economic-growth future driven by status quo consumption, rapid development increases food demand globally.)
				Sustainable diets	Higher demand for agricultural exports that meet environmental standards. (In a sustainable future, average global food demand is high as poverty reduction continues, with a shift in consumer preference for sustainable and plant-based diets.
				Everyone for themselves	Agricultural demand primarily within Canada and the US, resulting in lower demand for agricultural exports from the RRB. (In a future with resurgent nationalism and security concerns, countries pursue food and energy self-sufficiency, isolating markets to regional production, depressing global demand for exports.)
		ECOLOG-ICAL	**Global climate change** Global greenhouse gas (GHG)	**Optimistic** RCP[a] 1.9-2.6	Net zero emissions by 2050, curbing severe climatic shifts. Moderate impacts of climate change by 2050.
				Middle-of-the-road RCP 4.5	Emissions remain at 2015 levels to 2050. Significant impacts of climate change by 2050.

			emissions scenarios	**Severe** RCP 7.0-8.5	Emissions continue to rise and double by 2050. Severe impacts of climate change by 2050.
RIVER BASIN		SOCIAL	**Demographics** Population growth & distribution in the RRB	**Urbanization**	Moderate population growth (within projected range[b]) in urban centres. Continued rural depopulation.
				Rural revival	Moderate population growth (within projected range[b]) with outmigration to rural areas. Revival of rural economy & cultural life.
				Mass population growth	Significant population growth (exceeds projected range[b]) driven by migration to both rural and urban areas.
			Cultural & political drivers Dominant cultural & political priorities driving decision making in the RRB	**Private landowner & economic interests**	Decision making prioritizes private landowner interests and economic growth. Environment only restored or protected if near-term business case.
				Public goods & environmental interests	Decision making prioritizes public goods and environmental interests over private interests when required. Environment restored or protected to enable long-term resilience of the economy and ecosystems.
			Rural economy Dominant economic sectors driving the rural economy in the RRB	**Intensive agriculture**	Economy of the RRB continues to be driven by intensive agriculture on increasingly large-scale farms. Technological developments like precision agriculture offer opportunities for economic efficiencies.
				Regenerative agriculture and diversification	Economy of the RRB shifts toward regenerative agriculture and diversifies (either within the agricultural sector or beyond). Technological developments like precision agriculture offer opportunities for improved soil health and sustainability. Economy diversifies to include smaller-scale agriculture and local processing.
			Water availability Reliability of water availability to meet demand in the RRB (quantity only)	**Adequate**	Water availability generally adequate for demand. Seasonal deficiencies or issues manageable.
				Unequal	Water availability insufficient for demand in some seasons or locations. Deficiencies or issues unmanageable, leading to unequal access and competition across sectors and demographics.
				Chronically deficient	Water availability insufficient for demand across the RRB for multiple years in a row. Deficiencies and issues unmanageable, depressing economic activity. Higher risk of poor health outcomes, especially in rural areas.
			Indigenous water rights Degree of recognition of Indigenous water rights and values in governance and management of the RRB	**Fully recognized**	Indigenous water rights are fully recognized. (E.g., prioritizing Indigenous interests over private interests when required, protecting the environment for its inherent value, and including Indigenous knowledge in decision making.)
				Status quo	Indigenous water rights are not fully recognized, perpetuating the status quo. (E.g., de-prioritizing Indigenous interests, not recognizing inherent value of the environment, excluding lack of recognition of inherent cultural and social value of the environment, and excluding Indigenous knowledge in decision making.)
		ECO-LOG-ICAL	**Regional climate** Temperature	**Warmer & wetter**	Gradual increase of average annual temperature. Climate variability within recent historical range with overall increase of annual precipitation.

			and precipitation in the RRB under a changing climate	**Warmer & extremely unpredictable**	Gradual increase of average annual temperature. Increased atmospheric moisture content increases risk of rain-based summer flood events. Climate variability more extreme and unpredictable, with both floods and droughts possible within the same year.
				Hotter & drier	Rapid and extreme temperature increase and/or shifting storm tracks lead to severe, multi-year or multi-decadal droughts.
			Water quality Quality of water in the RRB and downstream water bodies (Lake Winnipeg)	**Improved**	Nutrient loading and pollution into the RRB reduced, improving the quality of water within the RRB and Lake Winnipeg.
				Poor	Nutrient loading and pollution into the RRB continue at a status-quo or increased rate, perpetuating contamination of water within the RRB and of Lake Winnipeg.
			Ecological integrity Broad indicator for the integrity of natural ecosystems in the RRB, including their stability, dynamics, and "naturalness"	**Improved**	Ecosystem structure and function are restored or protected. Natural resilience to shock (climatic and other) is high. Low vulnerability to invasive species and pests.
				Degraded	Ecosystem structure and function are disrupted and degraded. Natural resilience to shock (climatic and other) is low. High vulnerability to invasive species and pests.
	AGENCY	GOVERNANCE	**Transboundary governance** Nature of transboundary governance in the RRB	**Collaborative**	Collaboration driven by shared goals between all parties. Municipal, state, provincial, Indigenous, and federal governance entities meaningfully included. Transboundary organizations act as enablers of initiatives.
				Cooperative	Cooperation driven by independent goals and interests. Governance entities discuss when required, supported by formal agreements. Transboundary organizations are convenors of inter-jurisdictional discussions regarding transboundary issues or joint initiatives.
				Independent	No meaningful cooperation. Governance entities act independently and without consultation. Formal transboundary agreements frequently broken to pursue domestic interests. Transboundary organizations are mediators of inter-jurisdictional conflicts.
			Data & knowledge systems Type of data and modelling systems in the RRB	**Patchwork**	Data collection is patchy. Modelling and forecasting is uncoordinated and without linkages to clear decision points. Climatic forecasting capacity not significantly improved. No forum for integration across scientific, local or Indigenous data and knowledge.
				Coordinated & scientific	Data collection is comprehensive and shared across jurisdictions. Modelling and forecasting is coordinated basin-wide, with significant improvements in climatic forecasting. Modelling and forecasting have clear linkages to some decision points. No forum for integration across scientific, local, or Indigenous data and knowledge.

				Collective & integrated	Data collection is organized and shared across jurisdictions. Modelling and forecasting is done collectively, with clear linkages to most decision points. Climate forecasting is significantly improved. Basin-wide forum for integration across scientific, local, and Indigenous data and knowledge established and maintained.
			Government investment approach Type of resilience measures supported by government investment bodies (provincial, state, federal)	**Conventional**	Government investments focus on grey/hard infrastructure measures with large financial disbursements and clear returns.
				Enhanced	Government investments are more flexible to include soft (e.g., data monitoring), natural (e.g., wetland restoration), and grey (e.g., reservoirs) infrastructure measures. Investments disbursed in smaller increments with more flexible returns.
				Reactive	Government investments focus reactively on emergency support and insurance, due to insufficient spending on maintenance, preventative measures.
			Approach to infrastructure for resilience Dominant approach to water resilience	**Centralized infrastructure**	Hydroclimatic variability (i.e., floods, droughts, and seasonal precipitation) managed with large-scale infrastructure, including reservoirs, diversions, and intra/inter-basin transfers. Continued drainage from landscape, including uncontrolled tile drainage. Highly managed ecosystems with few or none of them in their natural state.
				Distributed infrastructure	Hydroclimatic variability managed with distributed system of ponds and controlled tile drainage. Large-scale infrastructure used to supplement distribution system if required. Highly managed ecosystems with few or none of them in their natural state.
				Natural ecosystems	Hydroclimatic variability buffered with natural ecosystems. Controlled drainage and ponds manage extremes beyond natural ecosystems' capacity when required. Large-scale infrastructure only built as a last resort. Significant restoration of natural ecosystems.
			Level of authority Dominant level of governance authority driving water resilience measures	**Bottom-up, watershed**	Bottom-up initiatives are dominant drivers of resilience. Continued or increased devolution of authority to local scales.
				Top-down, state/ province	Top-down initiatives are dominant drivers of resilience. Authority maintained at state/province or federal level, restricting local-level authority.

[a] Representative concentration pathways (RCP) are greenhouse gas emissions concentration scenarios used by the IPCC. The numbers represent radiative forcing (Watts per metres-squared).

[b] Population projections for the Red River Basin are not readily available. Manitoba projects the population will grow from a baseline of 1.35 million (2017) to 1.57-1.95 million by 2043 (https://www150.statcan.gc.ca/n1/en/pub/91-520-x/91-520-x2019001-eng.pdf?st=uNlp1A0v). North Dakota projects the population will grow from a baseline of 0.67 million (2010) to 0.92-1 million by 2040 (https://www.commerce.nd.gov/census/). Minnesota projects the population will grow from a baseline of 5.89 million (2019) to 6.46 million in 2050.

3.3.1.2 Influence judgments and multiple prototypes

The influence judgments characterize social-ecological and cross-scale interactions between descriptors and variants, generating a stability landscape for the future of the RRB as depicted in

Figure 3-3. Arrows indicate judgment sections containing non-zero influence judgments between the connected descriptors. Following round 2 interviews, many influence judgments were uncertain, primarily due to a lack of knowledge about the system (i.e., lack of clarity from interviewees and literature) and ambiguity (i.e., multiple interpretations of the system from interviewees and literature). The dashed lines represent influence judgments that remained uncertain following the literature validation. The influence judgments and their supporting evidence are summarized in Appendix F. The sensitivity analysis generated six model prototypes, which together represent the maximally diverse range of uncertainty in the model.

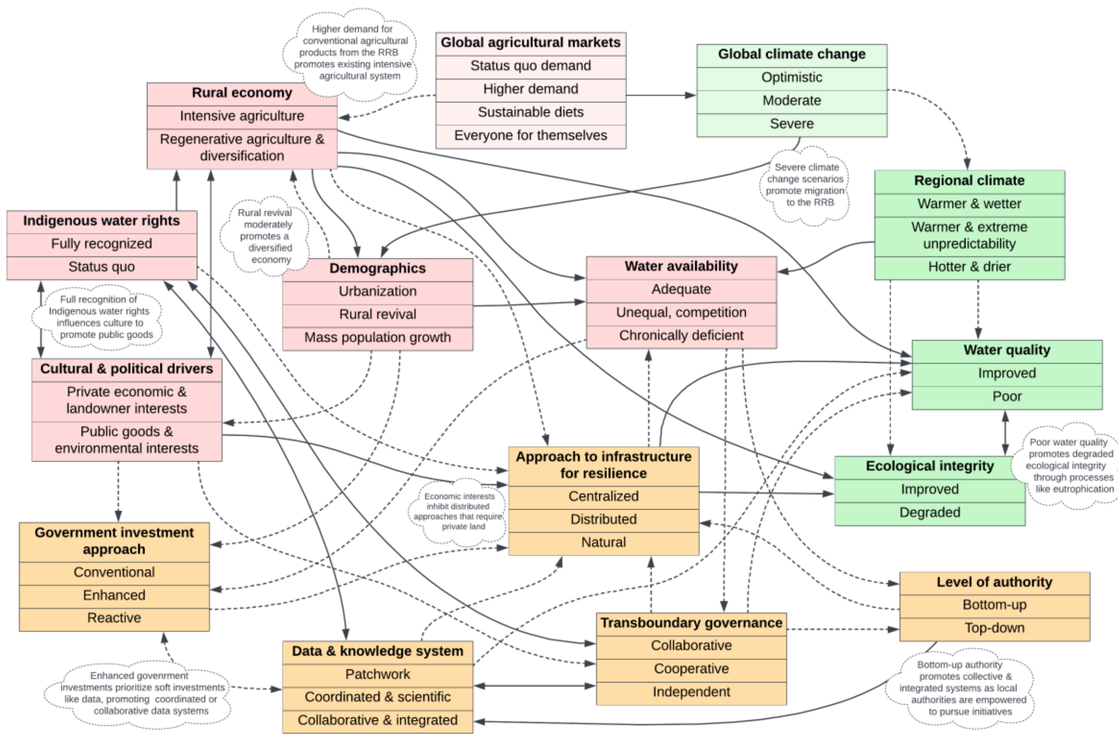

Figure 3-3: Descriptors, variants, and influence judgments in the scenario model. Arrows indicate judgment sections containing non-zero influence judgments. Dashed lines represent influence judgments that remained uncertain following the literature validation. Bi-directional arrows represent two influence judgments (i.e., in each direction), which are justified by different rationales.

3.3.1.3 Consistent scenarios and statistics

The six prototypes were analyzed in ScenarioWizard, each generating 13 to 23 internally consistent scenarios. The scenarios describe 'big picture' futures for the RRB under climate change and are basins of attraction on the stability landscape of social-ecological interactions defined by the influence judgments in each prototype. Eight of these scenarios were robust to model uncertainty, depicted in the scenario tableau in Figure 3-4. In the tableau, one scenario is described by the variants listed in a vertical column (enriched by the detailed descriptions for each variant in Table 3-2). A description of the robustness criterion, in addition to a broader set of seventeen scenarios that were less robust, are included in Appendix H.

Scenario #	*3*	*1*	*6*	*5*	*4*	*2*	*7*	*8*
Global ag markets	Status quo		Sustainable diets				Higher demand	
Global climate change	Moderate		Optimistic				Severe	
Demographics	Urbanization					Rural revival	Mass growth	
Culture & politics	Private	Public	Private			Public	Private	
Rural economy	Intensive agriculture					Regenerative agriculture & diversification	Intensive agriculture	
Water availability	Unequal			Adequate			Unequal	Deficient
Indigenous water rights	Status quo	Fully recognized	Status quo			Fully recognized	Status quo	
Regional climate	Warmer & extreme unpredictability		Warmer & wetter				Hotter & drier	
Water quality	Poor				Improved		Poor	
Ecological integrity	Low				High		Low	
Transboundary governance	Independent	Collaborative	Independent	Cooperative		Collaborative	Independent	
Data & knowledge	Patchwork	Collective & integrated	Patchwork	Coordinated & scientific		Collective & integrated	Patchwork	Coordinated & scientific
Government investment	Reactive			Conventional		Enhanced	Reactive	Enhanced
Infrastructure for resilience	Centralized	Distributed	Centralized	Distributed		Natural	Centralized	Distributed
Level of authority	Top-down	Bottom-up	Top-down	Bottom-up			Top-down	

Figure 3-4: Scenario tableau depicting 8 robust scenarios. Scenario numbers are listed along the top of the tableau (note: scenarios are not in numerical order as they were rearranged from their original ScenarioWizard output to improve readability).

These scenarios reveal important insights into the future of the RRB under climate change. For example, independent governance, patchwork data, and other generally undesirable governance interventions tend to co-occur (e.g., scenario 3, 6, 7), contributing to poor environmental outcomes.

More desirable governance interventions such as collaborative governance and integrated data also co-occur (e.g., scenario 1, 2, 4, 5), improving environmental outcomes. Still, the state of global descriptors has a strong influence over environmental outcomes, sometimes overshadowing positive governance interventions (e.g., scenario 1).

Figure 3-5 depicts the approximate active-passive diagram. Descriptors in the top left quadrant, such as Indigenous water rights, have a highly influential role on the system. Descriptors in the bottom right quadrant, such as water quality or ecological integrity, are strongly influenced by other descriptors in the system. Descriptors in the top right quadrant, such as the rural economy, are both strongly influencing and influenced by other descriptors, and thus are connected to complex system behavior (Weimer-Jehle 2021).

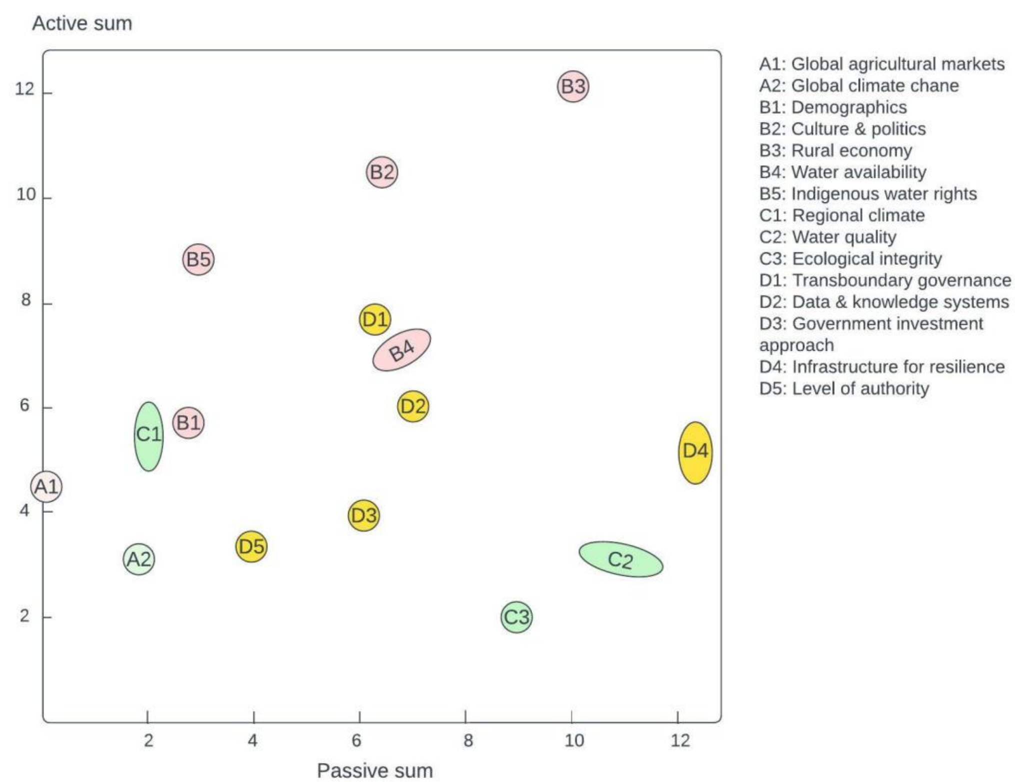

Figure 3-5: Active-passive diagram. Elongated circles represent deviations between prototypes.

The only variant with a bias statistic of less than 10 percent is the 'natural ecosystems' approach to infrastructure for resilience (5.6 to 8.3 percent). This bias is due to restricting influences from several variants including an intensive agricultural economy, reactive or conventional government investment approaches, patchwork data and knowledge systems, and private economic and landowner interests. Correcting this bias by adjusting the influence judgments associated with this variant would require changes that deviate significantly from supporting evidence, so the bias was accepted for the analysis.

Together, the bias statistics and active-passive diagram reveal important implications for resilience in the RRB. The presence of strong restricting influences on the natural ecosystems approach to infrastructure for resilience indicates that transformative change may be required in several areas for a natural ecosystems approach to be mainstream. Additionally, the complex behaviour associated with the role of the rural economy (i.e., due to its combined active *and* passive role in the system) reveals that isolated efforts to shift away from an intensive agricultural economy may have unexpected consequences. Importantly, the active role of Indigenous water rights, in combination with the concurrence of full recognition of Indigenous water rights with more desirable governance outcomes, reveals its potentially cornerstone role in realizing desirable outcomes overall.

3.3.1.4 Implications of strategies

The strategy assessment evaluated a collaborative response to scarcity, true market for ecological goods and services, and effective demand management, as described in Table 3-3. These strategies redefined specific influence judgments, shifting the stability landscape of social-ecological interactions in ways that may contribute to transformative change. Appendix J details the rationale for the changes in influence judgments.

Table 3-3: Summary of redefined influence judgments in strategy assessment

Strategy	*Description*
Collaborative response to scarcity	Chronically deficient water availability promotes (instead of restricts) collaborative and cooperative transboundary governance
True market for ecological goods and services	Ecosystem goods and services are valued in the economy (e.g., water quality and ecosystem services markets); private economic interests promote (instead of restricting) regenerative agriculture and distributed/natural approach to infrastructure
Effective demand management	State of the rural economy and demographics no longer directly influence water availability

Many participants discussed the importance of a *collaborative response to scarcity*, but the model showed that collaboration alone does not change outcomes in all cases. For example, under the assumption that the centralized infrastructure approach is the most effective for resilience, some chronically deficient water availability outcomes are avoided, but governance outcomes deteriorate. This surprising result is due to feedback effects; for example, shifting the relationship between water availability and transboundary governance indirectly influences the approach to infrastructure for resilience, which in turn influences water availability. In contrast, if natural infrastructure is assumed to be most effective for improving resilience, the collaborative response generates significant improvement in water availability and governance outcomes. Thus, collaboration, in combination with enhanced investment approaches, a collective and integrated data and knowledge system, and recognition of Indigenous water rights – can improve water availability.

The *true market for ecological goods and services* clearly increased the frequency of preferred outcomes in the scenario results (i.e., adequate water availability, improved water quality, improved ecological integrity). Additionally, several consistent scenarios flip from an intensive agricultural economy to regenerative agriculture and diversification. Importantly, this strategy created the least biased model prototype, in which no variant has a bias statistic under 10 percent. Thus, a true market for ecological goods and services partially decouples environmental and economic goals, creating an enabling environment for diversified and regenerative agriculture and desirable ecological outcomes. However, some consistent scenarios shift away from fully recognized Indigenous water rights, collaborative governance and collective data and knowledge systems. This unintended consequence is because under this version of the model, environmental outcomes are no longer contingent on an inclusive governance context. Thus, if not pursued carefully, a true market for ecological goods and services risks creating an environmentally desirable but socially undesirable system.

Few participants discussed *effective demand management,* but several consistent scenarios flipped toward improved water availability (e.g., chronically deficient to unequal; unequal to adequate). This finding reflects the direct impact of reducing anthropogenic pressure on water availability.

3.3.2 Knowledge (re)integration: Debrief workshop

The knowledge (re)integration phase was isolated to a simple knowledge sharing workshop (as discussed in Section 2.3), which focused on translating model outputs into more accessible formats and stimulating discussion among participants. Five of the eight strictly robust consistent scenarios from Figure 3-4 were selected for the debrief workshop to keep the number of scenarios manageable for participants. The scenarios were selected by including the most diverse scenarios in the set.

3.3.2.1 Narratives and visual art

A local artist depicted the scenarios as visual art, involving two rounds of feedback with researchers. The artist depictions are shown in Figure 3-6. The narratives for the five selected scenarios are included in Appendix K.

Figure 3-6: Artist visual depictions of 5 divergent robust scenarios for debrief workshop. Artist: Rhian Brynjolson

3.3.2.2 Sharing and discussion

The workshop breakout sessions split the 22 participants in four breakout groups, each with three to five participants and a facilitator. During the desirability ranking exercise, participants agreed on the best- and worst-case scenarios and discussed implicit trade-offs. For example, participants discussed scenario 4 as desirable, but recognized it only seems to benefit those with power. Participants also recognized that the most desirable scenario (i.e., scenario 2) represented the most significant transformation from the status quo. Yet, participants in two groups stated that many aspects of scenario 2 are already occurring at small scales.

Participants agreed that the most plausible scenarios (by 2050) were those that do not depart significantly from the status quo. Different groups ranked different scenarios as most plausible (i.e., 1, 3, 4, and 7), surfacing important assumptions about the future. For example, participants thought scenarios containing the optimistic global climate change outcome are implausible, and that improved social outcomes (e.g., full recognition of Indigenous water rights) are more plausible than improved environmental outcomes (e.g., high ecological integrity). This confidence in the plausibility of full recognition of Indigenous water rights is notable, given its active role in realizing desirable scenarios (Section 3.3.1.3).

Participants diverged more significantly in the discussion regarding how efforts to build resilience contribute to scenario outcomes. For example, one group thought a planned floodwater diversion scheme project promotes desirable outcomes for water availability (e.g., scenario 2), while the other discussed how such large-scale projects reinforce systems that are not resilient (e.g., scenario 3). This finding shows that participants not only hold divergent perspectives, but that participants may interpret scenarios according to their different views and interests.

The debrief at the end of the workshop revealed that the scenario process was valuable for three reasons: to make sense of complexity, surface different perspectives, and affirm the value of collaboration. Participant quotes supporting each of these statements are included in Appendix L, but examples include:

> "I don't think it changed how I thought about the basin, but… the scenario approach is just so effective. It presents a range, and you sort of look at these different gradations along the continuum and I just think it's an excellent, excellent way to consider during complex situations."

> "[We have] done a lot of work on kind of how decision-making is informed by both kind of facts and evidence but also perspectives… Being in these breakout groups is a good reminder that we all have priorities, biases, and just different places from which we're coming to."

> "It was kind of a reminder that by bringing people together… around scenarios like this may actually change the way our future is shaped and how we prioritize."

3.4 Study implications and conclusion

We facilitated a transdisciplinary scenario modelling process in the RRB that explores 'big picture' scenarios of a river basin under climate change, characterizing future change as emergent from interactions between diverse efforts to build resilience and a complex, cross-scale SES. We used CIB to structure the process, a semi-quantitative scenario method that has been underutilized in SES research. In doing so, we also aimed to explore the potential for the CIB method to surface diverse perspectives and drivers of change in SESs. The resulting 'big picture' scenarios reflect a more integrated and systemic picture than is offered by many quantitative scenario models and narrative scenario methods. To our knowledge, this is the first study to apply CIB in a participatory, transboundary context to explicitly characterize SES change, offering important implications for the RRB and sustainability research broadly.

3.4.1 Implications for the Red River Basin

The study results surfaced three important implications for the RRB. First, the internally consistent scenarios depict multiple basins of attraction for the RRB. The scenarios integrate a wide range of drivers, from global agricultural markets to Indigenous water rights and water quality, and a broad scope of outcomes. The seed concept (i.e., small-scale, present innovations at scale) pushed governance descriptors toward more transformative scenarios. Actors may use these scenarios in strategy and policy making, pushing discussions toward a richer scope of outcomes than may otherwise be considered.

Second, the CIB matrix characterizes the RRB as a complex stability landscape of social-ecological interactions, exposing influential variables and feedbacks that affect the trajectory of the future. Actors may use the findings of the CIB analysis to enrich their understanding of the system, helping leverage cornerstone drivers of change (e.g., recognition of Indigenous water rights; culture and politics), situate solutions within a bigger picture of social-ecological interactions (e.g., collaborative governance only improves water availability if accompanied by a suite of other enabling governance conditions), and connect existing initiatives to their potential long-term implications (e.g., large-scale infrastructure contributes to resilience in complex and contested ways).

Finally, the sensitivity analysis generated scenarios that are robust to uncertainty yet revealed uncertainty and disagreement regarding how drivers of change interact. Actors may direct research efforts toward lesser understood but important interactions, such as between the state of the economy, culture and politics, and Indigenous governance. More targeted and integrative studies may analyze the systemic effects of diverse efforts to build resilience. In addition, participatory and deliberative spaces are required where actors can expose and discuss divergent perspectives and interests in resilience.

3.4.2 Implications for sustainability science

The study offers important implications for sustainability science. First, the CIB method synthesized the expertise of diverse participants by integrating drivers of change represented by quantitative (e.g., water quality or climate) and qualitative knowledge (e.g., culture and politics), enabling the development of 'big picture' scenarios. Importantly, this integration process required a 'meet in the middle' approach. In other words, deriving descriptors and variants from highly detailed quantitative studies sacrificed some degree of numerical granularity, while deriving descriptors and variants from qualitative theories and experiences sacrificed narrative richness. Moreover, the process of quantifying influence judgments helped make assumptions about how descriptors interact explicit but were difficult to quantify in the matrix format of CIB. Thus, our study demonstrated the opportunities and constraints in the 'meet in the middle' process required to apply this scenario modelling approach, which affirms the potential for and guides more widespread adoption of semi-quantitative scenario methods like CIB in the toolbox of SES modelling approaches.

Second, scenarios are often used to make the inherent unpredictability of SESs explicit, but the complexity of SES change means that there are significant gaps in the knowledge required to systematically model the future. Rather than setting rigid assumptions that reduce or ignore this uncertainty, our approach for sensitivity analysis (i.e., using multiple prototypes to identify scenarios that are 'robust' to these uncertainties) demonstrates one of multiple possible approaches to acknowledging and systematically embedding a wide range of uncertainties into the scenario process.

We urge sustainability scientists using scenarios to draw from our experience to ensure scenario validity by addressing the full range of uncertainties (Dewulf and Biesbroek 2018) in a method- or context- specific and transparent way.

Third, we demonstrate the use of a unique guiding framework to structure the development of ‘big picture’ scenarios. Many scenario studies use frameworks like STEEPV (social, technological, economic, environmental, political, values) to maximize the scope of drivers (e.g., Proskuryakova 2022), or frameworks like Three Horizons to characterize transformation (Sharpe et al. 2016). However, few scenario studies bring together the details of these frameworks with the unique capacities of individual scenario methods, and thus miss out on a more systematic and transparent scenario development process. Instead, we developed scenarios underpinned by a unique social-ecological scenario framework (Section 3.2.2.2), which brings together existing knowledge about the dynamics of SES change and the structure of the CIB method. Thus, our study demonstrates the value of developing and using unique guiding frameworks in future applications of scenarios in sustainability science.

Finally, sustainability scientists should reflect upon the ways in which, despite best efforts, every scenario process has limitations that excludes certain perspectives and drivers. In this study, focusing on robust scenarios may have masked divergent scenarios that are internally consistent only under marginalized assumptions. Similarly, the positionality of the researchers and the choice to avoid coding Indigenous knowledge limited the degree of Indigenous participation, inhibiting opportunities to generate scenarios that challenge dominant narratives. Further, the ‘meet in the middle’ approach required to formalize interviewee knowledge into a CIB model excluded Indigenous knowledge due to ethical concerns and may favour scientific knowledge over local or practitioner knowledge given the academic bias to consult literature under uncertainty. Lastly, our study focused on a rigorous scenario development approach, but the final phase of ‘knowledge (re)integration’ lacked the deep collaboration required to fully reintegrate findings in the research context. Moreover, we did not use robust frameworks for evaluating learning through the process (Baird et al. 2014). Future applications of scenarios in sustainability science can draw from the limitations of our study to improve the rigor and impact of scenarios.

In sum, our analysis surfaced significant complexities surrounding efforts to build resilience and affirmed the potential for the CIB method to generate unique insights about the trajectory of SESs and opportunities for systemic interventions.

Chapter 4

Operationalizing ambiguity in sustainability science: Addressing the elephant in the room

4.1 Introduction

Transformative change is required for humanity to overcome the root causes of 21st century environmental crises like global climate change and biodiversity loss (United Nations 2015; Patterson et al. 2017). There is growing agreement that for sustainability science to contribute to this change, it must bridge the science-society interface through action-oriented, integrative, and pluralist knowledge production (Cornell et al. 2013; Caniglia et al. 2020; Fazey et al. 2020). The research paradigms of transdisciplinarity and knowledge co-production have emerged in response to this call, offering promising contributions to the future of sustainability science (Lang et al. 2012; Brandt et al. 2013; Klenk and Meehan 2017; Chambers et al. 2022). Yet, in their effort to make sense of and influence contemporary sustainability issues, these paradigms grapple with persistent ambiguity (i.e., existence of multiple frames), which is surfaced by the plural values and perspectives of diverse actors involved in knowledge production, resistance to integration via any singular frame offered by an individual discipline, and the inherent complexity of sustainability challenges (Leach et al. 2010; Preiser et al. 2018; Dewulf et al. 2020; Turnhout et al. 2020).

The ambiguity that permeates transdisciplinary research creates several challenges. Ambiguity generates misunderstanding and conflict when collaborating across paradigms (Strang 2009; Turnhout 2019), and potentially incommensurate frames may emerge from different theory orientations informed by different ontological (ways of being) and epistemological (ways of knowing) commitments (Kuhn 1970; Hertz and Schlüter 2015). In a common metaphor (i.e., the 'blind observers and the elephant'), researchers and other participants in co-production processes are standing too close to – or blindly grasping for – part of the elephant (i.e., reality) to embrace the partial, and ambiguous, contributions their observations play in relation to a complex whole. Additionally, local and Indigenous knowledges are increasingly called upon in science and policy processes for their unique contribution to more holistic understandings of environmental change (Klenk and Meehan 2015; Rathwell et al. 2015). However, knowledge integration processes can be risky as these marginalized frames may be co-opted, reduced, or instrumentalized by more dominant scientific perspectives (Ocholla 2007; Stein et al. 2020; Goodchild 2021). Moreover, in the cases of disagreement or incommensurability between frames (e.g., between a critical social science and natural science perspective), the more dominant frames are viewed as neutral and objective while marginalized frames are cast as political or subjective (Turnhout 2018; Turnhout et al. 2020). These challenges have real-world implications: Brugnach and Ingram (2012) posit that failures of more integrative natural resource management can be attributed to a mishandling of ambiguity.

While the challenges of ambiguity emerge through research practice, ambiguity itself is a slippery concept. The literature on uncertainty first recognized ambiguity in differing interpretations of numbers (Funtowicz and Ravetz 1990) and the subjectivity of a model's system boundaries (Walker et al. 2003). Dewulf and Biesbroek (2018) broadened this definition, defining ambiguity as "conflicts between fundamentally different frames about the issue at hand" and differentiating ambiguity as distinct from epistemic uncertainty (i.e., lack of knowledge) and ontological uncertainty (i.e., inherent variability). In sustainability science, ambiguity has been discussed through the systems ontology of the dominant social-ecological systems (SES) perspective, which views linked human-natural systems as complex adaptive systems (Folke 2016; Reyers et al. 2018). From this view, "we cannot know complex things completely" (Cilliers 2002, p.1), so ambiguity arises from complexity because any knowledge excludes pertinent system components and relationship elements (Matthews 2006; Preiser et al. 2018, 2021). Science and technology studies also highlights ambiguity as emergent from pluralism, where actors with diverse knowledges produce divergent framings that interact and challenge dominant system structures (Leach et al. 2010; Stirling 2014). This latter interpretation reveals how ambiguity involves the inextricability of epistemology and ontology – i.e., framings are interventions that both emerge from and shape future action. Thus, ambiguity appears to be a feature of complexity, but its origins and onto-epistemological dimensions remain unclear. Referring to the 'blind researchers and the elephant' metaphor: why do researchers see, smell, hear, or feel a different part of the elephant from others? Or are they seeing different animals entirely?

Different literature operationalizes aspects of the challenges presented by ambiguity. For example, epistemological pluralism addresses the multiple interpretations produced by diverse knowledge systems through limited forms of integration, weaving together multiple frames to develop an enriched picture while maintaining their individual integrity (e.g., Martin 2012; Tengö et al. 2014). Similarly, the STEPS pathways to sustainability approach grapples with the interaction between constructivist perspectives (which produce critical reflection between different framings) and positivist perspectives (which present a single objective reality), and how they can together inform more holistic and pluralist sustainability research (Leach et al. 2007). In contrast, some seminal work that speaks to the broader goals of sustainability addresses the multiple frames produced by ontological pluralism, and thus completely avoids integration (Goodman 1978; Escobar 2018). For example, Vervoort et al. (2015) suggest Goodman's 'worldmaking' as an appropriate framework for imaginative transdisciplinary processes that aim to contribute to sustainability transformation, because it enables 'ontological agency' (i.e., by building out futures as independent worlds rather than different narratives of the same world). Emerging literature takes a different perspective on ambiguity by turning attention back on the researchers themselves, including the role of their unique positionality and capacity in navigating the ambiguities of transdisciplinary research (e.g., Haider et al. 2018; Chambers et al. 2022).

This existing literature conceptualizes and operationalizes aspects of ambiguity, offering hints of how it can be understood and addressed in sustainability science. Yet, much of sustainability science still operates from a middle space, neither situated comfortably within a singular frame nor explicitly aware of or addressing the elephant in the room – i.e., ambiguity. Sustainability scientists operating in this middle space may embrace complexity and understand the need for pluralism broadly but struggle to overcome their tendency to evaluate knowledge against a singular 'unambiguous' frame. In such cases, ambiguity is not explicit yet persists, leaving research vulnerable to the risks and power dynamics associated with uncritical knowledge integration and transdisciplinary collaboration. Sustainability science needs new concepts and tools to operationalize ambiguity in a holistic and reflexive way, which can further strengthen the legitimacy of transdisciplinarity as a research paradigm and make the adaptive and emergent nature of the transdisciplinary research journey more explicit and deliberate (McGowan et al. 2014). Moreover, doing so can aid sustainability scientists trying to enter – or gesture toward – the 'ethical space' between frames required for truly pluralist transdisciplinary research (Goodchild 2021).

Operational research has a multi-decade history grappling with ambiguity, offering an opportunity for sustainability science. Operational research began with the use of hard systems models underpinned by expert-driven positivism, followed by a second wave of soft systems approaches underpinned by an interpretivist perspective (Midgley 1989; Flood and Jackson 1991; Jackson 2019). Divergence and conflict between first and second wave approaches emerged alongside the observation that understandings of a problem and what constitutes as 'improvement' may change significantly when system boundaries are altered (Churchman 1970). Thus, Churchman's pragmatist critique of the systems approach launched a third critical-emancipatory wave called critical systems thinking (CST) underpinned by tenets of critical awareness, emancipation, and pluralism (Flood and Ulrich 1990; Gao et al. 2003; Matthews 2006). CST explicitly grappled with both the conceptual challenges associated with ambiguity, including theoretical and methodological pluralism and paradigm incommensurability (Midgley 1989, 1992; Ulrich 2003), and the need for practical frameworks that operationalize ambiguity through reflection on system boundaries (Ulrich 1983; Midgley 2000).

Emerging research points to the promising lens offered by CST for sustainability research (e.g., Helfgott 2018; Rutting et al. 2022), yet the use of CST concepts and tools is still marginal. Thus, we were motivated by the opportunity to bridge key concepts, frameworks, and lessons from CST literature to the challenges presented by ambiguity in sustainability science. The resulting insights aim to establish 1) a holistic conceptualization of ambiguity that addresses its onto-epistemological dimensions while prioritizing its operationalization, and 2) recommendations for how sustainability scientists can operationalize our conceptualization of ambiguity as a valuable means of addressing sustainability challenges. Section 4.2 introduces our rationale for using system boundaries as the primary lens from which to conceptualize and operationalize ambiguity in sustainability science. Section 4.3 introduces our holistic conceptualization of ambiguity, which is comprised of three simultaneous and interacting boundary processes of being, knowing, and intervening in complex systems, which are each elaborated in turn. This conceptualization of ambiguity informs Section 4.4, which offers two overarching recommendations for sustainability scientists to operationalize ambiguity. First, we discuss how key lessons from CST point to the need to consider the potential for, and consequences of, paradigm incommensurability and discordant pluralism, thus broadening the theoretical orientation of sustainability science to all three boundary processes (i.e., being, knowing, and intervening) in our holistic conceptualization of ambiguity. Second, we present Reflexive Boundary Critique alongside four case study reflections to introduce and demonstrate an operational framework that aims to help transdisciplinary researchers embrace ambiguity as a fundamental part of rigorous sustainability science. We conclude with a discussion and conclusions in Section 4.5.

4.2 The importance of system boundaries

Ambiguity is often discussed as a feature of complex systems. Complexity emerged from the systems approach and has been studied from various perspectives (Bateson 1979; Prigogine and

Stengers 1984; Rosen 1991; Cilliers 1998; Levin 1999). Following conflicts between the first and second waves of systems thinking (Midgley 1992, 2011), critical systems theorists emphasized the role of pragmatism in operational research, which views all knowledge as partial, contextual, and contingent, as it is "impossible to apprehend (non-contextually) the whole system" (Matthews 2006, p. 185). This view drew attention to the importance of system boundaries, which are not value-free and fixed entities determined by the structure of reality, but rather depend on the subjective and value-laden choices of individuals setting and reinforcing them. A recent epistemological break moved away from the restricted complexity of this systems approach (i.e., studying specific types of systems called "complex) toward general complexity (i.e., the view that any system is complex), drawing attention to the relationship between the whole system and its parts (Morin 2008; Preiser et al. 2018).

This latter view is compatible with the dominant SES perspective in sustainability science, which views linked human and natural systems as complex adaptive systems (CASs), characterized by key features such as dynamic relations and complex causality (Levin et al. 2013; Preiser et al. 2018). The unique characteristics of CASs further explain the contextual, partial, and provisional nature of system boundaries. CASs are radically open as information, energy, and matter are constantly exchanged across a permeable boundary between the system and its environment (Preiser et al. 2018, 2021). They are also constituted relationally, meaning a system's behavior is determined more by the nature of its interactions than individual components, and these interactions connect systems in nested hierarchies across spatial and temporal scales (Gunderson and Holling 2003; Cash et al. 2006; Preiser et al. 2018). These features render the external boundary conditions as integral to system behavior as the system structure and make it nearly impossible to decide which system components are inside and outside the system (Juarrero 1999; Preiser et al. 2018). Thus, any representation of the system is partial, provisional, and dependent on subjective system boundaries. The chosen boundaries generate one of multiple partial frames that include certain components and exclude others and are dependent on the choices of the observer who is also a part of the system they seek to understand (Cilliers 2001; Audouin et al. 2013; Preiser et al. 2018).

4.3 Conceptualizing ambiguity in sustainability science

4.3.1 A holistic conceptualization of ambiguity

Given the importance of system boundaries described in Section 4.2, we offer an operational definition of ambiguity focused on boundary processes. This definition emerged through the discussions presented in Sections 4.3.2 to 4.3.4. We define ambiguity as an *emergent feature of the simultaneous and interacting boundary processes associated with being, knowing, and intervening in complex systems*. This definition draws on three considerations as depicted in Figure 4-1. First, Section 4.3.2 (observer dependence) demonstrates that an operational definition of ambiguity must acknowledge the boundaries of a researcher's subjective orientation. These boundaries influence their experience of complexity and how multiple frames are exposed, understood, and mediated through the research process *(Being)*. Second, Section 4.3.3 (knowledge as a boundary process) demonstrates how knowledge about complexity is produced through the process of making boundary judgments, generating a partial, contextual, and provisional frame *(Knowing)*. This frame may be one of multiple valid frames of a complex system. Third, Section 4.3.4 (boundaries as intervention) demonstrates how a researcher is part of the complexity they seek to understand, rendering any boundary process as an intervention that reinforces certain frames and marginalizes others (*Intervening)*. These three processes interact with one another in complex ways, producing emergent ambiguity.

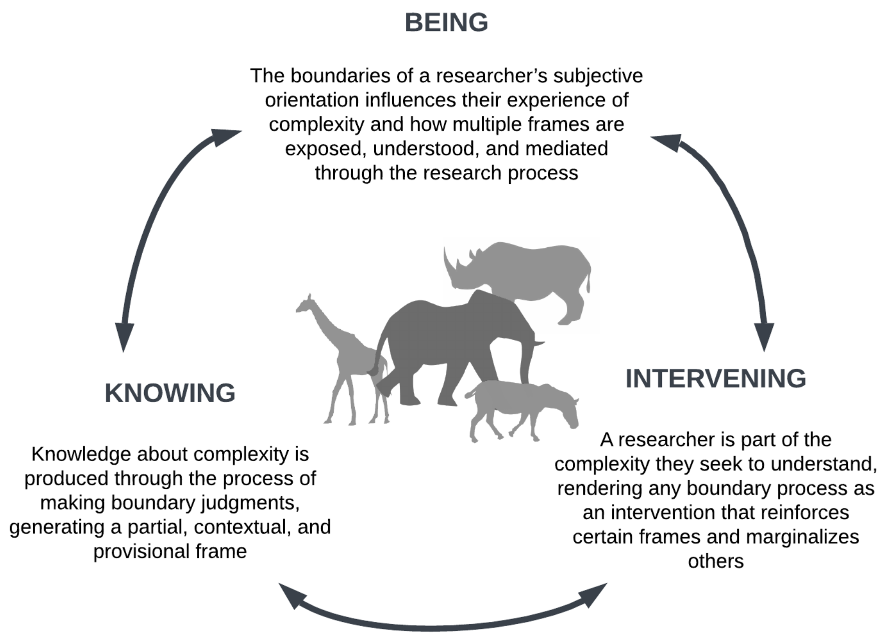

Figure 4-1: The visual depiction of an operational definition of ambiguity – an emergent feature of the simultaneous and interacting boundary processes of being, knowing, and intervening in complex systems. The animals refer to the 'blind observers and the elephant' metaphor introduced in Section 1.

4.3.2 *Processes of being*: Observer dependence

Our definition of ambiguity acknowledges the boundaries of a researcher's subjective orientation, which influences their experience of complexity and how multiple frames are exposed, understood, and mediated through the research process *(i.e., processes of being)*. This contribution emerged through reflection on the lessons of CST literature for sustainability science, which addresses the observer-dependence of system boundaries through the lens of theoretical and methodological pluralism.

Theoretical and methodological pluralism is an epistemological principle for CST, which describes and organizes the simultaneous use and integration of various systems approaches that produce diverse interpretations of a system. Theoretical and methodological pluralism emerged from attempts to reconcile debates between first and second wave system approaches by recognizing that methodologies derived from different or contradictory paradigms (e.g., positivist versus interpretivist) offer valid but partial and contextual framings of a system. While desirable in theory, "atheoretical pragmatism" surfaced in practice as individuals picked and chose methodologies without knowledge of their theoretical origins (Midgley 1992; Bowers 2019). This was perceived as a threat to the field, so critical system theorists sought an appropriate meta-theoretical framework to guide systemists who were operationalizing pluralism in practice (Bowers 2011). The system of systems methodology (SOSM) is the most prominent of such attempts, guiding which type of methodologies are appropriate for the type of system (i.e., simple, complex) and the relationship between participants (i.e., unitary, pluralist, coercive) (Jackson and Keys 1984; Jackson 2019).

While useful for orienting the field of CST, the use of meta-frameworks like SOSM was criticized for two reasons. First, they were too rigid, as *how* a methodology is used is as important as the theoretical context (Bowers 2011; Jackson 2019). Thus, the focus turned to the capacities and orientations of individual systemists as they navigated within and across theories and methodologies through boundary choices, influenced by the wider context in which they are a part (Bowers 2019); see Section 4.2. Second, they were considered problematic as all meta-theoretical frameworks are themselves a frame, and the assumption that a meta-theory exists at all assumes theoretical commensurability (Gregory 1996). This assumption of theoretical commensurability emphasizes pluralism as a form of complementarism focused on consensus and integration, which risks masking incommensurate observations through an (inadvertent) form of imperialist pluralism (Gregory 1996; Ulrich 2003; Jackson 2019). In other words, an assumption of theoretical commensurability can mask ambiguity, as discordant frames are discarded or rendered invisible through the process of integration. In response, some critical systems theorists encouraged *discordant* pluralism, which assumes that any claims about a system are contingent, local, and historically situated, and promotes communication between radically different perspectives (Gregory 1996).

Similar challenges with theoretical and methodological pluralism and its implications for ambiguity are evident in sustainability science. Transdisciplinary researchers operate from diverse theory orientations that produce multiple frames of sustainability challenges (Hertz and Schlüter 2015). For example, ‘resilience thinking’ (Folke et al. 2010; Folke 2016) and the ‘pathways to sustainability approach’ (Leach et al. 2010) are prominent paradigms in sustainability science. Both apply a systems approach but are rooted in divergent ontological and epistemological origins and thus call on different suites of theories and methods, which offer divergent interpretations of a system and recommendations for action (West et al. 2014; Haider et al. 2018). However, despite widespread acceptance of the benefits of such theoretical pluralism, the dominance of certain theory orientations (i.e., the SES perspective) can lead researchers to adopt their own as a meta-framework that describes reality, rather than offering one partial and contingent frame (West et al. 2020; e.g., the Fallacy of Misplaced Concreteness (Whitehead 1967)). In such cases, the boundaries of the researcher's frame are rendered invisible, as frames that are incommensurate with the SES perspective (e.g., due to differing onto-epistemological origins) are instrumentalized or discarded as they are subsumed under its purview. Relatedly, best practice frameworks for integrating knowledge systems (e.g., scientific, Indigenous, and local knowledge) aim to allow each knowledge system to maintain the integrity of its own frame (Tengö et al. 2014; Hill et al. 2020). However, these frameworks are not mainstream, and epistemological and ontological differences between frames can generate potentially discordant perspectives that challenge the integration imperative (Klenk and Meehan 2015; Turnhout 2019; Cockburn 2022).

4.3.3 *Processes of knowing:* Knowledge as a boundary process

Our definition of ambiguity characterizes knowledge about complexity as produced through the process of making boundary judgments, which generates a partial, contextual, and provisional frame *(i.e., processes of knowing).* This frame may be one of multiple valid frames of the same complex system. This contribution emerged through reflection on the relevance of CST's boundary critique and process philosophy to the system ontology of dominant perspectives in sustainability science.

CST operationalizes the subjectivity of system boundaries through boundary critique. According to Churchman, boundaries are social and personal constructs that determine the limits of knowledge that are considered pertinent for an analysis (Churchman 1970). Critical Systems Heuristics (CSH) was proposed as a framework to guide reflection upon boundaries through 'boundary critique' (Ulrich 1983; Ulrich and Reynolds 2010). According to CSH, any claim about a system depends on a reference system, which is made up of 'boundary judgments' that generate the dominant view of which facts and values are relevant, thereby indicating empirical and normative selectivity (Ulrich 1983). In other words, boundary judgments filter out and frame which observable and interpreted observations are considered relevant to the system or problem at hand. CSH includes a list of questions designed to facilitate boundary critique by revealing the sources of motivation, power, knowledge, and legitimation behind boundary judgments. Questions are asked in both the 'is' mode and the 'ought' mode to reveal contested and unresolved judgements (Jackson 2019), see Section 4.4.2.

Our definition of ambiguity draws directly from Midgley's process philosophy (2000), which is a philosophy of knowledge for CST that views knowledge as emergent from continuously unfolding boundary processes. Midgley's process philosophy was inspired by the process philosophy pioneered by Whitehead (1978). It proposes a shift from the *content* of knowledge to the *process* of bringing knowledge into being, in particular the *process of making boundary judgments*. Midgley (2000) claims this form of process philosophy overcomes the subject-object dualism of other theories that assume independent observation is possible (e.g., Popper's critical fallibilism, Kelly's personal construct theory, and Habermas' Three Worlds). In other words, process philosophy reveals both first-order *content* (i.e., the boundaries of the system) and second-order *content* (i.e., what it is that gives rise to these boundaries) via the same lens (i.e., the process of making boundary judgments). This lens deviates somewhat from other process philosophers who, as Midgley claims, take the 'systems' that give rise to boundary judgments as analytically prime, thus rendering them as 'content'. In doing so, Midgley's process philosophy is compatible with a complexity perspective, which situates observers as part of the systems they seek to understand. Moreover, it facilitates theoretical and methodological pluralism, because it allows different frames reflecting diverse paradigms (e.g., positivist versus interpretivist) to co-exist without contradiction (Midgley 2000; Jackson 2019).

Sustainability science relies heavily on systems approaches but has yet to grapple with the plurality of boundaries and its implications for ambiguity to the same degree. Discussion on boundaries has focused on using ambiguous concepts as boundary objects, wherein the potential for multiple interpretations of the concept (e.g., resilience, stewardship) serves as a tool to facilitate dialogue among different perspectives (Brand and Jax 2007; Peçanha Enqvist et al. 2018), and boundary work as the discursive process that delineates science from non-science in complex sustainability issues (Gieryn 1983; Miller 2013). Perhaps most relevant is the work of Audouin et al. (2013), who draw on critical complexity (Preiser and Cilliers 2010) to suggest five key questions that can surface the value judgments behind any framing of an SES. However, this discussion does not address the deeper onto-epistemological considerations underpinning ambiguity. Interestingly, discussion about the benefits and pitfalls of boundary setting permeates the 'relational turn' of sustainability science, which focuses on processes and relations and thus rejects the substantialism that necessitates boundaries in the first place (Hertz et al. 2020; West et al. 2020). Thus, a process philosophy focused on boundary judgments may serve to partially bridge this emerging strand of sustainability science (i.e., process-relationality) to the language and system ontology of more established domains (e.g., the SES perspective).

4.3.4 *Processes of intervening:* Boundary marginalization

Finally, our definition of ambiguity situates a researcher as part of the complexity they seek to understand, rendering any boundary process as an intervention that reinforces certain frames and marginalizes others *(i.e., processes of intervening)*. This statement emerged through reflection on the relevance of boundary critique and boundary marginalization from CST to the political and ethical implications of ambiguity in sustainability science.

The imperative for critique in operational research began with its orientation toward intervention (Flood and Jackson 1991; Midgley 2000). This positionality renders the boundary process as a form of intervention because it serves to reinforce or marginalize certain framings, which in turn reinforces or marginalizes certain actor perspectives, interests, and assumptions associated with real-world challenges. Without critique, dominant assumptions remain unquestioned because boundaries are considered objective and absolute, resulting in boundary marginalization as depicted in Figure 4-2 (Midgley et al. 1998; Midgley 2000).

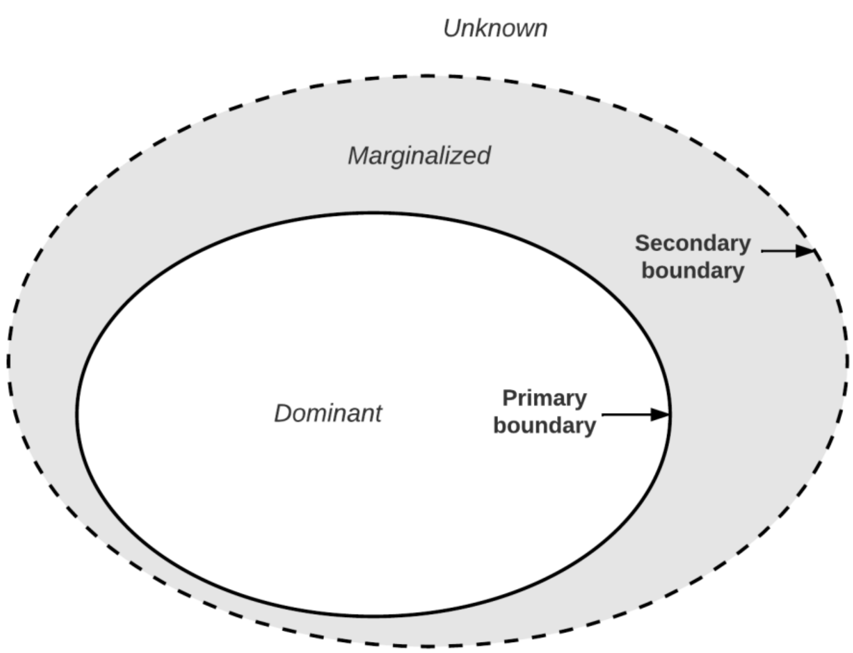

Figure 4-2: Boundary marginalization (adapted from Midgley, 2000)

Boundary marginalization characterizes the power dynamics between frames derived from different boundary judgments. In boundary marginalization, a primary boundary delineates what is *included* in the analysis, and a secondary boundary encompasses everything that is *known but excluded* from the analysis (Midgley 2000; Rajagopalan and Midgley 2015). The conceptual region beyond the primary boundary is marginalized, and anything beyond the secondary boundary is unknown. The hardening of boundaries occurs in the absence of critique when specific boundary judgments are stabilized and reinforced by social rituals and stereotypes. According to Midgley (2000), if the primary boundary is privileged, elements in the marginal area can be disparaged and become 'profane'. If the secondary boundary attracts attention and is reinforced, then the marginal elements become the focus of attention and are made ‘sacred'. This dynamic justifies the need to ‘sweep in’ relevant information and perspectives. For example, operational researchers working with Social Service Departments in the United Kingdom chose to explicitly recruit elderly populations in stakeholder engagement. Doing so was an effort to avoid marginalizing their views, which could disparage their perspective and thus justify their exclusion from social support (Midgley et al. 1998).

Transdisciplinary sustainability researchers are also oriented toward intervention, as they and their research are embedded in the systems and problems they are attempting to understand and address (van Kerkhoff and Lebel 2006; Clark et al. 2016; Caniglia et al. 2017; Preiser et al. 2018). Moreover, the increasingly transformative agenda of sustainability science (Shrivastava et al. 2020) demands intervention that opens up dominant frames (i.e., or ‘sweeps in marginalized frames’, in the language of CST) to embrace the novel ideas and practices from which transformation emerges (Westley et al. 2011; Moore et al. 2014). Thus, boundary marginalization is a relevant means to characterize the power dynamics between frames and knowledge systems that influences transdisciplinary research. For example, a recent review showed that Indigenous and local knowledge is currently neglected in transformations research (Lam et al. 2020a). This marginalization reflects historical epistemic injustices that place scientific knowledge holders in positions of power and safe from critique (Cundill et al. 2005; Cote and Nightingale 2012; Gregory et al. 2020). A similar dynamic applies to the privileging of certain perspectives over others in seemingly benign forms of knowledge integration, such as when qualitative social sciences is translated into quantitative natural sciences frameworks or models. In such cases, marginalization is perpetuated through political dynamics that render dominant frames (i.e., within primary boundaries) as neutral and objective and marginalized frames (i.e., within secondary boundaries) as political and subjective (Turnhout 2018;

Turnhout et al. 2020). Importantly, these processes of marginalization – and conversely the accrual of power – are not only political but constitute real-world interventions. For example, overriding Indigenous knowledges in natural resource management not only marginalizes their perspective, but forces an ontological disruption in the relationship between humans and nature that elevates solutions associated with environmental degradation and social harm.

4.4 Operationalizing ambiguity in sustainability science

The discussion about the holistic conceptualization of ambiguity in Section 4.3 points to two recommendations for operationalizing ambiguity in sustainability science. First, Section 4.4.1 suggests the need to *broaden our theoretical orientation* to grapple with the potential for and consequences of theoretical incommensurability and discordant pluralism. Second, Section 4.4.2 suggests the need to *nurture the capacities of transdisciplinary researchers to navigate ambiguity* as a fundamental part of rigorous sustainability science. We offer an operational framework of Reflexive Boundary Critique to help do so, which we adapted from CSH and refined through four case study reflections.

4.4.1 Broaden our orientation: Theoretical incommensurability and discordant pluralism

Our first recommendation for operationalizing ambiguity is that sustainability science must grapple with the potential for and consequences of *theoretical incommensurability* and *discordant pluralism.* Theoretical and methodological pluralism is considered an important means for sustainability science to better address complex 21st century sustainability challenges (Jerneck and Olsson 2020; Clark and Harley 2020) and offers the foundations for exposing and grappling with the implications of ambiguity in sustainability science. Yet, the philosophical stance underpinning such pluralism is often unclear (Cockburn 2022), leaving researchers in 'conceptual la-la land' (Haider et al. 2018) and reinforcing the myriad risks and power dynamics associated with uncritical knowledge integration, including those that emerge when interpretations are subsumed under the view of dominant frameworks (e.g., the SES perspective, see discussion in Section 4.3.2).

Efforts to expose and reconcile the diverse theory orientations of researchers adopting diverse methods are emerging in response (Hertz and Schlüter 2015; Preiser et al. 2022). For example, critical realism has recently been suggested as an appropriate theoretical orientation for pluralism and knowledge integration in sustainability science (Preiser et al. 2022; Cockburn 2022). Critical realism is thought to allow multiple frames to coexist without contradiction because it differentiates between the real (but unknowable) and observable worlds, thereby accepting that all knowledge is incomplete (Collier 1994; Bhaskar and Hartwig 2016). This view aligns with the partial, provisional, and contingent nature of knowledge under critical systems theory, and thus may help grapple with the *processes of being and knowing* (Section 4.3.2 and 4.3.3) that contribute to ambiguity.

While critical realism offers an important contribution for operationalizing ambiguity in sustainability science, the experience of critical systems theorists grappling with pluralism (i.e., Section 4.3.2) offers an important and timely lesson: the search for any organizing meta-theory or framework for pluralism reflects an assumption of theoretical commensurability. This assumption facilitates a complementarist or imperialist form of pluralism that risks masking ambiguity, in particular *processes of intervening* (Section 4.3.4), as discordant frames are marginalized through the process of integration. For example, the integration imperative of critical realism is implicit in critical realists' claim that criteria can be applied to evaluate different observations through judgmental rationality (Archer et al. 2016). However, critical realism does not address the power imbalance between different knowledge systems or frames (Klenk and Meehan 2015; Cockburn 2022). Consequently, while many frameworks in sustainability science may be compatible with critical realism (e.g., the SES perspective), other less mainstream philosophies may not be; for example, philosophies in which epistemology and ontology are entwined (e.g., posthumanism, and many Indigenous philosophies) are not aligned with critical realism's distinction between real and observable worlds. Thus, the lesson of CST points to the risk that integration under critical realism (or any other organizing meta-theory or framework) may inadvertently result in a form of imperialist pluralism that reduces or instrumentalizes incommensurate frames, thereby masking ambiguity.

A discussion about the potential for and consequences of *theoretical incommensurability* and *discordant pluralism* in sustainability science is required for transdisciplinary research to address all three boundary processes (i.e., being, knowing, and intervening) that contribute to ambiguity. Without addressing the potential for incommensurate interpretations through discordant pluralism, disagreement and conflict between the diverse onto-epistemological orientations of actors involved in knowledge production becomes an unacknowledged 'elephant in the room'. These unacknowledged power dynamics marginalize important perspectives in sustainability science, including the novel ideas and practices from which transformations to sustainability emerge. Questions should arise in response to these challenges, such as: under what conditions could or should any specific lens or framework (e.g., critical realism, or the SES lens) serve as a meta-theory for integration within sustainability science? How do we handle incommensurate observations? How can we draw from alternative theories to operationalize discordant pluralism?

4.4.2 Critique our frames: Reflexive boundary critique

In addition to an appropriate theoretical orientation, our second recommendation is to *nurture the capacities of transdisciplinary researchers to navigate ambiguity* as a fundamental part of the research process. This suggestion emerged from recognition of the pitfalls of meta-theories and frameworks for directing pluralism in CST (see discussion Section 4.3.2 and 4.4.1), which lent focus to the capacities of individual systemists as they navigated within and across theories and methodologies through boundary choices, influenced by the wider context in which they are a part (Bowers 2019). Reflexivity in particular is cited as a crucial capacity for navigating ambiguity and pluralism in transdisciplinary research (Popa et al. 2015; Moore et al. 2018).

The concept of reflexivity has been explored from various perspectives (e.g., Fook 1999; Salzman 2002; Johnson and Duberley 2003; Archer 2016), broadly involving the process of examining how one's own beliefs, judgments, and practices influences the research. In other words, reflexivity can help translate ambiguity from a slippery phenomenon 'out there' to a process that can be embedded in research. Yet, frameworks and tools for nurturing reflexivity in sustainability science are still under development and do not offer holistic guidance to operationalizing the three boundary processes (i.e., being, knowing, and intervening) that contribute to ambiguity. For example, the 'undisciplinary compass' highlights key capacities required to navigate the *processes of being and knowing* associated with transdisciplinary sustainability science (Haider et al. 2018). Frameworks like 'coproductive agility' address *processes of being and intervening* by detailing how a researcher's role can reinforce or challenge the status quo in service of transformation (Chambers et al. 2022). Additional literature focuses on a researcher's power and positionality (Williams 2014; Maclean et al. 2022), the ethical dilemmas that arise from adopting and bringing together different methodological approaches (West and Schill 2022), and the need for decolonization and unlearning for western-trained scientists to be open to the legitimacy of other ways of being or knowing (Stein et al. 2020). Early career researchers increasingly draw from this literature to reflect on how their positionality and philosophical orientation influences research outcomes (e.g., Haider 2017; Macdonald 2019;

González García-Mon 2022). However, this type of reflexivity lacks guiding frameworks and is not currently incentivized within traditional structures of academia.

4.4.2.1 An operational framework

We developed Reflexive Boundary Critique (RBC) as a framework that can be embedded into transdisciplinary research processes to operationalize ambiguity. The framework is underpinned by Midgley's process philosophy (Section 4.3.3). Process philosophy is appropriate for various reasons, including that it is compatible with open systems (i.e., complexity) and addresses the contextual, partial, and provisional nature of knowledge through the accessible language of subjective boundary judgments. However, claiming process philosophy as a meta-framework for sustainability science would contradict our call to embrace theoretical incommensurability and discordant pluralism (Section 4.4.1). Also, by applying process philosophy to develop the integrated framework of RBC, we risk contradicting a core tenet of process philosophy by taking a stance regarding which boundary judgments were most relevant (i.e., process philosophy views any integrated framework as still contextual, partial, and provisional). Thus, our framework attempts to give just enough shape to ambiguity to facilitate critical reflection.

The framework was adapted from CST's original boundary critique and applied and refined through four case study reflections (Section 4.4.2.2). As discussed in Section 4.3.3, boundary critique includes a series of questions that encourage reflection upon the way in which a claim depends on its reference system, and this reference system is a product of boundary judgments (Ulrich 1983; Ulrich and Reynolds 2010). Boundary critique is best applied alongside other systems approaches to provide them with legitimacy (Jackson 2019; Nicholas et al. 2019). Thus, boundary critique offers a unique starting point from which to build a framework that can be used to operationalize ambiguity by embedding reflexivity in transdisciplinary research.

The questions that guide RBC are presented in Table 4-1. The questions move beyond the process of making boundary judgments about the system (*knowing*), as per Ulrich's original boundary critique, to address the *simultaneous and interacting boundary processes associated with being, knowing, and intervening in complex systems*. In this way, RBC can enable reflection about first-order (i.e., the boundaries of the system) and second-order judgments (i.e., what it is that gives rise to these boundaries). Questions are asked under the four categories of the original boundary critique: sources of motivation, power, knowledge, and legitimacy. They are also asked in both the 'is' and 'ought' mode, where responses in the 'ought' mode clarify the ethical standpoint from which judgments in the 'is' mode are evaluated. Differences in response between these two modes, or between individuals, point to unresolved boundary issues and require greater scrutiny.

Operationalizing the framework requires embedding these questions throughout the research process, including before, during, and after a research process as needed, both within the research team and among other participants in co-production processes. Doing so facilitates a deliberative form of self-reflective critique that allows researchers to learn and evolve their practice according to otherwise unacknowledged practical and ethical considerations about ambiguity. By revisiting questions throughout the research process, changes in response may be recorded and point to emerging unresolved boundary judgments. Importantly, this framework should be considered a starting point for reflection to be used, adapted, and expanded upon as required.

Table 4-1: Reflexive boundary critique

Process of ambiguity	*Boundary judgments*			
	Sources of… Motivation	*... Power*	*... Knowledge*	*... Legitimacy*
Being Boundaries of the researcher's subjective orientation	What is/ought to be my motivation for pursuing this research? What are/ought to be my conditions for desirable change?	What power to facilitate desirable change is/ought to be in my control? What conditions for desirable change (e.g., resources) are/ought to be under my control? Which are/should not?	What is/ought to be the unique knowledge I bring to the research? What is/ought to be my theory orientation and onto-epistemological lens?	Which knowledge is/ought to be considered salient, valid, and legitimate, including incommensurate frames (according to my onto-epistemological lens)?
	How do these sources of motivation, power, knowledge, and legitimacy influence judgments under 'knowing' and 'intervening'?			
Knowing Boundaries of the system	Who does/ought to have a stake in this system? What is/ought to be the purpose of this system? What is/ought to be its measure of desirable change for the system?	Who is/ought to have the power to influence desirable change in the system? What conditions for desirable change (e.g., resources) are/ought to be controlled by the powerful? Which are/should not? What is/ought to be	Who is/ought to be providing relevant knowledge in the system? What is/ought to be relevant new knowledge in the system?	Who is/ought to be representing the interests and frames of those affected by but not part of the system? What conditions are/ought to secure the emancipation of those affected by but not part of the system?

		the guarantor of desirable change (e.g., consensus, inclusion, etc.)?		What process is/ought to be in place to integrate and/or validate across different types of knowledge or frames (e.g., visions of desirable change)?
Intervening Impact of the boundary process	Whose stakes and visions of desirable change will be/were reinforced or marginalized by the research?	Whose power will be/was reinforced or marginalized by the research?	Whose and what type of knowledge will be/was reinforced or marginalized by the research?	Whose interests and frames will be/were reinforced or marginalized by the research?

4.4.2.2 Case study reflections

Four of the co-authors used the questions from RBC to reflect upon their own case study research through collaborative dialogue and individual reflection. These reflections helped refine the framework and demonstrate the type of questions and insights that may emerge when using RBC to operationalize ambiguity.

Case A - Paradoxes of power and marginalization: Indigenous-led monitoring and evaluation in the Northern Territory, Australia (Simon West)

I arrived in Northern Australia as a visiting researcher with a specific aim and motivation (i.e., *process of being*). I was interested in applying theories and methods from interpretive policy analysis to descriptively explore tensions between Western scientists and Indigenous peoples working together in the field of Indigenous Land and Sea Management (ILSM). I felt at the time that such an approach might also contribute in a small way to a greater understanding of the issues at stake in intercultural collaboration, which might in the long-term contribute to greater equity for Indigenous peoples entering into land management partnerships. However, as I embarked on the *process of knowing* within these boundaries, moving continually between the ‘is’ and the ‘ought,’ I began to question the ethical and practical value of pursuing such an approach, which might have benefited my own agenda as a researcher much more than the interests of Indigenous peoples in the region (*processes of intervening*). I consequently became involved in actively volunteering and helping to fulfil one of the projects I had initially come to (descriptively) study, led by an Indigenous ranger group and a conservation NGO. This project – the Intercultural Monitoring and Evaluation Project (IMEP) – aimed to bring together Indigenous methodologies and participatory action research to build an intercultural monitoring and evaluation system for the ranger group (Campion et al. (a) *forthcoming*) as part of ongoing efforts to develop Indigenous-led approaches to land management in the region (Campion et al. (b) *forthcoming*). My motivation (*process of being*) had therefore changed, away from seeking to fulfil my own methodological interests as a researcher towards contributing to the initiative of the Indigenous rangers and Traditional Owners to nurture and care for their ancestral homelands.

The IMEP project engaged both Indigenous and Western methodologies through a multiple-evidence based approach that aimed to retain the integrity of both knowledge systems within a monitoring and evaluation framework still recognisable within Western funding and governance systems. This strategic approach of 'sweeping in' multiple perspectives into the *process of knowing* was led by senior Indigenous rangers and situated within a broader planning process that had already contributed to several tangible beneficial *interventions* in the region (not least the creation of an independent ranger group). However, this approach also raised tensions in the IMEP project when Indigenous methodologies were positioned in a central role in the monitoring and evaluation system on their own terms, without being made neatly commensurable with Western approaches and findings. For example, while the use of Indigenous methodologies arguably enhanced the worth and legitimacy of the emerging M&E system in the eyes of Indigenous rangers, local clans and Traditional Owners, they may have reduced the legitimacy of the M&E system in the eyes of some non-Indigenous scientists, planners, and policy actors in the broader ILSM governance network (*processes of intervening*). Therefore, by explicitly challenging core assumptions and concepts of Western planning frameworks, the risk was that IMEP might paradoxically reinforce or at least fail to address the marginalization of Indigenous interests from dominant processes in ILSM (at least in the short term). This highlights the ethical and political dimensions of strategically adopting and contesting boundary judgments, as well as their unavoidably interventionist character.

Case B - Making meaning of "just enough": Alpine dairy practices in Austria (Jamila Haider)

This study of alpine farming resilience was rooted in a strong sense of my subjective frame (i.e., *process of being*), mainly a motivation to use a process-relational approach to understand what makes family dairy farming in the Austrian Alps resilient. I took an ethnographic approach focusing on traditional daily practices of cheese-making. This meant 'being' in the process of summer-pasture cheese production and to focus on *farming* as a practice as opposed to *the farm* as a unit (Darnhofer

2020). The aim of the fieldwork also had a strong *process of knowing* component, in which I aimed to observe practices and elicit verbal knowledge through interviews across a number of different farms to synthesize characteristics that contribute to farming resilience and that could be further theorized and scaled. The *process of intervention* in the initial research design had as a primary objective to extract relevant practices and knowledge and to scale-up on-farm knowledge to contribute to more generalized knowledge required for food-systems transformation.

However, through the process of fieldwork, of *being* in the farming processes, I realized it might be possible to 'know' multiple farming logics, but it was not possible to 'be' multiple farming logics at the same time, and I therefore decided to focus on just one innovative farmer in Gastein valley, Präa Sepp, who works to produce "just enough." The intention of my data collection shifted from eliciting characteristics of resilience, to understanding what "just enough" is, and to making meaning of our dialogues. According to Sepp, our engagement was relational, dialogical and he felt that my aim was "to really understand him, on his land, rather than look for answers that I wanted to hear."

The research shifted to being co-produced with Präa Sepp, one of the few remaining farmers in the valley who processes milk in the summer pastures. Thus, his own reflexivity, and in particular his capacity to embrace novel or marginalized boundaries, is crucial to the research. For example, contrary to all other farmers in the valley, he only milks his cows once a day. This practice emerged from a crisis situation: a snowstorm forced the cows down the mountains from the summer pastures, and it became impossible to milk them more than once a day. Since then, the cows produce a bit less milk, but it's "enough," and Sepp has more time for himself, or for other work, and the cows "have a bit more for themselves too". In changing the traditional milking pattern, he was able to with-hold the larger tradition of milk processing on the summer pasture. But Sepp doesn't see this as a tradition. In fact, he sees traditions as "unreflective habits." And in his view, summer cheese making is not a tradition, but rather a practice that enables him to have autonomy over his own time and production: "just enough to have a good life" for himself and his family. In this sense, the framing of summer cheese-making shifts from being a tradition, to an act of resistance against the status-quo of increasing production, and arguably a transformative practice for food system transformation. My frame, as a sustainability scientist, aims to intervene in the food system by elevating and emancipating this perspective of the farmer, directly challenging its marginalization under the more dominant frame of mainstream industrialized agriculture, with the aim to contribute to more sustainable food systems. However, at the moment of writing, I am living between the ‘is’ and the ‘ought’ questions of RBC, resulting in unresolved boundary judgments and surfacing ambiguity and calls for hyper self-reflexivity on my part. My frame has shifted in that my entanglement in the research process has become part of the coproduced research, and that rather than my research elevating marginalized perspectives, it has become *our* perspective, which has more pragmatic aims of understanding meaning of being present, in place, in a moment of time and how this affects the decisions we make for the future.

Case C: Legitimate to whom? Climate resilient futures in the Red River Basin, USA and Canada (Anita Lazurko)

My own subjective frame (i.e., *process of being)* strongly influenced my research approach. My motivation for this study was a concern that the water sector is building ‘resilience’ to climate change according to a narrow vision of the future that may reinforce unsustainable and unjust systems. I was also motivated by the opportunity to test a semi-quantitative scenario methodology for its capacity to systematically open up the future to more diverse drivers and perspectives than is typical in the mainstream water sector, which often privileges empirical and positivist information and thus excludes social drivers of change or interactions across scales. As a transdisciplinary researcher familiar with SES theory, I aimed to apply my knowledge to the design and implementation of a transdisciplinary scenario modelling process in the Red River Basin (a transboundary basin shared by the US and Canada). This process aimed to co-develop exploratory scenarios that characterize future change as emergent from interactions between diverse efforts to build resilience to climate change and a complex, cross-scale SES (Chapter 3). I chose critical realism (Section 4.4.1) as the philosophical perspective for the scenario process, which allowed me to synthesize scientific and local/practitioner knowledge in one scenario model. This process of synthesis surfaced significant ambiguities in the research context (including potentially incommensurate frames), which I validated with literature and a sensitivity analysis to generate integrated findings that were robust across divergent assumptions.

These framing and methodological choices had implications for how the system was characterized (i.e., *process of knowing*) and whose interests and perspectives were reinforced or marginalized (i.e., *process of intervening*). My partnership with influential actors in the river basin lent legitimacy to the study and highlighted the interests and knowledge of those who had access to transboundary governance bodies, potentially marginalizing those of others. My choice to use a semi-quantitative scenario method underpinned by critical realism provided the appropriate grounds to integrate different data sources, effectively broadening the scope of the future to include diverse drivers and perspectives far beyond that which is typical in the mainstream water sector. However, the inclusion of Indigenous perspectives was isolated to Indigenous governance experts to avoid instrumentalizing or coopting the stories of Elders for a western scientific model. This and other issues of representation directly influenced the scenario outcomes, which were perceived as claustrophobic to participants who desired more radical transformations from the status quo. Moreover, the choice to validate incommensurate observations with literature and to use scenarios that were 'robust' to these divergences helped secure the legitimacy of the final scenarios in the eyes of dominant actors but may have excluded scenarios that may only be plausible under marginalized boundaries.

Case D: Causality and fisheries collapse in the Baltic Sea (Tilman Hertz)

This study (Hertz and Mancilla Garcia 2021) was strongly informed by my subjective frame (i.e., *process of being*), namely my motivation and onto-epistemological perspective. My motivation was twofold 1) to show how the constitutive and causal dimensions of an analysis are intra-active and 2) that there is no one "correct" way for this intra-action to realize. In debates around causation, a difference is often made between the constitutive dimension (what a system is made of) and the causal dimension (causal processes connecting elements of a system). If we consider the act of defining what a system is made of as partly political/ethical (i.e. making some aspects of reality matter at the expense of others) and that causal and constitutive dimensions intra-act, then we can assume that particular causal processes are specific to particular constitutive spaces.

I used the case study of cod collapse in the Baltic Sea because of its paradigmatic character and familiarity in social-ecological scholarship. My hope was to contribute to ongoing work that calls for rethinking the concept of causality (Barad 2012; Barad and Gandorfer 2021) beyond its purely efficient dimension and explore the political/ethical aspects of the constitutive-causal intra-action: Why is reality expressed in a particular way? Whose interest does it serve? What does it conceal and silence? Answering these questions might shift research and practice to consider constitutive spaces inherent in often-marginalized perspectives and point to novel intervention points for real-world sustainability challenges (i.e., *process of intervening*). The research question and subsequent boundary judgments in the *process of knowing* were formulated in such a way as to articulate and make the argument.

This approach was empowered/rendered possible by my own onto-epistemological commitments, which enabled a critique (from a political/ethical point of view) of the particular constitutive space of intelligibility that is specific to modernity (Latour 2005). The study argues with many others that it is a fundamental ethical obligation to keep open the possibilities for understanding reality thus attempting to highlight boundaries that are often marginalized. In saying that the possibilities for understanding reality should be kept open, I took a stance in the domain of 'ought'. My criterion for ‘ought’ was not ‘correspondence with reality’ or ‘coherence with an existing body of beliefs’, but was rather inspired by Isabelle Stengers’ notion of ‘relevance’ to maintain openness to multiple notions of reality.

4.5 Discussion and conclusions

While ambiguity is recognized as intrinsic to complex sustainability challenges, sustainability scientists often either ignore or attempt to reduce ambiguity rather than operationalizing it. As a result, sustainability scientists each interpret a specific part of ‘the elephant’ (i.e., reality), and are unaware of or resistant to the partial and subjective nature of their observations and the pluralism inherent to real-world sustainability contexts. This often-unacknowledged ‘elephant in the room’ leaves research vulnerable to the risks associated with uncritical knowledge integration and a lack of reflexivity in transdisciplinary collaboration. These risks threaten the ongoing salience and legitimacy of sustainability science and limit its capacity to fulfill its transformative agenda.

CST grew out of the need to develop critical appreciation of both theoretical and practical aspects of ambiguity in operational research. Thus, this paper aimed to explore how key concepts and frameworks from CST may be adapted to conceptualize and operationalize ambiguity in sustainability science. Through a discussion on the importance of system boundaries, observer-dependence, knowledge as a boundary process, and boundaries as intervention, we offer an operational definition of ambiguity as an *emergent feature of the simultaneous and interacting boundary processes associated with being, knowing, and intervening in complex systems*. This definition expands on previous understandings of ambiguity by explicitly foregrounding its onto-epistemological and ethical dimensions and prioritizing its operationalization. It also sets up discussion about how ambiguity can and should be operationalized in sustainability science.

Lessons from CST revealed that to operationalize ambiguity, sustainability science must grapple with theoretical incommensurability and discordant pluralism, which requires resisting any tendency to rely too heavily on an overarching meta-theory or framework. This lesson is relevant and timely, as two divergent streams of sustainability scientists emerge. On one hand, some are advocating for an integrated approach that acknowledges complexity but reduces ambiguity through integration within an overarching disciplinary paradigm (e.g., Clark et al. 2016; Clark and Harley 2020), viewing ambiguity as undesirable and a barrier to practical solutions. In contrast, others are trying to 'live with complexity' by remaining open to – and embracing – uncertainty and ambiguity through transdisciplinarity and pluralism (Cornell et al. 2013; Turnhout et al. 2019; Caniglia et al. 2020; West et al. 2020), viewing ambiguity as intrinsic to interventions that meaningfully address complex sustainability challenges. The former may serve to legitimize sustainability science from dominant disciplinary perspectives, while the latter may be better suited to fulfilling its transformative agenda, which demands an emancipatory approach that exposes and elevates the framings that are often excluded, instrumentalized, or politicized by those dominant perspectives. A starting point for future work is a collective dialogue among sustainability scientists about how pluralism and ambiguity can be addressed (including incommensurability and discordance) while maintaining the solutions-oriented and use-inspired nature of the field.

CST also reveals that amid the pitfalls of meta-frameworks and theories in CST (e.g., 'imperialist' pluralism and masking ambiguity), greater emphasis should be placed on the capacities and orientations of individual systemists navigating across theories and methods. This work has already begun due to challenges associated with sustainability science's 'transdisciplinary turn', which acknowledges that the context-specific, problem-driven, and embedded nature of transdisciplinary research demands skillful researchers with the agility and reflexivity to maintain academic rigor despite the lack of guiderails offered by conventional disciplinary boundaries. Future work should further characterize and nurture these capacities through research and education.

Reflexivity is a particularly important capacity for navigating the ambiguities in transdisciplinary research. CST offered the starting point for developing our novel operational framework of RBC. This framework is structured to guide the process of exposing, mediating, and ultimately embracing ambiguity as a fundamental part of the research process through critical reflection. The questions presented in the framework move beyond Ulrich's original boundary critique to reveal sources of empirical and normative selectivity involved in all three processes of being, knowing, and intervening in complex systems.

The case study reflections revealed the unique insights and challenges related to ambiguity that were experienced by each researcher. For example, all four reflections indicated that the researcher's motivation and onto-epistemological orientation was highly influential to the rest of the boundary judgments, and in one case a shift in motivation based on emerging ethical considerations transformed the research approach. Moreover, ambiguity presents unique challenges at different stages of the research process. For example, finding a path out of extreme ambiguity at early research stages involves navigating the uncomfortable space between the "is" and the "ought" modes of critique through tentative boundary judgments around which a researcher can iterate and learn. This differs to later stages, when judgments may become hardened and critical reflection can help researchers remain open to emergent ethical considerations. Thus, the case study reflections suggest that RBC may serve two complementary purposes: 1) helping deconstruct over-confident or 'blind' boundary judgments that lead researchers to unconsciously operate under limited, ineffective, or harmful yet 'hardened' boundaries, and 2) guiding researchers paralyzed by the ethical aspects of ambiguity by giving it shape, allowing them to reflexively move through the research journey.

The experience of using RBC as an *ex post* reflective tool demonstrates its potential use as an *a priori* guide in future research. In Case A, West reflected that if RBC had been integrated throughout the study, it may have helped explicitly surface and reflect on dilemmas that were encountered subliminally as constant sources of discomfort and disconcertment. Such reflection may have helped to speed up his learning, enabling a better understanding and capacity to navigate problematic experiences and situations 'in the moment,' rather than only begin to make sense of them retroactively. In particular, the continual shifting between the 'is' and 'ought' encouraged by RBC may have helped better navigate the ethical and political paradoxes raised in the pursuit of positive change in fundamentally inequitable systems. In Case B, Haider reflected that the use of RBC as an *apriori* guide may have influenced the study, primarily in guiding her to critically question the *intervention process.* The research may have set out to be co-produced from the beginning, as opposed to emerging throughout the fieldwork. At the same time, she questions whether such an entangled process can or should aspire to be linear, or whether the RBCs main contribution is to enable researchers to embrace the messy and entangled nature of transdisciplinary research. In Case C, Lazurko reflected that RBC may have helped her adjust to the nuances of the research context more quickly and explore marginalized boundary judgments more thoroughly. For example, it may have motivated the selection of an additional study partner who could help 'sweep in' more diverse perspectives. Further, it may have directed the methodology away from the identification of 'robust' scenarios (i.e., which reflects an assumption of commensurability, and thus excluded novel perspectives) and toward those outcomes that only emerge under marginalized boundaries. These adjustments would have shifted the *process of intervening* significantly by more explicitly elevating marginalized perspectives. Finally, in Case D, Tilman reflected that *ex ante* knowledge of RBC would have helped him explore the political and ethical aspects (*processes of knowing)* in a more structured manner.

Evaluating the potential impact of a novel operational framework like RBC on the ambiguities of transdisciplinary research requires significant further research. Most obviously, sustainability scientists should embed RBC into a research process and document the insights. This type of reflexivity is rare in peer reviewed literature, save isolated examples (McGowan et al. 2014). However, doing so in a structured way facilitated by RBC may surface novel theoretical insights regarding how ambiguity influences research outcomes, in addition to practical insights regarding how ambiguity can move from the 'elephant in the room' to a fundamental part of rigorous sustainability science. Alternatively, sustainability scientists can integrate boundary critique into the empirical aspects of their study. For example, sensitivity analysis is commonly used to evaluate the influence of data uncertainty on research outcomes, but few attempt to evaluate the influence of different boundary judgments (e.g., epistemological orientations) on research outcomes, save isolated examples (Van Asselt and Rotmans 2002).

Readers may find numerous sources of critique in the discussion offered in this paper. Embracing ambiguity may place a burden on the research process; for example, integrating reflection about theoretical incommensurability and boundaries may involve significant time and energy. However, this 'slowing down' may be part of a bigger-picture shift needed to ensure the ongoing salience and legitimacy of sustainability science. Similarly, others may be dissatisfied with the ambiguity that persists through a paper that aims to operationalize it. Yet, to claim to delineate the boundaries of ambiguity definitively and operationalize it objectively would fall into myriad traps that contradict the rationale for embracing ambiguity in the first place. Thus, we attempted to find a balance that gives ambiguity enough shape to nurture reflexivity, while holding our own definition and framework as lightly as possible. Ultimately, we hope this paper provokes and inspires discussion and tangible shifts that further expose and embrace this persistent ‘elephant in the room’.

Chapter 5

Conclusion

The goal of this chapter is to synthesize the significant and original contributions to knowledge made in this dissertation. I begin the chapter with a review of the dissertation's purpose and objectives and a summary of the individual findings in each of Papers I, II, and III (Chapters 2 to 4). These findings are then situated as academic contributions to theory and practice. Finally, I discuss the study limitations and opportunities for future research.

5.1 Purpose and objectives

As discussed in Chapter 1, this dissertation moves from the view that transdisciplinary scenario practice offers a promising avenue for making sense of complex and uncertain futures in sustainability science. Additionally, I view the social-ecological systems (SES) perspective as an important complexity-based lens for furthering this potential. However, these promising trends all grapple with persistent ambiguity, and the lack of concepts, frameworks, and tools to operationalize ambiguity through reflexivity presents risks to the salience and legitimacy of the outcomes of the research. While this research gap reaches beyond what is feasible to address within a single doctoral dissertation, I explored two opportunities to address it: 1) the field of operational research and its multi-decade history grappling with theoretical and practical aspects of ambiguity through critical systems thinking (CST), and 2) semi-quantitative methods like cross-impact balances (CIB) that may enrich scenario practice to reflect a wider range of drivers and perspectives than is typical in mainstream scenario methods, thereby taking complexity – and potentially, ambiguity – seriously.

These two opportunities were explored through three manuscripts presented in Chapters 2, 3, and 4. Chapter 2 (Paper I) aimed to develop and validate a reflexive framework for scenario practice in sustainability science. I call this framework the Boundaries of the Future framework, because the process of abductive inquiry that generated the framework was underpinned by the process philosophy of Midgley (2000) from CST. This lens highlights how key boundary judgments in the design of a scenario process influence the scope of future potential (i.e., future conditions and values) in the scenario outcomes and proposes the degree to which this scope of future potential may reflect the dynamics of, and/or conditions for, SES change. The 72 social-ecological scenario case studies used to validate the framework exhibited biases away from the unique complexities of SES change under some boundary judgments, which affirmed the need to experiment with 'big picture' scenario methods like CIB in Paper II. Moreover, while the Boundaries of the Future framework aims to operationalize ambiguity through a holistic reflexive framework, it remains a reflection of the onto-epistemological and methodological approach of the study. This reflection motivated the contribution of operationalizing ambiguity in sustainability science more broadly in Paper III.

Chapter 3 (Paper II) aimed to explore the potential for the CIB method to enrich scenario practice for a) the development of 'big picture' (i.e., integrative and holistic) scenarios in sustainability science and b) river basins attempting to build resilience to climate change. To address these objectives, I led a transdisciplinary scenario modelling process in the Red River Basin (RRB). Through the process, I also explored the potential for the CIB method to surface diverse perspectives and drivers of change in scenarios for sustainability science beyond those that are typical in the mainstream water sector. The scenario modelling process did surface more diverse perspectives and drivers, including by enriching some of the Boundaries of the Future that were under-addressed in the case studies in Paper I. However, reflections on the ambiguity that persisted through the modelling process, even one explicitly oriented toward developing 'big picture' scenarios, motivated and informed the contribution of Paper III.

Finally, Chapter 4 (Paper III) aimed to **explore how key concepts, frameworks, and lessons from CST may be adapted to help address the challenges presented by ambiguity in sustainability science (i.e., including and beyond scenario practice).** More specifically, it aimed to establish 1) a holistic conceptualization of ambiguity and 2) recommendations for how sustainability scientists can operationalize this conceptualization of ambiguity as a valuable means of addressing sustainability challenges. This contribution emerged from reflections on the challenge of irreducible ambiguity and the lack of operational frameworks to help address ambiguity's underlying onto-epistemological tensions from Papers I and II.

5.2 Major findings

The major findings were presented in three distinct but interrelated manuscripts. The findings of these manuscripts are briefly summarized in Section 5.2 and situated as significant and original contributions to knowledge in Section 5.3.

5.2.1 Paper I – Boundaries of the future

The Boundaries of the Future framework that was developed, applied, and validated in Paper I presents a theory-informed, practice-based framework for scenario practice in sustainability science. The framework highlights ten key boundary judgments involved in designing a scenario process under categories of framing, methodology, and system characterization. Each judgment is an active site of choice that influences the scope of future potential in the resulting scenarios in ways that reflect the dynamics of, and conditions for, social-ecological systems (SES) change. The boundary judgments are depicted as axes on a radar chart, in which the outermost choice reflects the conditions for transformation (i.e., fundamental, systemic shifts away from existing systems; desirable or undesirable; navigated or unintended; see Chapter 2). The framework can be operationalized as an *ex-ante* reflexive tool and an *ex-post* reflection tool to enable more intentional and transparent boundary judgments. Doing so facilitates a reflexive scenario practice by a) revealing the influence of subjective boundary judgments on scenario outcomes, including what the resulting scenarios include *and exclude*, and b) indicating how scenario practice can enrich status quo frames of the future to consider the unique and potentially transformative conditions of the 21st century.

The process of developing and applying the framework revealed further insights. Challenges encountered during the study indicate a lack of reflexivity in the use of scenarios in sustainability science. For example, many boundary judgments were not explicit in the case studies and had to be inferred, and the chosen methodological approach was not always commensurate with the way the scenario process was framed. The common boundaries of the future (i.e., average judgments in the 72 case studies overall) reveal a bias away from judgments that reflect the full scope of SES change (i.e., to include transformation); for example, few studies considered interactions between system structure and actor agency under the ‘drivers’ judgment. These limitations affirmed the need to experiment with novel methods like CIB to help enrich scenarios with the unique complexities of SES change, as was done in Paper II. Additionally, while the Boundaries of the Future framework aims to be holistic, it is still a reflection of the study approach. Consequently, and rather paradoxically, the framework makes ambiguity in scenario practice explicit through a focus on the ‘boundaries of the future’ but is itself delimited by subjective boundaries. This paradox and the challenge of irreducible ambiguity motivated the conceptualization and operationalization of ambiguity in Paper III.

5.2.2 Paper II – Exploring 'big picture' scenarios for resilience

The transdisciplinary scenario modelling process in Paper II characterized the RRB as a complex, cross-scale SES. The CIB model is made up of fifteen descriptors, representing the most important and uncertain drivers of change relevant to resilience to climate variability and change in the RRB. Ten of these descriptors make up the structure of the cross-scale SES, including social and ecological drivers of change at both river basin and global scales, and five governance descriptors characterize efforts to build resilience, introducing the influence of actor agency. Multiple variants for each descriptor cover a range of mutually exclusive outcomes, and several "seeds" of transformation (i.e., promising practices or projects that are marginal at present but hold promise for transformation) were included as variants to broaden the scope of outcomes. The matrix of influence judgments characterizes social-ecological and cross-scale interactions between variants, comprising a stability landscape for the future of the RRB. Significant uncertainty and ambiguity in the influence judgments was addressed through literature validation and sensitivity analysis, which resulted in eight robust, internally consistent scenarios. A brief strategy assessment revealed the complex and often surprising outcomes of interventions on the stability landscape of a river basin SES. Finally, the debrief workshop affirmed that the scenario process was valuable for making sense of complexity, surfacing different perspectives, and affirming the value of collaboration.

By characterizing the RRB as a complex, cross-scale SES, the scenario analysis surfaced significant complexities and ambiguities regarding efforts to build resilience to climate change in the RRB. For example, in the robust scenarios, several undesirable governance variants (e.g., independent governance, patchwork data) tend to co-occur and contribute to poor environmental outcomes, while more desirable governance variants also co-occur and improve environmental outcomes. However, the state of global descriptors has a strong influence over environmental outcomes, sometimes overshadowing positive governance interventions. Statistics offered by the CIB method (e.g., bias statistics, active-passive diagram) reveal additional details, such as the barriers to adoption of the natural ecosystems approach to infrastructure for resilience, the complex behaviour associated with the role of the rural economy (i.e., due to its combined active *and* passive role in the system), and the highly active role of Indigenous water rights in realizing desirable outcomes overall. The strategy assessment also surfaced interesting implications, such as that a collaborative response to water scarcity alone may not flip scenarios toward desirable outcomes in all cases.

The findings of Paper II complement those of Papers I and III. The CIB model characterizes scenarios as emergent from social-ecological complexity, considers interactions between top-down structure and bottom-up agency, and across scales. In doing so, the CIB method and supporting social-ecological scenario framework pushed some judgments to the outside of the Boundaries of the Future framework from Paper I (i.e., to consider SES change and transformation). Moreover, ambiguity persisted through the transdisciplinary scenario modelling process, which manifested as the uncertain and ambiguous influence judgments in the CIB model, the different interpretations that emerged during the debrief workshop, and reflections on the limitations of the CIB method itself. The role of ambiguity in the transdisciplinary scenario process in Paper II motivated and informed the conceptualization and operationalization of ambiguity in Paper III.

5.2.3 Paper III – Operationalizing ambiguity in sustainability science

Paper III explored concepts and frameworks from CST to conceptualize and operationalize ambiguity in sustainability science. CST has a multi-decade history grappling with theoretical and practical aspects of ambiguity, which relate to existing challenges in sustainability science. The resulting discussion addressed the importance and subjectivity of system boundaries, observer-dependence (e.g., through theoretical and methodological pluralism), knowledge as a boundary process (i.e., Midgley's process philosophy), and boundaries as intervention (e.g., boundary marginalization). This discussion led to an operational definition of ambiguity as *an emergent feature of the simultaneous and interacting boundary processes associated with being, knowing, and intervening in complex systems* (Section 4.3). This definition acknowledges how 1) the boundaries of a researcher's subjective orientation influences their experience of complexity and how multiple frames are exposed, understood, and mediated through research (Being), 2) knowledge about complexity is produced through the process of making boundary judgments, generating a partial, contextual, and provisional frame (Knowing), and 3) a researcher is part of the complexity they seek to understand, rendering any boundary process as an intervention that reinforces certain frames and marginalizes others (Intervening).

This operational definition set up discussion about operationalizing ambiguity in sustainability science. First, the tendency to search for meta-theories or frameworks to guide theoretical and methodological pluralism in sustainability science (e.g., dominance of the SES perspective, or convergence on critical realism as appropriate for SES research) should be tempered by a key lesson from CST: all meta-theoretical frameworks are themselves a frame and the assumption that a meta-theory exists at all assumes theoretical commensurability. This assumption emphasizes pluralism as a form of complementarism focused on consensus and integration, masking incommensurability, discordance, and ultimately, aspects of ambiguity. Rather, sustainability science should broaden its theoretical orientation to take incommensurability and discordance seriously. Second, given the risk and pitfalls of directing pluralism through organizing meta-theoretical frameworks, CST suggests more focus should be placed on the capacities of researchers navigating within and across theories and methods. This suggestion motivated the development of a reflexive boundary critique framework, which expands on Ulrich's original boundary critique from CST (which focused on *knowing*) to reveal sources of empirical and normative selectivity involved in all three processes of *being, knowing,* and *intervening* in complex systems. Four case study reflections, including the transdisciplinary scenario modelling study in the RRB from Paper II, demonstrate the unique insights that can be gained by embedding such critical reflection as a fundamental part of the research process.

5.3 Academic contributions to theory and practice

The findings from Papers I, II, and III offer numerous academic contributions to theory and practice. The primary audience for these contributions is the field of sustainability science, and by extension sustainability policy and practice, with specific findings relevant for the emerging field of anticipatory governance and water resilience. While this section may include some repetition of Section 5.2, it focuses on situating the contribution in literature to highlight its originality and significance. A summary of these contributions is depicted in Figure 5-1.

5.3.1 Ambiguity and reflexivity in scenario practice for sustainability science

The first theoretical contribution to sustainability science is the Boundaries of the Future framework from Paper I, which represents a *novel synthesis of literatures that makes ambiguity in scenario practice for sustainability science explicit*. CST has been suggested as a promising lens for improving foresight in sustainability research (Helfgott 2018b; Rutting et al. 2022), and its focus on system boundaries is compatible with the system ontology underlying the dominant SES perspective in sustainability science. However, it has not yet been operationalized. Through the lens of 'boundary judgments' and process philosophy from CST (Ulrich 1983; Midgley 2000), a theory-informed, practice-based framework emerged that synthesizes diverse literatures about how change emerges in complex SESs (e.g., Folke 2016; Folke et al. 2016; Reyers et al. 2018), the unique conditions for and dynamics of transformation (e.g., Leach et al. 2010; Moore et al. 2014; Scoones et al. 2020), and scenario practice for sustainability research (e.g., Elsawah et al. 2020b; Muiderman et al. 2020; Moallemi et al. 2021; Pereira et al. 2021). Numerous other syntheses and typologies of scenarios exist (e.g., van Notten et al. 2003; Börjeson et al. 2006; Muiderman et al. 2020), but few offer this bridge between practice and theory, and none are underpinned by CST. Moreover, the framework is unique in that it is explicitly normative, where more expansive boundary judgments may enrich scenarios with the dynamics of, and conditions for, transformation. This normative orientation thus addresses the need to consider the pursuit of deliberate transformations to sustainability (Moore et al. 2014; Patterson et al. 2017) and the potential for novelty and disruption under the unique conditions of the 21st century (Keys et al. 2019; Pereira et al. 2021)

While the theoretical contribution of the framework is that it makes ambiguity explicit through a novel synthesis of literatures, the practical contribution to sustainability science lies in *operationalizing the framework as an ex-ante and ex-poste reflexive tool in scenario practice* (Inayatullah 1998a; Scheele et al. 2018; Muiderman et al. 2020, 2022). Reflexivity is often cited as a crucial capacity for navigating ambiguity and pluralism in transdisciplinary research (Miller 2013; Miller et al. 2014; Popa et al. 2015) and has been explored from various perspectives (e.g., Fook 1999; Salzman 2002; Johnson and Duberley 2003; Archer 2016), broadly involving reflection on how a researcher's own self, contribution, or presence affects the research. Numerous scenario typologies help organize the use of scenarios (e.g., van Notten et al. 2003; Börjeson et al. 2006; Muiderman et al. 2020) and synthesis papers point to the unique opportunities and challenges in scenario practice for sustainability research (e.g., Elsawah et al. 2020; Muiderman et al. 2020; Pereira et al. 2021). However, neither offers a clear and granular strategy for how to address the challenge of linking the design of a scenario process to scenario outcomes in a way that can facilitate a more reflexive scenario practice. In other words, the Boundaries of the Future framework fills a strategic operational gap by guiding researchers through the specific choices made in designing a scenario process and connecting them to their implications for the scope of SES change reflected in scenario outcomes. By applying the framework to 72 social-ecological scenario case studies, the study also offers a practical indication of trends in existing case studies to date, which charts a future research agenda. Together, these practical contributions can inform and motivate a more reflexive and enriched scenario practice in sustainability science.

While anticipatory governance was not central to the dissertation, the Boundaries of the Future framework also offers a novel contribution to this emerging field by *demonstrating a means for operationalizing futures literacy*. Anticipatory governance literature points to the wide range of anticipatory processes in climate and sustainability research (Muiderman et al. 2020). It also argues for the importance of futures literacy (i.e., and reflexivity) to navigate this future diversity (Miller 2007; Mangnus et al. 2021), and the need for more critical and plural anticipation to contribute to sustainability transformation (Vervoort et al. 2015; Bourgeois et al. 2017; Muiderman et al. 2022). The Boundaries of the Future framework is a theory-informed, practice-based framework that demonstrates a means to fill an important gap between anticipatory governance theory and practice by connecting the specific choices (i.e., boundary judgments) involved in the design of an anticipatory governance process (i.e., scenarios) to existing theories about how the future of complex sustainability challenges emerges in a specific field of practice (e.g., SES change and transformation in sustainability science). In the language of anticipatory governance, the framework demonstrates how the field may operationalize futures literacy.

5.3.2 Cross-impact balances method for SES modelling

The transdisciplinary scenario modelling process in the RRB in Paper II revealed the *unique insights about water resilience in river basins that emerge through 'big picture' scenario modelling* using methods like CIB. A significant and growing body of research applies resilience thinking to the challenge of water governance under climate change (Rockström et al. 2014b; Falkenmark et al. 2019b; Pahl-Wostl 2020; Baird and Plummer 2021). Numerous scenario studies address water resilience from different perspectives, such as to forecast the implications of climatic and socio-economic change on supply and demand or investment strategies (Varis et al. 2004; Dong et al. 2013; Elsawah et al. 2020) or to collaboratively envision and strategize pathways toward sustainable or resilient river basin systems amid top-down pressures (Schneider and Rist 2014; Carpenter et al. 2015; Hirpa et al. 2018). The emerging community of research and practice called 'decision making under deep uncertainty' focuses explicitly on decision methods appropriate for climatic non-stationarity in the water sector (Kwakkel et al. 2016; Marchau et al. 2019). Still, most of these methods involve trade-offs between quantitative models and qualitative models, and focus *either* on top-down structural changes, i.e., boundary conditions (e.g., Lempert 2003), *or* on strategic pathways (e.g., Haasnoot et al. 2013). Efforts have been made to link qualitative narrative scenarios about the 'big picture' future of river basins to quantitative models (e.g., Booth et al. 2016), but no study (to my knowledge), attempts to systematically model efforts to build resilience in river basins as part of a landscape of social-ecological, cross-scale, and structure-agency interactions. Thus, the CIB model in Paper II offers unique insights about water resilience (see Section 5.2.2) that situate emerging solutions within a complex and a long-term trajectory.

The transdisciplinary scenario modelling process in the RRB in Paper II also *demonstrates the value of an underutilized method for SES modelling in sustainability science*. Scenarios are increasingly popular tools for characterizing uncertainty and complexity in SESs (e.g., Peterson et al. 2003; Mistry et al. 2014; Oteros-Rozas et al. 2015; Falardeau et al. 2019). Yet, the common 'boundaries of the future' from the 72 social-ecological scenario case studies in Paper I indicate how a minority of cases adopt methods that link qualitative and quantitative drivers (24 of 72), few cases view future trajectories as emergent from social-ecological complexity (18), and a minority consider the interactions between top-down and bottom-up drivers (25) or across spatial scales (21). In other words, many social-ecological scenario case studies side-step aspects of complexity, and thus ignore the potential for ambiguity. While such processes may still offer meaningful contributions to the field, they are vulnerable to myriad challenges (Section 1.1.4) and may not respond to the need to "get the big picture roughly right" (Polasky et al. 2020).

The semi-quantitative scenario method of cross-impact balances (CIB) offered an opportunity to model 'big picture' (i.e., integrative and holistic) scenarios that 'open up' scenario practice to a wider range of perspectives and drivers. In the RRB case study, CIB effectively integrated local and practitioner with scientific knowledge, qualitative with quantitative data, and social with ecological variables. Moreover, using a social-ecological scenario framework to guide the transdisciplinary CIB modelling process helped ensure the scenarios emerge from social-ecological complexity. Thus, the eight internally consistent and robust scenarios can be understood as multiple stable states or basins of attraction for the RRB (i.e., stable states, according to the metric of internal consistency) and the CIB matrix characterizes the RRB as a complex landscape of social-ecological interactions across scales, exposing the influential variables and feedbacks that affect the trajectory of the future. Moreover, the process of systematically integrating the knowledge from diverse interviewees into the scenario model surfaced significant ambiguity, which was addressed through a sensitivity analysis. The clear compatibility between the CIB method and SES theory and its capacity to enrich the 'boundaries of the future' to consider the unique complexities and ambiguities of SES change, affirms the value of elevating CIB in the toolbox of SES modelling approaches in sustainability science. However, further reflection on ambiguity that persisted through the process motivated the conceptualization and operationalization of ambiguity in Paper III.

5.3.3 Operationalizing ambiguity and reflexivity in sustainability science

The unique lens offered by CST in the development of the Boundaries of the Future framework in Paper I led to a broader theoretical contribution, which is a *novel conceptualization of ambiguity for sustainability science* in Paper III. Ambiguity has been defined and addressed in various literatures, including as a unique form of uncertainty related to differing interpretations of numbers, system boundaries, or problem framings (Funtowicz and Ravetz 1990; Walker et al. 2003; Dewulf and Biesbroek 2018). In SESs, ambiguity arises from complexity because any knowledge about SESs excludes pertinent system components and relationships elements (Matthews 2006; Preiser et al. 2018, 2021). Science and technology studies also highlights ambiguity as arising from challenges developing a common understanding regarding how to “select, partition, characterize, prioritize, bound or interpret the meanings of [different] outcomes” (Stirling 2006, p. 19). These myriad definitions reveal how ambiguity is understood differently by different fields and sub-fields, and how it implicates both epistemology and ontology, i.e., framings are interventions that both emerge from and shape future action. Thus, through a discussion of the importance of system boundaries, observer-dependence, knowledge as a boundary process, and boundaries as intervention, a novel, operational definition of ambiguity emerged that addresses its onto-epistemological dimensions while prioritizing its operationalization.

As with the Boundaries of the Future framework, the theoretical contribution (i.e., an operational definition of ambiguity) in Paper III is accompanied by a practical contribution related to its operationalization. Disparate literature operationalizes aspects of ambiguity. For example, epistemological pluralism operationalizes ambiguity from *processes of knowing* through limited forms of integration (e.g., Martin 2012; Tengö et al. 2014), and other literature operationalizes *processes of being* by turning attention back on the unique positionality and capacities of the researcher to navigate the ambiguities of transdisciplinary research (e.g., Haider et al. 2018; Chambers et al. 2022). The STEPS pathways to sustainability approach most explicitly operationalizes *processes of intervention* through reflection on how both constructivist and positivist perspectives together inform inclusive, pluralist, and potentially transformative sustainability research (Leach et al. 2007). However, much of sustainability science still ignores or attempts to reduce ambiguity, leaving research vulnerable to the risks and power dynamics associated with uncritical knowledge integration and transdisciplinary collaboration.

Thus, the practical contribution from Paper III is clear recommendations for how ambiguity can and should be operationalized in sustainability science. These recommendations align with calls for reflexivity and pluralism in sustainability research (Tengö et al. 2014; Popa et al. 2015; Haider et al. 2018; Moore et al. 2018; Chambers et al. 2022) but are novel in that they are informed by key lessons and concepts from the field of CST. The first recommendation is a call to temper any search for meta-theories or frameworks to guide theoretical and methodological pluralism with the knowledge that any meta-framework is itself a frame and thus emphasizes consensus and integration, potentially masking (irreducible) ambiguity. Rather, sustainability science must broaden its theoretical orientation to take incommensurability and discordance seriously. This finding is relevant and timely, as two divergent streams of sustainability scientists differ on this topic. Some acknowledge complexity but aim to reduce ambiguity through integration within an overarching disciplinary paradigm (e.g., Clark et al. 2016; Clark and Harley 2020). Others are trying to 'live with complexity' by remaining open to – and embracing – uncertainty and ambiguity through transdisciplinarity and pluralism (Cornell et al. 2013; Turnhout et al. 2019; Caniglia et al. 2020; West et al. 2020). The former may serve to legitimize sustainability science from dominant disciplinary perspectives, while the latter may be better suited to the emancipatory approach required to fulfill sustainability science's increasingly transformative agenda.

Second, the development and demonstration of the framework of Reflexive Boundary Critique offers an opportunity to help avoid the pitfalls of the search for or use of a meta-theoretical framework for integration (i.e., consensus and complementarism that masks ambiguity) by nurturing the capacity of researchers navigating irreducible ambiguity. This contribution can help further establish the legitimacy of transdisciplinary and pluralist sustainability science (Cornell et al. 2013; Caniglia et al. 2020; West et al. 2020) by making the adaptive and emergent nature of the transdisciplinary research journey explicit and deliberate (McGowan et al. 2014) and by operationalizing an emancipatory approach that aligns with sustainability science's transformative agenda (Shrivastava et al. 2020). The framework expands on Ulrich's original boundary critique from CST (which focused on *knowing*) to reveal sources of empirical and normative selectivity involved in all three *processes of being*, *knowing,* and *intervening* in complex systems. Four case study reflections, including the transdisciplinary scenario modelling study in the RRB from Paper II, demonstrate the unique insights and challenges that emerge through application of the framework.

5.3.4 Summary

A summary of the theoretical and practical contributions to knowledge from Sections 5.3.1 to 5.3.4 are depicted in Figure 5-1. The arrows show how the contributions in Papers I, II, and III influenced and informed each other.

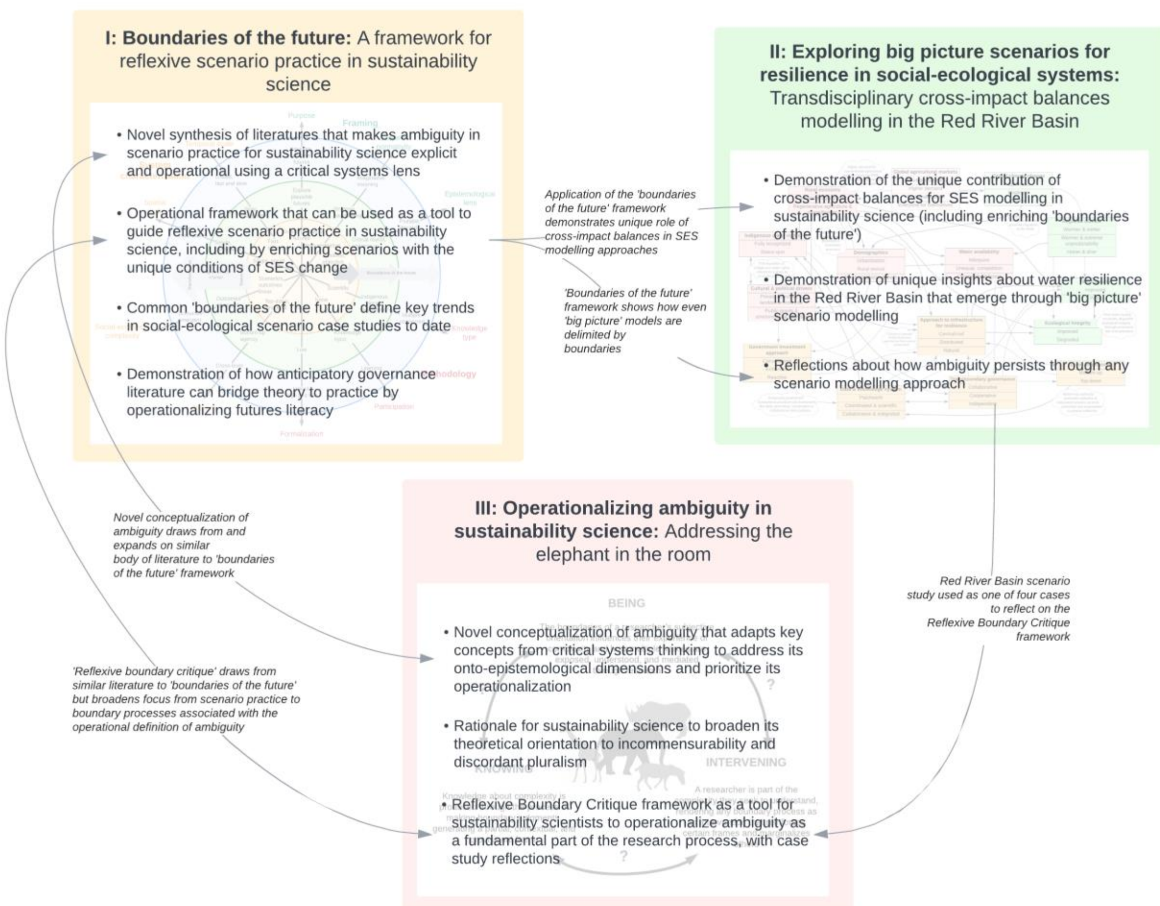

Figure 5-1: Summary of theoretical and practical academic contributions from the dissertation

5.4 Study limitations and future research

The study limitations and opportunities for future research discussed in each chapter are summarized in Table 5-1. The main limitations of Paper I relate to the potential biases and subjectivities involved in the process of abductive inquiry that generated the Boundaries of the Future framework. Similarly, the limitations of Paper II relate to potential biases and constraints in data collection and analysis, which may have limited the scenario outcomes. Finally, Paper III emerged from reflection on Papers I and II and was thus not embedded through the dissertation (e.g., to structure the transdisciplinary scenario modelling process in Paper II), presenting important opportunities for future research.

Table 5-1: Summary of study limitations and opportunities for future research

Paper	*Limitations*	*Opportunities for future research*
I	• Bias in literatures used to generate the framework • Subjectivity in interpretation through abductive inquiry • Limited case studies used to validate the framework • Boundaries of the 'boundaries of the future' framework	• Update the framework and revisit case studies as new understandings of SES change and applications of scenarios in sustainability science evolves • Empirically test theoretical assumptions underpinning each axis of the framework, directly connecting each judgment to scenario outcomes • Apply the framework to case studies from other areas of scenario practice in sustainability science (e.g., integrated assessment models, Shared Socioeconomic Pathways)
II	• Bias in recruitment of interview participants • Constraints on whose knowledge 'counts' due to methodology choice • Robust scenarios excluded scenarios that are internally consistent under marginalized assumptions	• Similar studies can ensure that non-academic partnerships and interviewee sampling prioritizes marginalized actors • Complementary imaginative or narrative scenario processes may enrich the future of the RRB in different ways than CIB (e.g., to embrace Indigenous knowledges) • Instead of using the sensitivity analysis to find robust scenarios, use the sensitivity analysis to explore novel scenarios that only emerge under marginal assumptions
III	• Potential critiques of unbounded relativism and threats to sustainability science • Reflexive boundary critique not embedded in four reflective case studies or the dissertation (e.g., to guide scenario modelling in Paper II)	• Collective dialogue among sustainability scientists about how to embrace ambiguity while maintaining the solutions-oriented and use-inspired nature of the field • Embed reflexive boundary critique into transdisciplinary research processes and document the insights

In addition to the specific limitations in Table 5-1, an additional overarching limitation relates to my application of Midgley's (2000) process philosophy in Papers I and III. Midgley's process philosophy (2000) is a philosophy of knowledge for CST that shifts focus from the *content* of knowledge to the *process* of bringing knowledge into being, in particular the *process of making boundary judgments*. This form of process philosophy was selected for various reasons, including that it is compatible with open systems (i.e., complexity), helps operationalize ambiguity through reflexivity by shifting from content to *process*, and discusses the contextual, contingent, and provisional nature of knowledge through the more accessible language of subjective boundary judgments. However, by applying Midgley's process philosophy to develop integrated frameworks (i.e., the Boundaries of the Future framework in Paper I and Reflexive Boundary Critique in Paper III), I took a stance regarding which boundary judgments were most relevant, thereby lending some focus to 'content' and potentially 'hardening' specific boundaries. This could be criticized as acting in contradiction to the foundations of process philosophy, which points out that any integrated framework is still observer-dependent, partial, and provisional. My hope is that I managed to find an appropriate balance that gives enough shape to ambiguity to render it operational (i.e., by defining *which* processes may be relevant and influential for specific domains of sustainability science), while holding my own lens 'as lightly as possible' (i.e., by acknowledging my positionality and the partial, provisional nature of these integrated frameworks in the discussions of Papers I and III).

The second overarching limitation relates to the exploratory nature of this dissertation. The contributions made in Papers I, II, and III are a product of an emergent learning process and may lack some degree of coherence and integration (see Figure 5-1). This gap is primarily because Paper III takes a birds' eye view on the frameworks and methods used in Papers I and II but emerged upon reflection after Papers I and II were complete. Ideally, I would have applied reflexive boundary critique as a critical reflection tool before and during the transdisciplinary scenario process. Similarly, the Boundaries of the Future framework (Paper I) and the RRB scenario study (Paper II) were developed concurrently, so while they informed one another, the relationship is not explicit in the two manuscripts. Ideally, the Boundaries of the Future framework could have structured reflection on the unique contribution of the CIB method more explicitly. Still, this open and adaptive research process was required for the contributions of this dissertation to emerge, and thus reflects the importance of nurturing reflexivity through the 'journey' that is transdisciplinary research (McGowan et al. 2014).

In sum, the contributions and limitations of this dissertation offer a starting point for a rich body of research that operationalizes ambiguity through reflexivity in scenario practice for sustainability science. My hope is that this contribution helps translate ambiguity from an undesirable ‘elephant in the room’ to an inevitable and embedded part of rigorous research about the future of complex sustainability challenges.

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Appendix A

Search protocol and final literature for development of the reflexive framework

The following appendix describes the literature search protocol for the seminal literature from scenario practice (Group A) and sustainability science (Group B) used to for the inductive review used to generate boundary judgments in the reflexive framework in Chapter 2. The case studies used to develop the framework are summarized in Appendix B.

GROUP A: LITERATURE ON SCENARIO PRACTICE

<u>Goal</u>: To retrieve seminal literature on scenario practice for sustainability science.

<u>Databases</u>: The literature was retrieved from Scopus and Google Scholar. Scopus was selected because it focuses on contemporary literature and thus includes emerging futures-oriented journals that may be excluded from other databases. Google Scholar was selected because it casts a wide net over the literature and thus may fill in gaps in the Scopus searches. Only English language studies were included, and the searches were all complete before December 2021.

<u>Search terms and search protocol:</u> The primary search terms were *scenario** OR *foresight* OR *futures* OR *anticipatory governance* AND *sustainability* (OR *sustainability science* OR *sustainability research*), limiting the search to the subjects of 'Environmental Sciences', 'Environmental Studies', 'Social Sciences', and related fields. Upon an initial search and review of these terms, it was clear that the databases were returning a highly disparate and wide-ranging set of literature that mentioned the term "scenario" but did not focus on the use of scenarios as a research practice. Thus, the search protocol was adapted to return more targeted and relevant literature for scenario practice by combining the terms in different ways, adding additional keywords to the initial search (e.g., *scenario develop** OR *scenario analys** OR *scenario plan**), and/or scanning the reference list of papers that were already selected. This led to a more iterative, and adaptive search protocol than would be required for a systematic review but was appropriate to find the literature relevant to generate the reflexive framework.

<u>Literature selection:</u> Each search was sorted by 'Relevance' and 'Citation (high to low)', and the title and abstract of the first 100 hits of each search were reviewed. The inclusion criteria were: a) the paper focuses on the use of scenarios as a research practice, either theoretically or methodologically, b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case), and c) the paper is targeted to an interdisciplinary/transdisciplinary audience, with preference for sustainability science. The search continued until the authors were satisfied that the list of literature was as close to saturation as would be feasible for the review.

<u>Return to literature:</u> Emerging boundary judgments from the initial review of the literature pointed to gaps in the initial search protocol. Thus, the initial literature search was revisited with additional search terms relevant for specific themes (e.g., *spatial scale* or *knowledge type*) to complete the list.

Example searches:

1) *Scopus: scenario** OR *foresight* OR "*anticipatory governance*" AND *sustainability* + LIMIT to "Environmental Science" subject area – 6, 770 results
    a. *Scenario develop** – 266 results

b. *Scenario analys** - 942 results
c. *Scenario plan** - 264 results

2) *Scopus: scenario** OR *foresight* OR "*anticipatory governance"* AND *sustainability* + LIMIT to "Social Sciences" subject area – 3,466 results
    a. *Scenario develop** – 266 results
    b. *Scenario analys** - 942 results
    c. *Scenario plan** - 264 results

<u>102 papers total (23 added after initial review to address emergent boundary judgments)</u>

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GROUP B: LITERATURE ON SOCIAL-ECOLOGICAL SYSTEMS CHANGE (including transformation)

Goal: To retrieve seminal literature on the dynamics of change in social-ecological systems (SES), including transformation.

Databases: The literature was retrieved through iterative searches in Scopus and Web of Science. These two databases were selected to cover a comprehensive scope of literature. Only English language studies were included, and the searches were all conducted before December 2021.

Search protocol: The literature search protocol was conducted in four categories.

> *Category 1 (General SES):* General literature that addresses the dynamics of change in SESs was found simply using the search term *social-ecological system** and limiting the search to relevant subjects (e.g., 'Environmental Sciences', 'Environmental Studies', 'Social Sciences', 'Sustainability Science' depending on the database). The results of each search were sorted in order of 'Cited by (Highest)' and the title and abstract of the first 100 results were reviewed. The inclusion criteria were a) the paper focuses on the dynamics of, and conditions for, SES change and b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case).
>
> *Category 2 (deliberate SES transformation):* Literature that addresses deliberate transformation from an SES perspective was found using the searches (*social-ecological system** AND *transformat**) and limiting the search to relevant subjects (e.g., 'Environmental Sciences', 'Environmental Studies', 'Social Sciences', 'Sustainability Science' depending on the database). The results of each search were sorted in order of 'Cited by (Highest)' and the title and abstract of the first 100 results were reviewed. The inclusion criteria were a) the paper focuses on the dynamics of, and conditions for, SES transformation, with at least some focus on deliberate transformation (i.e., desirable futures), and b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case).
>
> *Category 3 (counterpoint to deliberate SES transformation):* The SES approach to deliberate transformation is one of multiple transformation approaches. Thus, additional literature that provides a counterpoint to the SES approach through a critique of the SES perspective, and in particular of SES transformation, was also included. This literature was retrieved from the results of Category 2 searches, and by conducting additional searches including (transformat* AND (sustainability OR "social-ecological system*") AND critique OR politic* OR emancipat*). The results of each search were sorted in order of 'Cited by (Highest)' and the title and abstract of the first 50 results were reviewed. The inclusion criteria were a) the paper focuses on the dynamics of, and conditions for, SES transformation, with at least some focus on deliberate transformation (i.e., desirable futures), and b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case).
>
> *Category 4 (unintended SES transformation):* Literature that addresses unintended transformations in SESs beyond that covered in Category 1 was found using the search terms ("*social-ecological system*"* AND *Anthropocene*; *social-ecological system*"* AND *"regime*

shift"; "social-ecological system*" AND "tipping point"; Anthropocene AND risk; complexity AND risk) and limiting the search to relevant subjects (e.g., 'Environmental Sciences', 'Environmental Studies', 'Social Sciences', 'Sustainability Science' depending on the database). The results of each search were sorted in order of 'Relevance' and 'Cited by (Highest)' and the title and abstract of the first 50 results were reviewed. The inclusion criteria were a) the paper focuses on potential for more disruptive, turbulent, sudden, and/or systemic changes (i.e., undesirable transformations) in SESs, and b) the paper is a seminal framework, commentary, review, synthesis, or highly cited case study (i.e., not a highly specialized method or case).

Return to literature: Emerging themes (i.e., boundary judgments) from the initial review of the literature pointed to gaps in the initial search protocol addressing specific themes. Thus, the initial literature search was revisited with additional search terms relevant for specific themes (e.g., *spatial scale* or *knowledge type*) and complete the list.

General SES theory

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Participation

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Appendix B

72 case studies coded against the reflexive framework

	Lead author	*Year*	*Title*	DOI
1	Allan	2022	Developing socio-ecological scenarios: A participatory process for engaging stakeholders	https://doi.org/10.1016/j.scitotenv.2021.150512
2	Andreotti	2020	Combining participatory games and backcasting to support collective scenario evaluation: an action research approach for sustainable agroforestry landscape management	https://doi.org/10.1007/s11625-020-00829-3
3	Baggio	2016	Multiplex social ecological network analysis reveals how social changes affect community robustness more than resource depletion	www.pnas.org/cgi/doi/10.1073/pnas.1604401113
4	Bennett	2016	Community-based scenario planning: a process for vulnerability analysis and adaptation planning to social–ecological change in coastal communities	DOI 10.1007/s10668-015-9707-1
5	Bohensky	2011a	Future makers or future takers? A scenario analysis of climate change and the Great Barrier Reef	doi:10.1016/j.gloenvcha.2011.03.009
6	Bohensky	2011b	Scenarios for Knowledge Integration: Exploring Ecotourism Futures in Milne Bay, Papua New Guinea	doi:10.1155/2011/504651
7	Bohnet	2007	Planning future landscapes in the Wet Tropics of Australia: A social–ecological framework	doi:10.1016/j.landurbplan.2006.07.001
8	Booth	2016	From qualitative to quantitative environmental scenarios: Translating storylines into biophysical modeling inputs at the watershed scale	http://dx.doi.org/10.1016/j.envsoft.2016.08.008
9	Brown	2016	Participatory scenario planning for developing innovation in community adaptation responses: three contrasting examples from Latin America	DOI 10.1007/s10113-015-0898-7
10	Bruley	2021	Actions and leverage points for ecosystem-based adaptation pathways in the Alps	https://doi.org/10.1016/j.envsci.2021.07.023
11	Brunner	2016	Policy strategies to foster the resilience of mountain social-	http://dx.doi.org/10.1016/j.envsci.2016.09.003

			ecological systems under uncertain global change	
12	Bush	2010	Scenarios for Resilient Shrimp Aquaculture in Tropical Coastal Areas	https://www.jstor.org/stable/26268149
13	Butler	2016	Scenario planning to leap-frog the Sustainable Development Goals: An adaptation pathways approach	http://dx.doi.org/10.1016/j.crm.2015.11.003
14	Carpenter	2015	Plausible futures of a social-ecological system: Yahara watershed, Wisconsin, USA	https://www.jstor.org/stable/26270183
15	Daconto	2010	Applying Scenario Planning to Park and Tourism Management in Sagarmatha National Park, Khumbu, Nepal	https://www.jstor.org/stable/mounresedeve.30.2.103
16	Dada	2021	Towards West African coastal social-ecosystems sustainability : Interdisciplinary approaches	https://hal.ird.fr/ird-03251456
17	de Chazal	2008	Including multiple differing stakeholder values into vulnerability assessments of socio-ecological systems	doi:10.1016/j.gloenvcha.2008.04.005
18	Enfors	2008	Making Investments in Dryland Development Work: Participatory Scenario Planning in the Makanya Catchment, Tanzania	https://www.jstor.org/stable/26267979
19	Franklin	2019	Studying Kenai River Fisheries' Social-Ecological Drivers Using a Holistic Fisheries Agent-Based Model: Implications for Policy and Adaptive Capacity	doi:10.3390/fishes4020033
20	Fredstrom	2021	Reimagining climate futures: Using critical futures studies to explore scenarios for Ljungby municipality in Sweden	https://www.diva-portal.org/smash/record.jsf?pid=diva2:1569411
21	Garteizgogeascoa	2020	Contextualizing Scenarios to Explore Social-Ecological Futures: A Three Step Participatory Case Study for the Humboldt Current Upwelling System	doi: 10.3389/fmars.2020.557181
22	Gaube	2009	Combining agent-based and stock-flow modelling approaches in a participative analysis of the integrated land system in Reichraming, Austria	DOI 10.1007/s10980-009-9356-6
23	Gibon	2010	Modelling and simulating change in reforesting mountain landscapes using a social-ecological framework	DOI 10.1007/s10980-009-9438-5

24	Gourguet	2021	Participatory Qualitative Modeling to Assess the Sustainability of a Coastal Socio-Ecological System	doi: 10.3389/fevo.2021.635857
25	Gray	2015	Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems	https://www.jstor.org/stable/26270184
26	Hanspach	2014	A holistic approach to studying social-ecological systems and its application to southern Transylvania	https://www.jstor.org/stable/26269673
27	Harmáčková	2014	Linking multiple values of nature with future impacts: value-based participatory scenario development for sustainable landscape governance	https://doi.org/10.1007/s11625-021-00953-8
28	Hashimoto	2019	Scenario analysis of land-use and ecosystem services of socialecological landscapes: implications of alternative development pathways under declining population in the Noto Peninsula, Japan	https://doi.org/10.1007/s11625-018-0626-6
29	Henriques	2021	The future water environment — Using scenarios to explore the significant water management challenges in England and Wales to 2050	http://dx.doi.org/10.1016/j.scitotenv.2014.12.047
30	Huber	2021	Agent-based modelling ofwater balance in a social-ecological system: A multidisciplinary approach for mountain catchments	https://doi.org/10.1016/j.scitotenv.2020.142962
31	Iwaniec	2020	The co-production of sustainable future scenarios	https://doi.org/10.1016/j.landurbplan.2020.103744
32	Jiren	2021	Participatory scenario planning to facilitate human–wildlife coexistence	DOI: 10.1111/cobi.13725
33	Jiren	2020	Reconciling food security and biodiversity conservation: participatory scenario planning in southwestern Ethiopia	https://doi.org/10.5751/ES-11681-250324
34	Kamei	2021	A Future Outlook of Narratives for the Built Environment in Japan	https://doi.org/10.3390/su13041653
35	Kankam	2021	Envisioning alternative futures of cultural ecosystem services supply in the coastal landscapes of Southwestern Ghana, West Africa	https://doi.org/10.1007/s42532-021-00090-7
36	Karner	2019	Developing stakeholder-driven scenarios on land sharing and land sparing – Insights from five European	https://doi.org/10.1016/j.jenvman.2019.03.050

			case studies	
37	Kebede	2018	Applying the global RCP–SSP–SPA scenario framework at sub-national scale: A multi-scale and participatory scenario approach	https://doi.org/10.1016/j.scitotenv.2018.03.368
38	Lacitignola	2007	Modelling socio-ecological tourism-based systems for sustainability	doi:10.1016/j.ecolmodel.2007.03.034
39	Langmead	2009	Recovery or decline of the northwestern Black Sea: A societal choice revealed by socio-ecological modelling	doi:10.1016/j.ecolmodel.2008.09.011
40	Le	2010	Land Use Dynamic Simulator (LUDAS): A multi-agent system model for simulating spatio-temporal dynamics of coupled human–landscape system 2. Scenario-based application for impact assessment of land-use policies	doi:10.1016/j.ecoinf.2010.02.001
41	Liu	2017	A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects	http://dx.doi.org/10.1016/j.landurbplan.2017.09.019
42	Malinga	2013	Using Participatory Scenario Planning to Identify Ecosystem Services in Changing Landscapes	http://dx.doi. org/10.5751/ES-05494-180410
43	Manuschevich	2019	Integrating socio-ecological dynamics into land use policy outcomes: A spatial scenario approach for native forest conservation in south-central Chile	https://doi.org/10.1016/j.landusepol.2019.01.042
44	Martinez-Fernandez	2021	An integral approach to address socio-ecological systems sustainability and their uncertainties	https://doi.org/10.1016/j.scitotenv.2020.144457
45	Martinez-Sastre	2017	Mediterranean landscapes under change: Combining social multicriteria evaluation and the ecosystem services framework for land use planning	http://dx.doi.org/10.1016/j.landusepol.2017.06.001
46	Merrie	2018	Radical ocean futures-scenario development using science fiction prototyping	http://dx.doi.org/10.1016/j.futures.2017.09.005
47	Mistry	2014	Our common future? Cross-scalar scenario analysis for social–ecological sustainability of the Guiana Shield, South America	http://dx.doi.org/doi:10.1016/j.envsci.2014.05.007

48	Mitchell	2015	Scenario analysis for biodiversity conservation: A socialeecological system approach in the Australian Alps	http://dx.doi.org/10.1016/j.jenvman.2014.11.013
49	Newell	2020b	Spaces, places and possibilities: A participatory approach for developing and using integrated models for community planning	http://dx.doi.org/10.1016/j.cacint.2020.100040
50	Norman	2012	Developing spatially explicit footprints of plausible land-use scenarios in the Santa Cruz Watershed, Arizona and Sonora	http://dx.doi.org/10.1016/j.landurbplan.2012.06.015
51	Onaindia	2015	Nature and human wellbeing in Biscay: Ecosystem Services Assessment; research applied to management	ISBN: 978-84-9082-207-4
52	Palacios-Agundez	2013	The Relevance of Local Participatory Scenario Planning for Ecosystem Management Policies in the Basque Country, Northern Spain	http://dx.doi.org/10.5751/ES-05619-180307
53	Palacios-Agundez	2015	Relevance for decision making of spatially explicit, participatory scenarios for ecosystem services in an area of a high current demand	http://dx.doi.org/10.1016/j.envsci.2015.07.002
54	Palomo	2011	Participatory Scenario Planning for Protected Areas Management under the Ecosystem Services Framework: the Doñana Social-Ecological System in Southwestern Spain	https://www.ecologyandsociety.org/vol16/iss1/art23/
55	Pereira	2018	Using futures methods to create transformative spaces: visions of a good Anthropocene in southern Africa	https://www.ecologyandsociety.org/vol23/iss1/art19/
56	Planque	2019	A participatory scenario method to explore the future of marine social-ecological systems	DOI: 10.1111/faf.12356
57	Plieninger	2013	Exploring Futures of Ecosystem Services in Cultural Landscapes through Participatory Scenario Development in the Swabian Alb, Germany	http://dx.doi.org/10.5751/ES-05802-180339
58	Poonacha	2018	Using transformative scenario planning to think critically about the future of water security in Bangalore	https://idl-bnc-idrc.dspacedirect.org/handle/10625/58619
59	Qui	2018	Scenarios reveal pathways to sustain future ecosystem services in an	https://www.jstor.org/stable/10.2307/26623131

			agricultural landscape	
60	Raudsepp-Hearne	2020	Seeds of good anthropocenes: developing sustainability scenarios for Northern Europe	https://doi.org/10.1007/s11625-019-00714-8
61	Ravera	2011	Envisioning Adaptive Strategies to Change: Participatory Scenarios for Agropastoral Semiarid Systems in Nicaragua	http://www.ecologyandsociety.org/vol16/iss1/art20/
62	Rawluk	2018	Value-based scenario planning: exploring multifaceted values in natural disaster planning and management	https://doi.org/10.5751/ES-10447-230402
63	Ruiz-Mallen	2015	Participatory scenarios to explore local adaptation to global change in biosphere reserves: Experiences from Bolivia and Mexico	http://dx.doi.org/10.1016/j.envsci.2015.07.027
64	Sahroui	2021	Integrating ecological networks modelling in a participatory approach for assessing impacts of planning scenarios on landscape connectivity	https://doi.org/10.1016/j.landurbplan.2021.104039
65	Saito	2019	Co-design of national-scale future scenarios in Japan to predict and assess natural capital and ecosystem services	https://doi.org/10.1007/s11625-018-0587-9
66	Sellberg	2020	Using local initiatives to envision sustainable and resilient food systems in the Stockholm city-region	https://doi.org/10.1016/j.gfs.2019.100334
67	Shoyama	2019	Development of land-use scenarios using vegetation inventories in Japan	https://doi.org/10.1007/s11625-018-0617-7
68	Song	2021	Adaptation and transformation planning for resilient social-ecological system in coastal wetland using spatial-temporal simulation	https://doi.org/10.1016/j.scitotenv.2021.148007
69	Termansen	2019	Modelling land use dynamics in socio-ecological systems: A case study in the UK uplands	http://pure.iiasa.ac.at/id/eprint/15844/
70	Thompson	2019	Spatial Simulation of Codesigned Land Cover Change Scenarios in New England: Alternative Futures and Their Consequences for Conservation Priorities	10.1029/2019EF001348
71	Zavalloni	2021	Farmland abandonment, public goods and the CAP in a marginal area of Italy	https://doi.org/10.1016/j.landusepol.2019.104365

72	Zia	2011	Cross-Scale Value Trade-Offs in Managing Social-Ecological Systems: The Politics of Scale in Ruaha National Park, Tanzania	https://www.jstor.org/stable/26268960

Appendix C

Comprehensive summary of boundary judgments

Boundary judgment		*Dimensions (innermost → outermost)*		
Purpose Overarching objective that determines the most important criterion for scenario evaluation	*Definition*	***Probable futures*** • Scenario probability as a key criterion (i.e., likely to happen, based on current trends (Voros 2017)) • Used for formal planning and strategy development (Muiderman et al. 2020) • Viewed as scientifically credible; based on historical data or expert probability judgments (Rounsevell and Metzger 2010)	***Plausible futures*** • Scenario plausibility as a key criterion (i.e., could happen based on existing knowledge (Voros 2017)) • Used to build up societal preparedness and capacity to navigate uncertainty (Peterson et al. 2003; Muiderman et al. 2020) • Scientific credibility maintained through evaluations of internal consistency or expert plausibility judgment (Schweizer and Kriegler 2012; Bhave et al. 2018)	***Possible/diverse futures*** • Scenario possibility and diversity as key criteria (i.e., might happen based on future knowledge (Voros 2017)) • Used to evaluate robustness to the widest scope of uncertainty (Lord et al. 2016) and/or to mobilize actors to co-create new futures (Bourgeois et al. 2017; Moore and Milkoreit 2020; Pereira et al. 2020a) • Trade-offs in reproducibility, perceived scientific credibility, and compatibility with other scientific processes

	Justification for placement	• Excludes conditions that are scientifically non-verifiable according to existing (historical) knowledge (Pereira et al. 2007; Wiek et al. 2013) • Excludes future SES conditions that are novel and/or for which there is no historical data ○ *e.g., may exclude the increasing the structural, dynamic, and functional complexity of 21st century systems and risks, which increases the potential disruption, nonlinearity, and surprise (Young et al. 2006; Brewer 2007; Liu et al. 2007; Helbing 2013; Centeno et al. 2015; Keys et al. 2019)* ○ *e.g., may exclude the novel ecological dynamics experienced as Earth systems are pushed past critical tipping points, producing emergent SES behavior (e.g., regime shifts (Rocha et al. 2015)* ○ *e.g., may exclude transformative change that emerges from innovative practices, ideas, and perspectives (Biggs et al. 2010; Bennett et al. 2016)*	• Includes non-verifiable future conditions as long as they can be evaluated as "occurable" according to plausibility metrics (Pereira et al. 2007; Wiek et al. 2013) • Includes *some* future SES conditions – including transformations – that are novel and/or for which there is no historical data (*see examples left*); still excludes conditions that are based on future knowledge (i.e., that cannot be deemed "occurable" based on existing knowledge) • Plausibility is undertheorized and contested (Schmidt-Scheele 2020); subjective plausibility judgments may still exclude "occurable" but counterintuitive phenomena	• Includes widest range of conditions due to explicit rejection of metrics of probability and plausibility • Includes future SES conditions that are novel and/or for which there is no historical or existing/present-day knowledge (*see examples left*) • Includes the widest scope of transformative conditions that deviate significantly from the present; e.g., those that emerge from experimental, creative techniques for modelling or imagining the future (Vervoort et al. 2015; Bendor et al. 2017; Merrie et al. 2018)
Normativity The degree to which the	*Definition*	***Neutral*** • Scenario process explores range of futures without considering	***Strategic*** • Scenarios consider desirable futures that are strategic; strong	***Visioning*** • Scenarios consider desirable futures that are primarily visions,

desirability of scenarios is considered		desirability ○ *E.g., to assess robustness (Brown et al. 2016) or whether desirable strategies are enabled or constrained by broader contexts (Bohensky et al. 2011)*	connection to near-term action ○ *e.g., to identify objectives and strategic pathways to achieve them, or to evaluate the implications of strategic options (Robinson 2003; IPBES 2016)*	without clear connection to near-term strategic ○ *E.g., focusing on imagination and creativity to inspire deliberate transformation (Wiek and Iwaniec 2014; Pereira et al. 2018a)*
	Justification for placement	• N/A (normative aspects of scenarios no explicitly considered; may be underrepresented or underdeveloped in the scenario set)	• Includes scenarios that are policy relevant and actionable; may favour incremental or adaptive actions and exclude longer-term, more radical changes that reflect transformative change (Iwaniec et al. 2020)	• Includes scenarios that are highly desirable and potentially imaginative; often framed to help change what people expect from the world and what they deem possible; i.e., to inspire and inform deliberate transformation (Bennett et al. 2016; Iwaniec et al. 2020; Moore and Milkoreit 2020) • Visions of a "good life" identified as a leverage point to positive societal transformation (Chan et al. 2020)
Epistemological lens The theory of knowledge that distinguishes what constitutes a valid belief and how multiple perspectives are integrated in the	*Definition*	***Positivist*** • Objectivity; expert-informed and model driven; scenarios attempt to reflect an objective reality (Vervoort et al. 2015; Carlsen et al. 2017) • Reflects the view of those advocating for more neutral, transparent approaches to scenario development (Carlsen et al. 2017)	***Critical realist*** • Consensus; integrative; scenarios incorporate multiple perspectives to gain an enriched understanding of the future (Bhaskar and Hartwig 2016; Cockburn 2022) • Reflects the view that all knowledge is eternally complete, but approximations of truth are required for action (Groff 2004;	***Constructivist, pluralist*** • Discord; knowledge about the future is subjective and constructed through experience (Moon and Blackman 2014) • Embraces multiple perspectives that cannot be reconciled by avoiding integration (Gregory 1996; Vervoort et al. 2015) • Reflects more of a critical-emancipatory lens on scenarios

scenario process		• Aligns with sustainability science roots in natural sciences, engineering (e.g., Holling 2001)	West et al. 2014; Preiser et al. 2022) • Aligns with the open, integrated, knowledge systems required to address complexity of 21st century sustainability challenges (Lang et al. 2012; Cornell et al. 2013; Bai et al. 2016; Verburg et al. 2016)	(Inayatullah 1998a; Scheele et al. 2018); i.e., "the future cannot be a source of freedom without a critique of dominant narratives" (Gugerli 2010)

	Justification for placement	• Only includes perspectives that can be evaluated as neutral and objective according to a single knowledge system; integration is avoided or discards any knowledge that is incommensurate with the dominant frame (Turnhout et al. 2019)
		  ○ *e.g., local or Indigenous knowledge considered important for understanding long-term change in SESs (Armitage et al. 2011; Lam et al. 2020a) but is rejected as "unscientific" (Martin 2012)*
		• May exclude important social considerations in understandings of SES change (e.g., subjective, political elements)
		  ○ *E.g., positivist SES frameworks criticized as*
			• Includes knowledge that can be evaluated according to the criteria of its own knowledge system; integration is consensus-based and focused on developing an enriched picture (Miller et al. 2008; Tengö et al. 2014)
			• Includes multiple understanding of SES change and multiple perspectives and interests in deliberate transformation (Bennett and Zurek 2006; Preiser et al. 2018; Cockburn 2022)
			• May exclude highly novel or discordant understandings of SES change and truly critical-emancipatory lens on transformation
			  ○ *i.e., the "integration imperative" of critical realism (Klenk and Meehan 2015; Cockburn 2022) does not explicitly address the*
				• Includes knowledge that can be evaluated according to the criteria of its own knowledge system; avoids integration entirely to emphasize pluralism and discordance (Vervoort et al. 2015)
				• Includes plural understanding of SES change and critical-emancipatory lens on both scenario practice (Inayatullah 1998a; Scheele et al. 2018) and transformation (Stirling 2014; Blythe et al. 2018)
				• May include more imaginative scenarios that could reflect more transformative changes from the present, which would be rejected under more strict evaluations of objectivity or consensus; e.g., using novel experimental methods (Mangnus et al. 2019; Pereira et al. 2021)

		oversimplifying social systems as a puzzle of "getting the rules right" (Olsson et al. 2015) and undervaluing socio-political factors that lead to divergent framings (Leach et al. 2010; Brown 2014; Stirling 2014) • Perpetuates a tendency toward top-down, command-and-control views of deliberate transformation; excludes bottom-up, critical-emancipatory views of deliberate transformation (Stirling 2014; Blythe et al. 2018)	*politics of integration; introduces risk that marginalized perspectives are reduced, instrumentalized, or coopted by more dominant perspectives (Ahenakew 2016; Turnhout et al. 2020) and highly novel or discordant framings are rejected (Vervoort et al. 2015; Turnhout et al. 2020)*	
Knowledge type The dominant form of knowledge included in the scenario process	*Definition*	***Scientific only*** • Scenario methodology only draws from formal, scientific knowledge (i.e., experts, models) • Results hold legitimacy in some more disciplinary academic and policy contexts (Verburg et al. 2016)	***Other*** • Scenario methodology only draws from other forms of knowledge (i.e., local, practitioner, experiential, Indigenous, traditional, etc.) • May encounter legitimacy challenges due to ongoing marginalization of certain knowledge systems (e.g., Indigenous, local) sustainability-related research (Ocholla 2007; Inoue and Moreira 2016)	***Multiple*** • Scenarios are purposefully, systematically informed by both scientific and other forms of knowledge (Tengö et al. 2014; Verburg et al. 2016; Falardeau et al. 2019) • Requires intentional integration processes to ensure integrity of different knowledge types are maintained (see *epistemological lens* boundary judgment)
	tion for placeme	• Includes a wide range of future SES conditions that can be scientifically studied and	• Includes a wide range of future SES conditions that are experienced and understood from	• Includes a wide range of future SES conditions that draw from the benefits of both scientific and

		modelled, particularly as sustainability science is increasingly systemic and integrative (Cash et al. 2003; Clark and Harley 2020)
		• May exclude highly complex, non-intuitive, and/or surprising SES dynamics
		  ○ *i.e., scientific knowledge has a legacy of reductionism, breaking it down into understandable parts (Holling et al. 2000); this tendency is limiting when addressing complex sustainability challenges that emerge from interdependencies across scales and disciplines* (Swart et al. 2004b; Miller et al. 2008; Tàbara and Chabay 2013; Cornell et al. 2013)
		• May exclude or underemphasize subjective, normative, and plural aspects of deliberate transformation (Blythe et al. 2018)
			various perspectives
			• Includes an alternative understanding of SES change, including transformation (Cornell et al. 2013; Lam et al. 2020a)
			  ○ *E.g., Indigenous knowledge was developed through experimentation and adaptation over long periods (Armitage et al. 2011; Tengö et al. 2014; Rathwell et al. 2015) and holds fundamentally different conceptions of time, progress, language, self, communication, and decision making (Jimmy et al. 2019)*
			  ○ *E.g., practitioner or local knowledge that is derived from integrative real-world experience (Cundill et al. 2005; Reed and Abernethy 2018)*
			• May include subjective, normative, and plural aspects of deliberate transformation that are experienced by different knowledge holders (Leach et al. 2010)
			• May exclude future conditions that can only be understood
				diverse other types of knowledge (Miller et al. 2008; Tengö et al. 2014)
				• Includes an enriched understanding of SES change, including related to transformation
				  ○ *E.g., scenario processes become sites for exposing complementarities and dissonances between knowledge types, surfacing new insights (Peterson et al. 2003; Bennett and Zurek 2006; Rathwell et al. 2015; Lam et al. 2020a)*
				  ○ *E.g., surfaces the different framings and expectations for the future of different actors associated with transformation (Stirling 2006; Leach et al. 2010)*
				• Introduces important risks and considerations associated with knowledge integration (see *epistemological lens* boundary judgment)

			through scientific processes and models	
Participation The nature and purpose of the inclusion of non-expert participants in the scenario process	*Definition*	***None*** • Only experts are included (no participation)	***Knowledge input*** • Non-expert participants are included to input knowledge into an expert-driven process (Moallemi et al. 2021)	***Engagement and learning*** • Higher degrees of participant as non-experts are embedded through the research process through scenario co-production and learning (Robinson 2003; Wilkinson and Eidinow 2008)
	Justification for placement	• Includes the knowledge, interests, values and perspectives held by experts; excludes those held by more diverse participants (Fazey et al. 2020) • Excludes SES changes not easily represented in expert-driven processes (Bennett et al. 2003; van Vuuren et al. 2012; Lord et al. 2016; Verburg et al. 2016); see *epistemological lens* and *knowledge type* boundary judgments for examples • Actors remain without any role in the development of scenarios that may be relevant to them (Arnstein 2019) • Limits the transformative potential of scenario process that could occur through participant learning (Pahl-Wostl et al. 2013; Pereira et al. 2018b)	• Enriches scenarios with diverse understandings and experiences with SES change; e.g., feedbacks and surprises not easily represented in data-intensive models (Bennett et al. 2003; van Vuuren et al. 2012; Lord et al. 2016; Verburg et al. 2016) • Excludes participants from ongoing reflection, iteration, and learning, so future conditions and val ues are limited to those considered relevant by experts (Reed et al. 2013; Moallemi et al. 2021) • May result in tokenism or instrumentalization of their perspective for the gain of experts (Arnstein 2019); can reinforce power dynamics if participant selection is done uncritically (Morgan 2014). • Limits transformative potential	• Enriches scenarios with diverse understandings and experiences of SES change • Facilitates learning and experimentation required to manage complex SES behavior (Armitage et al. 2009; Biggs et al. 2012) • Potentially facilitates transformative learning by challenging participants to question and deliberate about existing assumptions and paradigms about the future (Pahl-Wostl et al. 2013; Pereira et al. 2018b) • More power is delegated to participants through greater ownership of the scenario process (Arnstein 2019)

			of scenario process that could occur through participant learning (Pahl-Wostl et al. 2013; Pereira et al. 2018b)	
Formalization The degree to which input assumptions are quantified or codified into a formal structure or model in the scenario process	*Definition*	***High*** • Scenarios are highly formalized, meaning they are quantitative (i.e., usually in a model) • Highly formalized scenarios provide transparency and analytical rigour to underlying assumptions; ability to reproduce and validate system behavior improves (Moallemi et al. 2021)	***Low*** • Scenarios have a lower level of formalization, meaning they are qualitative (i.e., usually in narrative form) • Rely on broader conceptualisations and assumptions about system behavior and human agency; may be associated with higher uncertainty and lower granularity (Berkhout et al. 2002; Swart et al. 2004b; Carpenter et al. 2009; Moallemi et al. 2021)	***Combined*** • Scenarios combine both high and low levels of formalization, meaning they are hybrid and combine qualitative and quantitative

	Justification for placement	• Include future conditions that can be codified and modeled by the chosen method
		  ○ *E.g., future conditions that emerge from modelled social-ecological interactions and feedbacks*
		• Includes a higher level of granularity in the scenarios, but models become specialized and difficult to reconcile across other models and epistemologies (Gerst et al. 2014; Verburg et al.
			• Includes any future conditions that can be conceptualised qualitatively; may enrich scenarios with future conditions that are difficult to codify and model in formalized methods (*see examples left)*
			• May enable scenarios to consider more perspectives and a wider range of transformative future conditions
			  ○ *E.g., creative methods (e.g., experimental methods, art) are used to imagine*
				• Includes future conditions that can be understood using both qualitative and quantitative methods, thus enrich scenarios with the benefits of both (Verburg et al. 2016; Moallemi et al. 2021; Pereira et al. 2021)
				  ○ *e.g., using qualitative narrative scenarios to define inputs into expert-driven quantitative models (e.g., the Story-and-Simulation approach (Kok et al. 2006;*

		2016) • Excludes any future conditions that are incompatible with the codified language of the chosen method, and for which appropriate theory and data are unknown ○ *E.g., May exclude novel, wildcard, or "surprise" events due to bias toward computable, measurable, and testable aspects of a system (Carpenter et al. 2009)* ○ *E.g., may exclude complex, emergent (and difficult-to-model) properties of deliberate and unintended transformation (Rocha et al. 2015; Sharpe et al. 2016; Pereira et al. 2018b),* ○ *E.g., may exclude important social drivers of change that are difficult to quantify, yet are expected to dominate 21st-century change (Gerst et al. 2014)*	*transformation and facilitate transformative learning (Galafassi et al. 2018)* ○ *Certain types of knowledge (e.g., Indigenous knowledge) are incompatible with formalized models but enrich understanding of SES change and transformation (see knowledge type boundary judgment)* • Reliance on human intuition may exclude counter-intuitive and emergent conditions of complex SESs (Peterson et al. 2003; Ramirez and Wilkinson 2014; Bai et al. 2016)	*Alcamo 2008))* ○ *e.g., semi-quantitative scenario methods that develop narrative scenarios from a complex network of interacting drivers of change (Zwicky 1969; Weimer-Jehle 2006; Ritchey 2006; Lord et al. 2016)*
Drivers The dominant part of the	*Definition*	***Top-down (structural)*** • Scenarios characterize the future according to top-down drivers of	***Bottom-up (agency)*** • Scenarios characterize the future according to bottom-up change	***Cross-level*** • Scenarios characterize the future according to both top-down

system from which change is assumed to occur in the scenario process		change, which are outside of direct human control (Schwartz 1991; Lempert 2003)	and drivers that actors do have agency to control (Robinson 2003; Pereira et al. 2021)	(structural) and bottom-up (agency) change

	Justification for placement	• Characterizes the top-down drivers that influence SES change, including transformation
		  ○ *e.g., the boundary conditions of the system; characterizing critical uncertainties to inform efforts to build resilience (Peterson et al. 2003)*
		  ○ *E.g., changes to institutional structures that enable deliberate transformation (e.g., social networks, experimentation) or constrain it (e.g., rigidity); changes to the broader system that create windows of opportunity for transformation (Olsson et al. 2006; Gelcich et al. 2010; Sendzimir et al. 2010)*
		• Excludes the bottom-up processes that produce emergent outcomes in SESs
		  ○ *E.g., excludes how high-level SES behaviour emerges from lower-level social-ecological interactions (Levin et al. 2013; Reyers et al. 2018)*
			• Characterizes the bottom-up drivers that influence SES change, including transformation
			  ○ *E.g., reflects the view that high-level SES behavior emerges from bottom-up interconnectivity and self-organization (Levin et al. 2013; Reyers et al. 2018)*
			  ○ *E.g., may characterizes dynamics of deliberate and unintended transformation, such as when underlying, low-level drivers reach tipping points and allow novelty to scale (Moore et al. 2014; Rocha et al. 2015; Bennett et al. 2016; Filbee-Dexter et al. 2017)*
			• Focus on human agency reflects important social dimensions of SES related to transformation
			  ○ *E.g., agency creates change as innovative ideas, practices, etc. are nurtured to scale through individual leadership, institutional entrepreneurs, and the*
				• Enriches the scope of potential to reflect how both top-down and bottom-up drivers influence SES change
				  ○ *E.g., reflects the understanding that future change in SESs involves interacting drivers and feedbacks across various domains and levels* (Swart et al. 2004b)
				  ○ *E.g., reflects how deliberate transformation emerges from the interplay of structure and agency (Westley et al. 2011; Moore and Westley 2011)*

		○ *E.g., excludes the role of human agency, which interacts with the system structure to produce SES transformation (Westley et al. 2011; Moore and Westley 2011)* • Focus on top-down change may generate scenarios that are not rooted in the local realities for which they are meant to be applied (Pereira et al. 2021)	*exercise of transformative agency (Moore and Westley 2011; Westley et al. 2013; Lam et al. 2020b)* ○ *E.g., potential for more critical-emancipatory view on transformation; emphasis on how people exercise agency according to diverse assumptions and values (Leach et al. 2010; Blythe et al. 2018) and the role of social diversity and power in SES change (Fabinyi et al. 2014)* • An emphasis on bottom-up processes may generate aggregated scenarios rooted in local realities and practical action (Pereira et al. 2021) • Lack of constraining influence of top-down/structural conditions may not reflect real-world SES behavior; e.g., potential for SES to be trapped in a structure and resist transformation (Carpenter and Brock 2008; Chapin III et al. 2010)	
Social-ecological complexity	*Definition*	***Low*** • Scenarios reflect the view that scenario trajectories and their	***Moderate*** • Scenarios reflect the view that scenario trajectories are linear,	***High*** • Scenarios reflect the view that scenario trajectories are emergent

The degree of complexity (e.g., unpredictability, and emergence) that is assumed to influence change within the scenario process		social-ecological outcomes/impacts are linear and predictable • Reflects the view of 20th-century natural resource management in which ecosystems exist in one stable state and respond to human intervention in linear and controllable ways (Dietz et al. 2003; Westley et al. 2011; Reyers et al. 2018)	but their outcomes/impacts of emergent and difficult to predict; i.e., scenarios set the context in which complex SES behavior can be explored • Partially reflects the SES perspective on natural resource management, which sees human and natural systems as intimately linked, co-evolving systems (Levin et al. 2013; Folke et al. 2016; Biggs et al. 2022)	and difficult to predict; i.e., the scenarios themselves represent complex SES behaviour • Reflects the SES perspective on natural resource management, which sees human and natural systems as intimately linked, co-evolving systems (Levin et al. 2013; Preiser et al. 2018; Biggs et al. 2022)
	Justification for placement	• Includes clear, linear and predictable future conditions of an SES ○ *i.e., reflects the view that risk can be governed without reference to broader systemic connectivity or ecosystem limits* (Rockström et al. 2009a; Renn et al. 2011a; Westley et al. 2011; Helbing 2013) • Excludes the complex, emergent, and more unpredictable dynamics of complex SESs, particularly in the 21st century ○ *E.g., intertwined social-ecological interactions and feedback effects that produce emergent, and often counterintuitive outcomes*	• Scenario trajectories still include clear, linear, and predictable future conditions of an SES • Scenario trajectories exclude the complexity of SES change *(see examples left)*, in particular transformation *(see examples right)* • Scenario trajectories set a context in which the outcomes/impacts may consider the complexity of SES change (*see examples left)*	• Scenario trajectories may reflect the complexity of SES change (*see examples left)*, including the emergent and unpredictable nature of transformation ○ *i.e., SES behavior is emergent from complex social-ecological interactions and feedbacks (Levin et al. 2013); transformation creates new stability landscapes* (Olsson et al. 2004b; Walker et al. 2004) ○ *Transformative changes that are more likely to emerge in the presence of multiple interacting social and ecological drivers than individual drivers alone*

		(Helbing 2013; Moore et al. 2014; Bauch et al. 2016; Reyers et al. 2018) ○ *E.g., the increasing the structural, dynamic, and functional complexity of 21st century systems that increase the potential for disruption and surprise events (Young et al. 2006; Brewer 2007; Liu et al. 2007; Helbing 2013; Centeno et al. 2015; Keys et al. 2019)* ○ *E.g., assumption that a system has one single equilibrium excludes potential for transformation into new system equilibria; e.g., through regime shift or deliberate transformation* (Crépin et al. 2012; Moore et al. 2014; Rocha et al. 2015; Biggs et al. 2018; Tàbara et al. 2018)		*(Westley et al. 2011; Lade et al. 2013; Moore et al. 2014; Rocha et al. 2015)* ○ *Transformative trajectories are emergent and cannot be predetermined (Moore et al. 2014; Scoones 2016)*
Spatial scale The type of spatial dimension used to measure and study phenomena in	*Definition*	***Single, social/governance*** • Scenarios consider a single spatial scale that is compatible with the mode of social organization (i.e., governance scale, e.g., local or federal administration)	***Single, biophysical*** • Scenarios consider a single spatial scale that is compatible with the biophysical landscape (e.g., ecotone, river catchment, mountain range, etc.)	***Multi- or cross-scale*** • Scenarios explicitly link multiple spatial scales (e.g., local ←→ national; watershed ←→ global, etc.) • Multi-scale assessments focus on two or more scales without

the scenario process				systematically linking them, while cross-scale assessments foreground the interactions between them (Scholes et al. 2013); i.e., "loosely" or tightly" linked multi-scale scenarios (Biggs et al. 2007)
	Justification for placement	• Includes conditions compatible with the governance context (Epstein et al. 2015); potentially easier to link scenarios to policy relevance and action • Excludes important dynamics of SESs, including transformation ○ *E.g., ecological dynamics that fall outside of the governance boundary (Epstein et al. 2015)* ○ *E.g., the cross-scale interactions that produce emergent SES behavior; including dynamics of panarchy, e.g., how transformation at lower scales may maintain resilience at higher scales in the face of exogenous stress or shock behavior (Holling 2001; Allen et al. 2014)* ○ *E.g., the increasingly globally networked, cross-*	• Enriches scenarios with a wider scope of ecological dynamics (Epstein et al. 2015); which may be more compatible for capturing SES change • Excludes the cross-scale interactions that produce emergent SES behavior, including transformation (*see examples left)* • If biophysical boundary is compatible with the governance context, may resolve scale mismatches (i.e., when scale of environmental change and social organization are not aligned) to help ensure more of the important components of the system are included (Cumming et al. 2006; Folke et al. 2007) • If biophysical boundary is not compatible with a governance context, scenarios may be disconnected from policy processes and difficult to link to	• Reflects the knowledge that SESs are highly influenced by cross-scale dynamics, and that they are increasingly globally networked and tele-connected across scales (Liu et al. 2013; Verburg et al. 2016; Keys et al. 2019); (*see further examples left)* • Analysing cross-scale dynamics highlights important social dynamics of SESs (Chaffin and Gunderson 2016) • Present several challenges, including mismatches between social and biophysical scales, difficulty reconciling scenario drivers, loss of validity at alternative scales, and ambiguity regarding how scales are delineated (Cash et al. 2006; Biggs et al. 2007; Schweizer and Kurniawan 2016)

		scale linkages that define the unique characteristics of the 21st century (Renn et al. 2011b; Keys et al. 2019)) ○ *E.g., if scales are mismatched (i.e., when scale of environmental change and social organization are not aligned) important components of the system are lost (Cumming et al. 2006; Folke et al. 2007)* ○ *E.g., transformative changes (e.g., regime shifts) that emerge when cross-scale feedbacks that hold the system within its current state are altered, allowing the system to cross thresholds to other equilibria (Walker et al. 2004)*	action (Epstein et al. 2015); scale mismatches not resolved (Cumming et al. 2006; Folke et al. 2007)	
Temporal scale The length of the temporal duration used to measure and study phenomena in the scenario process	*Definition*	***Fast*** • Short-medium time scale (i.e., a few years to two decades)	***Slow*** • Long time scale (i.e., two decades or more)	***Linked*** • Linking fast and slow time scales • Can consider multiple discrete scales (i.e., loosely linked) or systemic interactions across scales (i.e., tightly linked) (Biggs et al. 2007; Scholes et al. 2013)
	cation for place	• Includes faster, shorter cycles of change in SESs	• Includes, slower, longer cycles of change in SESs; scenarios have	• Enriches the scope of future potential to consider the

		○ *E.g., political and management time scales, potentially facilitating the link to action (Elsawah et al. 2020)* ○ *E.g., short-term innovations and experimentation that may contribute to transformation if scaled to higher level systems* (Holling 2001; Westley et al. 2013; Bennett et al. 2016) • Excludes slower, longer cycles of change in SESs *(see examples right);* scenarios may not have time to diverge significantly from the present ○ *E.g., risk that scenario users to attribute the impacts of slow-changing, underlying drivers of SES change to faster-changing proximate drivers (Filbee-Dexter et al. 2017)*	time to diverge more significantly from the present ○ *E.g., may include the long-term preparation phase that precedes a sudden transformation triggered by a crisis* (Olsson et al. 2004b; Elsawah et al. 2020) ○ *E.g., include the time-lagged ecosystem responses (Adrian et al. 2012) and slow variables and feedbacks in SESs* (*Biggs et al. 2012)* ○ *E.g., may include slow-changing ecological drivers that may trigger regime shifts (Ellis 2015; Filbee-Dexter et al. 2017; Biggs et al. 2018)* • Excludes faster, shorter cycles of change in SESs; may underemphasize the role of novelty and experimentation *(see examples left)*	complexity of SES change, including cross-scale interactions (Holling 2001; Falkenmark et al. 2019b) • Tightly linked temporal scales (Biggs et al. 2007) in particular reflect SES dynamics ○ *e.g., how fast cycles of change in the panarchy framework can revolt and influence slower cycles, and how the accumulated memory of slower scales can enable or inhibit these faster scales (Holling 2001; Walker et al. 2006; Reyers et al. 2018)* • Challenging due to incomparable data and results at different scales and the potential loss of scientific credibility when translating one scale to another (Döll et al. 2002; Biggs et al. 2007)

Appendix D

Coding of 72 case studies for each boundary judgment

Lead author	Purpose			Score	Rationale
	Probable futures (1)	Plausible futures (2)	Diverse futures (3)		
Allan		x		2	Explorative scenarios of socio-economic and biophysical elements related to coastal livelihoods in Bangladesh
Andreotti		x		2	Explorative scenarios of agroforestry management strategies using participatory forecasting and backcasting, including serious games and future visioning
Baggio		x		2	Plausible future scenarios based on changes in resource abundance or distribution, shifts in cultural practices, and key productive households
Bennett		x		2	Community-based scenarios considering socio-economic and biophysical change/stressors; enrich vulnerability analysis and adaptation planning in a coastal community
Bohensky (a)		x		2	Explorative scenarios reflecting how key uncertainties influence threats (climate change, local/regional pressures) and their impact on the Great Barrier Reef and adjacent catchments
Bohensky (b)		x		2	Explorative scenarios for Milne Bay Province, Papua New Guinea's nascent ecotourism industry, focused on climate change and technology
Bohnet		x		2	Explorative stakeholder-driven scenarios exploring future land use planning in case studies in the Wet Tropics
Booth		x		2	Develops spatiotemporally explicit biophysical inputs consistent with the qualitative scenarios in Carpenter et al. (2015) study of Yahara Watershed
Brown		x		2	Explorative scenario narratives to synthesize knowledge types and define adaptation responses that are robust across multiple futures.
Bruley		x		2	Explore a desirable vision for ecosystem-based adaptation and strategies/levers for achieving it in a mountain SES in the

					French Alps
Brunner		x		2	Explorative scenarios of global change used to model and evaluate an indicator for resilience
Bush		x		2	Explore two scenarios considered as possible ends of a spectrum of sustainable shrimp aquaculture approaches.
Butler			x	3	Stakeholder-driven visioning and explorative scenario development for livelihoods in 2090; used back-casting to design "no-regrets" strategies to achieve the vision under explorative scenarios; adopted a reflexive interventionist approach to incorporate perceptions of livelihoods/adaptation.
Carpenter		x		2	Explore plausible trajectories of the Yahara Watershed to 2070 under different regimes.
Daconto		x		2	Stakeholder-driven explorative scenarios exploring plausible future evolutions of Khumbu and the associated tourism industry in Sagarmatha National Park and Buffer Zone, a mountain-protected area in Nepal.
Dada		x		2	Plausible 21st-century coastal systems scenarios to test how these contribute to new long-term pressures and short-term pulse dynamics on west African coastal systems.
de Chazal		x		2	Propose a new method for analyzing SES vulnerability explicitly by linking value-based judgments of ecosystem services to scenario-based ecosystem change stimulus. Ecosystem properties are then linked to scenario projections.
Enfors		x		2	Explorative scenarios to analyze four alternative development trajectories for a smallholder farming community in semi-arid Tanzania; contribute to increasing the robustness of current investments in small-scale water system technologies.
Franklin		x		2	Use explorative scenarios of key ecological, social, and policy changes on a system dynamics model of a social-ecological system of Kenai Fisheries.
Fredstrom			x	3	Develop local, context-specific climate change scenarios; aimed to analyze and challenge assumptions that surface in a way that aims to contribute to transformative change.
Garteizgogeas		x		2	Develop exploratory scenarios to deepen

coa					the understanding of dynamics shaping the Humboldt Current Upwelling System, a marine SES, and refine and enrich general marine ecosystem visions on a regional scale
Gaube		x		2	Uses explorative scenarios of changes to external framework conditions to analyze outcomes of an agent-based model
Gibon		x		2	Uses an integrated understanding of a local landscape as an SES to build an ABM/LUCC that projects plausible behavior of the system under a range of alternative scenarios, focusing on colonization by ash (Fraxinus excelsior) in an agricultural landscape in the Pyrenees National Park area (France)
Gourguet		x		2	Used perturbation scenarios to assess the response of a system model of shellfish aquaculture in the Normand-Breton Gulf in France; findings used to identify actions that may improve the sustainability of shellfish aquaculture.
Gray		x		2	Explore current and projected equilibrium states and their relationship to desired/undesired state outcomes under different pressures and management.
Hanspach		x		2	Explore how current development trends may be amplified or dampened in the future in southern Transylvania, based on assessments of social conditions and natural capital bundles, SES dynamics, and current development trends.
Harmáčková		x		2	Develop values-based participatory scenarios that consider multiple values, actions by different types of stakeholders, and their potential impacts on people in protected areas in Czechia; using a combination of Life Framework of Values and Three Horizons opens up futures.
Hashimoto		x		2	Explore the implications of alternative development pathways on land use, biodiversity, and ecosystem services; highlighting the role of a rapidly declining population in rural Japan
Henriques		x		2	Elaborated existing management scenarios for water management challenges in England and Wales, using DPSIR to identify drivers, interdependencies, and influence on system dynamics.
Huber		x		2	Projects water supply and demand under six

					explorative socioeconomic/climate scenarios; uses the language of prediction rather than projection/plausibility.
Iwaniec			x	3	Co-develop positive and long-term alternative future visions in the Central Arizona-Pheonix Long-term Ecological Research site; explicitly aim to open up the solution space to incorporate diverse perspectives and question the limits of what is normally considered possible/desirable/inevitable.
Jiren (a)		x		2	Developed explorative scenarios for the future of human-wildlife coexistence in the Zambezi region of Namibia based on stakeholder engagement.
Jiren (b)		x		2	Engaged with drivers of SE change and possible development trajectories for a rural landscape in southwestern Ethiopia, and how these scenarios influence food security and biodiversity conservation.
Kamei		x		2	Develop narrative scenarios for Japan's built environment that are consistent with the shared socio-economic pathways.
Kankam		x		2	Explore the supply of cultural ecosystem services under different land use planning scenarios in southwestern Ghana.
Karner		x		2	Develop regional land use scenarios reflecting land sharing, land sparing, and more intermediate developments for five different European landscapes.
Kebede		x		2	Combined the global RCP, SSP, and SPA scenario framework to explore climate mitigation and adaptation options in three deltas in West Africa and South Asia.
Lacitignola		x		2	Develop a minimally descriptive model of a tourism destination in southern Italy and tested the model against different scenarios related to the coexistence of different tourism classes and equilibria stability.
Langmead		x		2	Modeled the effects of four explorative future development scenarios on the marine environment of the northwestern Black Sea Shelf.
Le		x		2	Uses the Land Use Dynamics Simulator framework to assess the relative impacts of policy interventions (i.e., the widest plausible range of options for a given policy) of a mountain watershed in central Vietnam.
Liu	x			1	Propose a future land use simulation model

					to simulate long-term spatial trajectories of multiple land use cover changes; demonstrated in China.
Malinga		x		2	Developed explorative scenarios of social-ecological changes in an agricultural landscape in South Africa, from which ecosystem services can be identified.
Manuschevich		x		2	Explore the consequences of three conservation and land use scenarios for native forest conservation in Chile.
Martinez-Fernandez		x		2	Used scenarios as one (relatively small) part of an integrated methodological framework for SES assessment; scenarios used to represent exogenous drivers and test system's vulnerability; demonstrated in the Canary Islands in Spain.
Martinez-Sastre		x		2	Assessed future scenarios under different drivers of land use change, including analyzing how changes impact people and their access to ecosystem services in the Sierra Morena mountain range in Spain; uses the language of likelihood (i.e., probability) but develops explorative scenarios.
Merrie			x	3	Uses science fiction prototyping to develop scenarios for the future of global fisheries in a changing ocean. Study explicitly using novel methods to loosen cognitive restrictions
Mistry		x		2	Develops context-specific futures for an SES in Guyana to evaluate whether indigenous strategies to respond to environmental challenges are "future-proof".
Mitchell		x		2	Evaluates governance possibilities against different context scenarios in the Australian Alps.
Newell		x		2	Developed scenarios of different community development patterns for Squamish, British Columbia, Canada; implications of community development explored within an integrated assessment model.
Norman		x		2	Envision and evaluate plausible future scenarios of land use change to the year 2050 in the Santa Cruz Watershed (Arizona), and use these scenarios to develop spatially explicit footprints of land use change under these scenarios.
Onaindia		x		2	Scenarios explored current and future

					changes to ecosystem services and the associated influence on human wellbeing in Biscay.
Palacios-Agundez		x		2	Describe plausible scenarios for 2050 in Biscay that analyze how ecosystem services and human wellbeing may change.
Palacios-Agundez		x		2	Scenarios explored the plausibility of scenarios developed by Onaindia et al. (2015) by modeling them within a spatially explicit model.
Palomo		x		2	Used participatory scenario planning to explore social perceptions about conditions, trends, trade-offs, and future ecosystem services and wellbeing in the Doñana social-ecological system and its protected areas in southwestern Spain.
Pereira			x	3	Scenarios used to envision radical transformations toward sustainable futures in southern Africa, explicitly to create transformative spaces.
Planque			x	3	Aimed to develop explorative scenarios for a marine SES based on contrasting 'perspectives' and then incorporate them into common multiperspective scenarios; explicit aim to produce a broad range of contrasting futures and to enable deliberation.
Plieninger		x		3	Assess the possible future drivers of cultural landscape changes and their likely impacts on ecosystem services provision as perceived by local actors in a biosphere reserve in southern Germany.
Poonacha		x		2	Use a participatory "transformative scenario planning" process to develop explorative scenarios for Bangalore.
Qui		x		2	Simulated ecosystem service changes under four contrasting narrative scenarios depicting the future of the Yahara Watershed by Carpenter et al. (2015).
Raudsepp-Hearne			x	3	Develop scenarios depicting plausible sustainability transitions; use the Manoa mashup from Pereira et al., which opens up futures.
Ravera		x		2	Develop explorative scenarios to evaluate livelihood vulnerability in a semiarid agropastoral system in Nicaragua, including how it has been affected by multiple drivers over time, and identify policy options.
Rawluk		x		3	Introduce an approach for developing plausible values-based scenarios applied to

					bushfire management in Australia.
Ruiz-Mallen		x		2	Develop four plausible scenarios for climatic, policy, and socio-economic horizons to 2030 in Bolivia and Mexico; use these to explore desired adaptation options of rural communities in each country.
Sahroui		x		2	Evaluates impacts of land use planning scenarios on landscape connectivity using combined ecological network modeling with a participatory approach in the metropolitan region of Bordeaux.
Saito		x		2	Develops national-scale future scenarios exploring changes in natural capital, ecosystem services, and human well-being in Japan.
Sellberg			x	3	Explored a transformed sustainable food system in the Stockholm city-region in Sweden.
Shoyama		x		2	Evaluate changes in land use land cover on biodiversity and ecosystem services in Japan.
Song	x			1	Predict land use changes through a spatial-temporal evaluation model and use results to establish adaptation/transformation plans for a coastal wetland in South Korea.
Termansen		x		2	Project how land use may change under different environmental/policy scenarios in the UK Uplands, and evaluate the impact of land use change on landscape vegetation patterns.
Thompson		x		2	Use four divergent narrative scenarios to describe changes to land use in New England; translate scenarios into spatial simulations.
Zavalloni		x		2	Assess land use, public goods, and welfare consequences from agricultural production from three alternative scenarios (e.g., 1 - land use allocation driven by maximization of agricultural income).
Zia		x		2	Explore implications of management scenarios for Ruaha National Park in Tanzania.

Lead author	Scope of normativity			Score	Rationale
	Non-normative (1)	Strategic, backcasting (2)	Imaginative, visioning (3)		
Allan	x			1	Scenarios were exploratory only. Used to inform policy implications at the end of the scenario process
Andreotti		x		2	Used participatory games and workshops to conduct a backcasting process. Visions simply guided the backcasting process and focused on landscape change; were not explicitly imaginative.
Baggio	x			1	Exploratory scenarios only (i.e., the interaction of changing resource abundance, shifting cultural practices, loss of key productive households)
Bennett		x		2	Indicated the 'controllability' of different explorative drivers of change. Envisioned possible and plausible futures, including one desirable scenario. Discussed actions to adapt to change and achieve the desired future.
Bohensky (a)	x			1	Exploratory scenarios only.
Bohensky (b)	x			1	Exploratory scenarios only. Focused on uncertainties affecting the possibility to sustain ecotourism in the future.
Bohnet			x	3	Elicited desirable visions, depicted visually to inform discussions, and used those normative visions as inputs into a mapping process.
Booth	x			1	Quantitative simulation of exploratory qualitative scenarios.
Brown	x			1	Exploratory scenarios are used to evaluate policy robustness.
Bruley		x		2	Stakeholders envisioned one desirable future. The study focused on backcasting to achieve that vision.
Brunner		x		2	Developed explorative scenarios of global change (non-normative) combined with policy strategies with combinations of different interventions; evaluated for changes to ecosystem services local residents value.
Bush	x			1	Scenarios are exploratory only.
Butler			x	3	Combined explorative scenarios for livelihoods, aspirational visioning, and normative backcasting.

Carpenter	x			1	Process focused on exploratory scenarios that included both desirable and undesirable outcomes.
Daconto		x		2	Exploratory scenarios included strategies (controllable drivers of change), though these were integrated with uncontrollable drivers in the scenarios.
Dada	x			1	Scenarios are exploratory and only focused on analyzing the implications of long-term (press) and short-term (pulse) dynamics.
de Chazal	x			1	Develop scenarios that focus on the ecosystem services valued by stakeholders, but the scenarios themselves are non-normative.
Enfors	x			1	Scenarios are exploratory, helping evaluate the robustness of small-scale water system technologies to future change.
Franklin	x			1	Scenarios were exploratory only, elicited from critical uncertainties.
Fredstrom			x	3	The study encouraged imagination, though results were both desirable and undesirable. E.g., workshops began with writing news headlines about futures that are frightening, exciting, etc.
Garteizgogeascoa	x			1	Scenarios were exploratory, focusing on key uncertainties and their implications.
Gaube	x			1	Explorative scenarios are primarily non-normative.
Gibon		x		2	Used scenarios of alternative future policies to evaluate outcomes on the local landscape.
Gourguet	x			1	Explorative scenarios are non-normative; used to identify actions to improve sustainability.
Gray	x			1	Scenarios are exploratory (multiple stable states for the SES). Analyzed later for desirability.
Hanspach	x			1	Scenarios are exploratory only.
Harmáčková		x		2	The process was value-based and participants envisioned future impacts, but scenarios were primarily non-normative. Three Horizons Framework discussion focused on pathways to achieve "balance" as a desirable state.
Hashimoto	x			1	Exploratory scenarios of alternative development pathways; non-normative
Henriques	x			1	Scenarios are exploratory.

Huber	x			1	Scenarios are exploratory only. Scenarios consider water supply and demand as influenced by socio-economic trajectories and climate change scenarios.
Iwaniec			x	3	Scenarios are informed by the 'Sustainable Future Scenarios' framework, which combines strategic, adaptive, and transformative scenario logics.
Jiren	x			1	Scenarios are non-normative, derived from causal loop diagrams and critical uncertainties that generated scenario narratives.
Jiren	x			1	The scenario process focused on exploratory scenarios; used to motivate a discussion about moving toward desirable future trajectories.
Kamei	x			1	Scenarios are non-normative scenarios for the future of the built environment in Japan that are consistent with shared socio-economic pathways
Kankam	x			1	Focused on exploratory scenarios; depicting the potential increase in the relevant supply of cultural ecosystem services under possible land use land change scenarios
Karner		x		2	Scenarios are exploratory, focusing on different land use options in the context of global scenarios. Stakeholders discuss the desirability of scenarios after they are generated.
Kebede		x		2	Scenarios focused on adaptation policy trajectories under different socio-economic trajectories.
Lacitignola	x			1	Scenarios generated from a model that explores interactions between the type of tourism and ecosystem quality.
Langmead	x			1	Scenarios focused on bayesian relief network modeling; quantifying causal relationships of alternative development pathways (not strategic; assumed target audience of scenarios has no control over development)
Le		x		2	Scenarios evaluate the implications of various strategic policy options.
Liu	x			1	Scenarios explore long-term land use land cover change scenarios and simulate four development trajectories that consider socio-economic and climatic factors.
Malinga	x			1	The scenarios were exploratory, focusing on changes that impact people and ecosystem services in the future.

Manuschevich		x		2	Analyzed both desirable and undesirable scenarios; comparing business-as-usual with different policy approaches to land use and conservation
Martinez-Fernandez		x		2	Process explicitly framed around strategic sustainability goals, strategic questions, and indicators
Martinez-Sastre	x			1	Developed non-normative plausible scenarios of landscape configurations and socioeconomic trajectories, then evaluated desirability and preferences among stakeholders for different land use configurations
Merrie	x			1	Ocean futures were explorative; one scenario identified as "most normatively positive" in the discussion
Mistry		x		2	Scenarios non-normative; used to test strategies for whether they were 'future proof'.
Mitchell	x			1	Scenarios are exploratory, focusing on both biophysical, social, and governance drivers
Newell		x		2	Baseline and community development scenarios represented future conditions if all existing strategic plans were approved (residential and commercial developments)
Norman	x			1	Scenarios are exploratory; evaluating plausible land use scenarios to 2050.
Onaindia	x			1	Scenarios themselves are non-normative; used to facilitate discussions about the 'positive' and 'negative' elements of the explorative scenarios.
Palacios-Agundez		x		2	Combined exploratory scenarios with a backcasting process that generated management strategies.
Palacios-Agundez		x		2	Used non-normative explorative scenarios to analyze the sustainability of policy options.
Palomo		x		2	Backcasting process is used to propose management strategies to achieve a desirable future
Pereira			x	3	Aim to envision positive narratives for the future in southern Africa; explicitly used creative experimental techniques to create a transformative space
Planque	x			1	Scenarios include desirable and undesirable aspects of the future; different 'perspectives' do not represent visions of a desirable future but rather different views on how the marine SES works

Plieninger	x			1	Explorative scenarios describe both positive and negative future outcomes from cultural landscape change
Poonacha			x	3	Included a visioning process and strategic identification of key actions to achieve it.
Qui	x			1	Quantitative simulation of exploratory qualitative scenarios.
Raudsepp-Hearne			x	3	Focuses primarily on envisioning desirable futures, and also focuses on actions moving toward those futures.
Ravera			x	3	Combined envisioned desirable futures, explorative climate scenarios, and backcasting strategic scenarios.
Rawluk	x			1	Scenarios are non-normative, developed from contrasting values in a 2x2 matrix.
Ruiz-Mallen		x		2	Combined non-normative explorative scenarios with backcasting to move toward more 'desirable' scenarios.
Sahroui			x	3	Combined several approaches to develop strategic (realistic) and transformative (ideal-realistic) scenarios and explore desirable outcomes from visioning.
Saito	x			1	Scenarios are explorative, considering key indirect and direct drivers of change that are non-normative.
Sellberg			x	3	Envisioned novel transformed food futures and pathways; included discussion about conflicts and opportunities for moving towards the envisioned future.
Shoyama	x			1	Land use simulations were based on non-normative explorative scenarios.
Song		x		2	Scenarios analyze land use change and fragmentation of wetlands under different socio-economic and policy trajectories.
Termansen		x		2	Scenarios explore land use change under different policy and environmental scenarios.
Thompson	x			1	Scenarios were exploratory land use change only, translated to spatial simulations.
Zavalloni		x		2	Analyze land use, public goods, and welfare outcomes from various policy approaches (e.g., land use allocation based on the maximization of agricultural income versus societal welfare).
Zia		x		2	Evaluates different management scenarios against several criteria (economic welfare, good governance, etc.)

Lead author	Epistemological lens			Score	Rationale
	Positivist, objective (1)	Critical realist, consensus (2)	Pluralistic, discord (3)		
Allan		x		2	Downscaled SSPs, translated to narrative scenarios and then quantified. Assumed one common set of scenarios validated by stakeholders.
Andreotti		x		2	Incorporated various perspectives and knowledge systems, ultimately aiming to achieve consensus regarding the desired vision and pathway to achieving it
Baggio	x			1	Focused on hypothesis testing and mathematical modeling.
Bennett		x		2	Developed a common set of scenarios through a participatory process. Not explicit about how knowledge was validated through the process.
Bohensky (a)		x		2	Scenarios were developed by combining different sources of data and perspectives of academic and non-academic sources. Discussed how broad participation improves credibility, salience, and legitimacy.
Bohensky (b)		x		2	One common set of scenarios is used explicitly to build consensus, though authors acknowledge that a diversity of perspectives is desirable.
Bohnet		x		2	Includes diverse perspectives and values (e.g., 2 distinct visions of a desirable future) yet also aims for integration and shared goals. Also reflects these as quantitative measures for analysis in disciplinary models.
Booth		x		2	Biophysical modeling reflects a positivist perspective; though informed by qualitative scenarios that served as inputs to the study (Carpenter et al).
Brown			x	3	The process allowed for diverse ways of engaging and learning about the future; attempted to adopt a reflexive approach
Bruley		x		2	The process drew from participant preferences and perspectives to generate a common scenario set.
Brunner	x			1	Use of integrated assessment models validated against traditional scientific metrics.
Bush	x			1	Discussion of resilience, uncertainty, and risk-oriented toward positivism.
Butler			x	3	Explicitly adopts a reflexive approach, surfacing multiple actor perspectives and

					values.
Carpenter		x		2	Discussion about 'provocative' scenarios and multiple perspectives reflects some degree of pluralism, though focus on 'combining' perspectives and ensuring they are consistent with scientific knowledge reflects critical realism
Daconto		x		2	The participatory process allowed groups to arrive at a consensus on focal questions
Dada		x		2	Combined an SES framework with various forms of data to develop and test scenarios; embracing different perspectives but ultimately developing a common set of scenarios
de Chazal			x	3	Used multiple stakeholder values to enable multiple assessments of vulnerability in the same or different locations
Enfors		x		2	Comparison of participants' contributions to scientific knowledge reflects critical realism and consensus-oriented lens
Franklin		x		2	The approach to developing and analyzing the agent-based model reflects a more positivist stance, but scenario development based on stakeholder workshops that elicit key system drivers reflects more critical realism
Fredstrom			x	3	Used critical futures methods to try to open up the scenario process to transformative change
Garteizgogeascoa		x		2	Process collected diverse views of the future; scenarios developed from most common drivers and respective narratives
Gaube		x		2	Stakeholder and expert involvement ensured validity; comment that they were not able to validate data on historical trends due to lack of data
Gibon		x		2	Combining and applying diverse methods to understand interactions and feedbacks in a local landscape/land-use system
Gourguet		x		2	Process elicited diverse stakeholder views, which were reconciled into a conciliated view of the system
Gray		x		2	FCM model is used to collect and "standardize" the perceptions of diverse stakeholders; used to aggregate and encode perspectives into one representation of shared knowledge
Hanspach		x		2	Combined multiple forms of knowledge and perspective into an integrative causal loop

					diagram; combined previous stages to map perceived trends for each village
Harmáčková			x	3	Used the Life Framework of Values and Three Horizons to co-create pathways explicitly rooted in multiple actor values and perspectives
Hashimoto	x			1	The analysis focused on simulation models; validated according to historical data.
Henriques		x		2	Scenarios developed through stakeholder workshops; validated by experts with diverse backgrounds
Huber		x		2	Participatory scenario development and simulation modeling verified scenario plausibility; stakeholder dialogues and diverse perspectives are considered important for a shared understanding
Iwaniec		x		2	Scenarios incorporate diverse perspectives in co-producing future visions, yet also building consensus around the desired future; process oriented to broadening the limits of what is possible
Jiren		x		2	While the process allowed for disagreement among participants (e.g., about preferred scenario), scenario development itself assumed one common set of scenarios
Jiren		x		2	Participatory scenario development, use of causal loop diagrams, narratives, and other methods; validated through stakeholder workshops
Kamei	x			1	Drew primarily from literature, trend analyses, etc. from scientific studies. Expert panel to validate.
Kankam			x	3	Study was framed around expectations that stakeholders would have divergent perceptions of - and preferences for - land use systems. Some indication of a 'consensus-based' approach where stakeholders had to agree on narratives, but narratives themselves incorporate divergent views.
Karner		x		2	Combining stakeholder knowledge with biophysical data into one set of scenarios.
Kebede		x		2	Combine stakeholder-expert perspectives; collaborative development, testing, and validation of scenarios; integrating multiple perspectives
Lacitignola	x			1	The simulation model aimed to be as 'realistic' as possible
Langmead		x		2	A multidisciplinary approach was used to model development; historical data was used

					to validate model performance where possible
Le	x			1	Focuses on scientific experimentation and modeling to characterize system behavior
Liu	x			1	Simulation model
Malinga		x		2	Embraces pluralist perspective to some extent by focusing on diverse perspectives and stakeholders, though ultimately aims to build consensus for one set of scenarios
Manuschevich	x			1	Focused on scientific data for modeling land use and other indicators under different scenarios
Martinez-Fernandez		x		2	Explicitly encourage co-production of knowledge that brings together academic and non-academic perspectives to obtain the "best available" knowledge for each case. These are said to contribute to deliberative processes and help with decision-making.
Martinez-Sastre		x		2	Involve local stakeholders in aspects of the scenario assessment, in addition to simulation models. Validated during a stakeholder workshop.
Merrie		x		2	Drew from diverse sources of data including technology trends, marine/natural sciences, fisheries science, etc.; aimed to generate a high degree of content credibility
Mistry		x		2	The approach aims to draw explicitly from multiple types of knowledge. Framing of the process of scenario development as a tool for 'consensus-building'.
Mitchell		x		2	Participatory process bringing together different perspectives to generate one common framework for scenarios; validated by participants
Newell		x		2	The approach draws from community participants' knowledge, which is then modeled and refined based on feedback.
Norman	x			1	Scientific modeling
Onaindia		x		2	Scenarios developed primarily through participatory methods, no evidence of evaluation against metrics; validated participatory process against landscape outcomes (consensus)
Palacios-Agundez		x		2	Participatory methods focused on consensus among perspectives (e.g., choosing most relevant drivers)
Palacios-Agundez		x		2	Scenario mapping was used to test the credibility and internal consistency of the scenarios; iterative feedback from

					stakeholders was used to improve the quality of the scenarios
Palomo			x	3	Process explicitly focused on divergent visions, but then ultimately wanted consensual management strategies
Pereira			x	3	Uses diversity to push boundaries; focuses on 'radically different' scenarios and visions of a good Anthropocene; explicitly described as experimental
Planque		x		2	Scenarios developed from multiple perspectives; integrated into the final stages of the process but explicitly called "multi-perspective" scenarios
Plieninger		x		2	Drew from local actor perspectives to develop scenarios; used credibility/dependability criteria that relied on consensus among participants
Poonacha		x		2	Participatory scenario development; relied on consensus to determine key drivers; aimed to promote shared understanding
Qui		x		2	Scientific modeling of participant knowledge
Raudsepp-Hearne		x		2	Epistemological lens not explicit; seeds method aimed to explore transformative futures; represent diverse perspectives
Ravera		x		2	Triangulated a range of information including scientific and participatory research
Rawluk			x	3	Scenarios rooted in different value systems; represent different - and divergent - perspectives on the future
Ruiz-Mallen		x		2	Participatory method; validated by stakeholders
Sahroui		x		2	Companion modeling approach; scientists and stakeholders co-constructed together; stakeholders involved for ever step of model validation
Saito		x		2	Agreement among survey participants in the Delphi method used for validation
Sellberg			x	3	Participatory method; validated by participants; methodological choices made to maximize diversity; focused on conflicts and tensions
Shoyama	x			1	The simulation model validated against historical data
Song	x			1	The simulation model validated against historical data
Termansen	x			1	Scientific modeling; combine methods explicitly to improve validation
Thompson		x		2	Epistemological lens not explicit. Used

					participatory scenarios as inputs into land use land cover change simulations
Zavalloni		x		2	The simulation model developed through a participatory approach; concerned with validation
Zia			x	3	Methodology explicitly aims to demonstrate variability across stakeholder values under different management scenarios

Lead author	Formalization			Score	Rationale
	High (1)	Low (2)	Linked, high & low (3)		
Allan			x	2	Story-and-simulation approach
Andreotti		x		2	Serious games to explore farmer decision processes and participatory backcasting
Baggio	x			1	Network modeling
Bennett		x		2	Qualitative narrative scenarios; group drawing and storytelling exercises
Bohensky			x	3	Used formalized ecohydrology model to estimate qualitative changes to ecosystem services and well-being under 4 qualitative scenarios
Bohensky		x		2	Focused on the participatory development of narrative scenarios
Bohnet			x	3	Used participant visions of a desirable future as inputs into land simulation models
Booth			x	3	Introduces a new, transparent method for developing spatiotemporally explicit biophysical models consistent with qualitative scenario narratives
Brown		x		2	Focused on qualitative participatory scenarios for social learning
Bruley		x		2	Participatory process including serious games to identify adaptation objectives; supplemented by a qualitative analysis to identify NCA (nature's contributions to adaptation) solutions
Brunner	x			1	Quantitative modeling of priority ecosystem services under various global change outcomes
Bush		x		2	Scenarios are narrative descriptions of possible strategies
Butler		x		2	Qualitative analysis of drivers of change, drivers of change, and explorative scenarios; backcasting as well
Carpenter			x	3	Narrative scenarios fed into quantitative time series of weather, land use cover, etc.
Daconto		x		2	Narrative scenarios from participatory mapping exercises, etc.
Dada		x		2	Qualitative description of 3 scenarios; evaluated against more rigorous (but still qualitative) SES framework
de Chazal			x	3	Social and ecological drivers linked through semi-quantitative matrices
Enfors		x		2	Focused on developing narrative scenarios of agroecological conditions, livelihood sources, and lifestyles

Franklin			x	3	Linked stakeholder-driven narrative scenarios to ABM
Fredstrom		x		2	Manoa method and causal layered analysis are both qualitative methods
Garteizgogeascoa		x		2	Exploring futures through the use of narratives
Gaube			x	3	Translated social goals and visions from a participatory approach into scientific categories and formalized modeling language
Gibon	X			1	ABM of land use cover change simulations
Gourguet		x		2	Qualitative participatory modeling of system feedback
Gray			x	3	FCM as a tool for semi-quantitative scenario analysis; encoding stakeholder knowledge
Hanspach			x	3	Linked semi-quantitative and qualitative methods like system dynamics and narrative scenarios with spatial mapping
Harmáčková		x		2	Qualitative, value-based scenarios
Hashimoto			x	3	Qualitative storylines simulated in spatially explicit scenarios; reflecting Story and Simulation (SAS) approach
Henriques		x		2	Qualitative scenarios explored with significant detail; remain qualitative with no quantitative models
Huber	x			1	Agent-based model and spatially explicit mapping
Iwaniec			x	3	Linked a wide range of low and high formalization techniques to enrich the scenario process
Jiren		x		2	4 qualitative narrative scenarios
Jiren		x		2	Used causal loop diagrams and scenario narratives to generate narrative scenarios
Kamei		x		2	Used narratives, tables, and other qualitative ways of describing the future of the built environment in Japan
Kankam			x	3	Scenario narratives combined with spatially explicit modeling tools and participatory mapping exercises
Karner			x	3	Linked global storyline, regional qualitative storylines, stakeholder workshops, and spatially explicit land use maps
Kebede			x	3	Narratives from shared socio-economic pathways used for quantitative simulation models
Lacitignola	x			1	Focused primarily on simulation modeling
Langmead			x	3	Driver–Pressure–State-Impact-Response framework used to construct conceptual

					models, simulated using Bayesian Belief Networks
Le	x			1	Uses multi-agent system models; empirically validated all sub-models and multi-agent model
Liu	x			1	Focused primarily on simulation modeling
Malinga		x		2	Focused on developing narrative storylines
Manuschevich	x			1	Started with points of contention from a congressional discussion as roots of scenarios, which were formalized models
Martinez-Fernandez			x	3	Proposes a whole SES sustainability assessment approach; including formalized simulation models in addition to more qualitative narrative scenarios and participatory approaches.
Martinez-Sastre			x	3	Paired narrative scenarios with mapping using GIS
Merrie		x		2	Narrative scenarios developed by combining multiple types of data/methods on existing and emerging themes
Mistry		x		2	Used the Delphi technique and the 2-axis scenario method to develop qualitative narratives
Mitchell		x		2	4 qualitative narrative scenarios
Newell			x	3	Scenarios developed by local government and community stakeholder groups; explored in an integrated assessment model (SAS)
Norman	x			1	Spatially explicit scenario modeling
Onaindia		x		2	Storylines developed through a participatory process describing possible futures for Biscay
Palacios-Agundez		x		2	4 qualitative narrative scenarios
Palacios-Agundez			x	3	Established plausibility and coherency of storylines about the future of Biscay from Onaindia et al. (2015) using a spatially explicit land use model
Palomo		x		2	Focused on developing qualitative storylines
Pereira		x		2	Used a combination of qualitative futures methods (seeds, future wheels, three horizons) combined with artistic media (theatre)
Planque		x		2	Qualitative storylines maintained through early scenarios (from different perspectives) and integration into multiperspective scenarios
Plieninger		x		2	Open, narrative-based approach

Poonacha		x		2	Narrative scenarios (2x2 matrix)
Qui			x	3	Integrating qualitative scenarios with biophysical models
Raudsepp-Hearne		x		2	Qualitative narrative scenarios using futures wheels, backcasting/forecasting using Three Horizons, and creative storyline development
Ravera		x		2	The participatory method combined with conceptual mapping to develop a qualitative understanding of the system
Rawluk		x		2	Focus on qualitative narrative scenarios
Ruiz-Mallen		x		2	Qualitative narrative scenarios
Sahroui			x	3	The companion modeling approach; included qualitative scenarios, landscape graphs
Saito		x		2	Qualitative scenarios from the Delphi method
Sellberg		x		2	Bottom-up, participatory narrative scenarios (using bright spots, seeds method)
Shoyama			x	3	Translated qualitative land-use scenarios into quantitative simulations
Song	x			1	Focus on simulation modeling
Termansen	x			1	Focus on simulation modeling
Thompson			x	3	Translated participatory scenarios into simulations of land use and land cover change
Zavalloni	x			1	Land allocation model
Zia		x		2	Qualitative multi-criteria decision analytical framework used to evaluate management scenarios

Lead author	Participation			Score	Rationale
	None (1)	Knowledge (2)	Learning (3)		
Allan			x	3	The purpose of the scenarios was to inform policy discussion, but also explicitly discuss how the scenario development process can contribute to a learning loop
Andreotti			x	3	Participatory game sessions aimed to explore farmer decision-making and stimulate social learning; an approach aimed to support collective scenario evaluation toward landscape transition
Baggio		x		2	Surveys were conducted to collect information as inputs to the model
Bennett			x	3	A survey of participants after the scenario development process showed that the process contributed to participant learning.
Bohensky		x		2	Participants contributed their knowledge to the scenario development process
Bohensky			x	3	Participants contributed their knowledge to the development of scenarios; changes in perception before and after the scenario process demonstrated learning
Bohnet			x	3	Focused on participatory tools to facilitate social learning
Booth		x		2	Scenarios developed through an iterative approach including stakeholder elicitation
Brown			x	3	Scenario process explicitly aimed to stimulate social learning; evidence of double loop learning (Reframing)
Bruley			x	3	Participatory backcasting and series games aimed to initiate a reflection on strategies for achieving a shared vision
Brunner	x			1	A simulation model with no stakeholder input
Bush	x			1	None
Butler			x	3	Adopted a participatory systemic inquiry approach
Carpenter		x		2	Participation contributed to scenario development (knowledge) and garnering new insights
Daconto			x	3	The scenario process aimed to promote strategic reflection on on-term challenges for park management
Dada		x		2	Participation is primarily framed around

					knowledge contributions
de Chazal		x		2	Participation focused on knowledge contributions
Enfors		x		2	Rigorous participation to input knowledge into the scenarios. Brief mention of empowerment of local stakeholders in the discussion.
Franklin		x		2	Stakeholder workshops primarily contributed to the identification of key system drivers
Fredstrom			x	3	The study aimed to reveal the power of a transdisciplinary scenario approach for sustainability transformation; the CLA method explicitly seeks 'action learning' modes of knowing through the creation of transformative spaces
Garteizgogeascoa			x	3	The participatory scenario process aimed to explore different futures and create a collaborative space for co-learning and strengthening connections between researchers, policymakers, and users of the marine SES
Gaube			x	3	Transdisciplinary modeling with participant reflection designed into the process
Gibon	x			1	The study was preceded by a multidisciplinary participatory study; the process outlined in the paper focused on modeling
Gourguet		x		2	Participatory qualitative modeling approach; focused on knowledge elicitation, no mention of participant learning
Gray		x		2	This study focuses on participation as knowledge input, though advocates for the use of FCM as a "quick and dirty" method to promote social learning and deliberation among diverse stakeholders
Hanspach		x		2	Participation is prominent in the method but focused on inputs to scenario development with no mention of social impact/learning
Harmáčková		x		2	While participant learning is often a goal of transdisciplinary co-creation, the paper does not explicitly discuss the learning component. Assumed that participation focused primarily on knowledge input.

Hashimoto	x			1	None.
Henriques		x		2	Most participation focused on knowledge inputs to scenario development; inclusion of stakeholders in dialogue also aimed to help create strategic conversations about water and the environment (reflective thinking, etc.)
Huber		x		2	Participation contributed primarily to scenario development (specifically spatially explicit scenarios for land use and tourism development)
Iwaniec			x	3	Rigorous engagement via several methods aimed to expand traditional future projections, broaden decision-making capacity
Jiren		x		2	Engagement primarily focused on knowledge contributing to scenarios.
Jiren			x	3	Participation contributed to scenario development (causal loop diagrams, identification of critical uncertainties). Researchers also had clear intentions to build "adaptive capacity" and evaluated whether the exercise helped participants think about the future in different ways.
Kamei		x		2	Participation primarily contributed to scenario development and validation; no indication of participant learning
Kankam		x		2	Participation primarily contributed to scenario development and analysis
Karner		x		2	Stakeholder workshops focused on scenario development
Kebede		x		2	Participation focused on knowledge contributions, including inputs, evaluation/validation, and revisions/remodeling
Lacitignola	x			1	None
Langmead	x			1	None
Le		x		2	Stakeholder analyses and focus group results are used as inputs into the modeling process
Liu	x			1	None
Malinga			x	3	The original aim was to use participation as knowledge generation, though latter insights focused on how scenario development triggers important discussions among stakeholders

Manuschevich	x			1	Participation was only included in the up-front determination of policy narratives, which were points of discontent observed during discussion unrelated to the scenario process
Martinez-Fernandez		x		2	The proposed SES sustainability assessment approach suggests a deliberative participatory process to feed the assessment
Martinez-Sastre			x	3	Study participants contributed to scenario development but also explored scenarios in detail using various methods, framed as a co-learning process
Merrie	x			1	Academic exercise, not participatory
Mistry			x	3	Framed the participatory scenario process as a platform for dialogue and shared learning
Mitchell			x	3	After stakeholders participated in scenario generation, the questionnaire revealed that high percentages of participants learned through the process
Newell		x		2	Participation used to solicit feedback on the model; shown to produce scenarios with higher relevance to local context and needs
Norman	x			1	The framing of the study is informed by public dialogues, but the study itself does not include participation
Onaindia		x		2	Participation is used to ensure scenarios are relevant to the local contexts and to foster the application of the conclusions drawn from the scenarios
Palacios-Agundez			x	3	Participation was primarily framed around knowledge contributions, but discussion highlighted learning as participants began to see other points of view
Palacios-Agundez	x			1	Evaluated participatory scenarios from Onaindia et al. (2015) within a spatially explicit land use change model
Palomo			x	3	Participation contributes to scenario development, but the study had the explicit aim to contribute to social learning
Pereira			x	3	Highly creative participatory process; aimed to create a transformative space that inspires action; third day of participatory dedicated to reflecting on

					learning through the futuring process
Planque			x	3	Discusses the role of scenarios in helping participants confront their notions of the future and to be better prepared for a range of scenarios; the scenario process did not explicitly evaluate this learning
Plieninger			x	3	The aim was to generate enriched knowledge and for local participants to enhance their capacity to deal with landscape change
Poonacha			x	3	Transformative Scenario Planning (TSP) explicitly aims to transform understandings, relationships, and intentions among actors
Qui		x		2	Significant participation to develop scenario narratives (which were not the focus of this paper), which were then integrated into the biophysical modeling done here to analyze spatial/temporal characteristics
Raudsepp-Hearne			x	3	The process was designed to include participant reflection and to explore factors not typically central in scenario development
Ravera		x		2	Participation primarily focused on knowledge input also aimed to stimulate discussion
Rawluk			x	3	Value-based participatory scenario planning is explicitly framed to engage stakeholders in a meaningful discussion about different perspectives and possible conflicts between them
Ruiz-Mallen		x		2	Rigorous participation likely encouraged the learning of participants, but this was not explicit in the framing or discussion of the process
Sahroui		x		2	Explicit aim to develop a common knowledge base between scientists and stakeholders
Saito		x		2	An expert working group assembled to input knowledge into the process
Sellberg		x		2	Rigorous participation likely encouraged the learning of participants, but this was not explicit in the framing or discussion of the process
Shoyama	x			1	None
Song	x			1	None
Termansen	x			1	None

Thompson			x	3	Scenario co-design process; framed around the need for participants to make sense of complexity and learn
Zavalloni		x		2	A participatory approach for model development; stakeholders provided input
Zia	x			1	None

Lead author	Knowledge type			Score	Rationale
	Scientific (1)	Local, Indigenous (2)	Multiple, connected (3)		
Allan			x	3	Participatory process integrated qualitative/quantitative data and the perspectives of diverse stakeholders
Andreotti			x	3	Used serious games to elicit farmer knowledge and behavior; linked with expert knowledge through participatory backcasting
Baggio	x			1	Focused on mathematical network modeling. They collected information from participants via targeted surveys, which generated scientific knowledge.
Bennett		x		2	The participatory scenario planning process involved local stakeholder groups.
Bohensky	x			1	Scenarios developed in expert workshops
Bohensky			x	3	The purpose of scenario development was to integrate the knowledge of scientists, experts, stakeholders, etc., and to evaluate changes in perception
Bohnet			x	3	Considered local and practitioner knowledge on equal footing with scientific knowledge, using both throughout all stages of the process
Booth			x	3	Used Yahara scenario narratives developed by linking different types of knowledge (see Carpenter et al), but this paper focused on developing spatiotemporally explicit biophysical models consistent with those narratives
Brown		x		2	Participatory scenario planning primarily to surface local knowledge and diverse perspectives; no formal effort to link with scientific/expert knowledge
Bruley			x	3	Focus primarily on the participatory process that elicited stakeholder perspectives on appropriate strategies or 'levers' to achieve visions. Also used simulation models alongside the qualitative data
Brunner	x			1	The simulation model focused on scientific knowledge.
Bush	x			1	Knowledge type not explicitly stated, two scenarios assumed to be drawn from expert knowledge only.

Butler		x		2	Participatory scenario and adaptation pathways approach focused on stakeholder knowledge
Carpenter			x	3	Brought together local stakeholder perspectives, and social and natural sciences.
Daconto		x		2	Scenarios focused on local knowledge through participatory workshops with local stakeholders
Dada	x			1	The study involved participatory processes for understanding SES dynamics, linked with scenarios that were developed using literature review and co-author experience. However, scenarios themselves only developed using expert/scientific knowledge
de Chazal			x	3	Stakeholder processes to identify and prioritize drivers; linked with scientific data in the development of interlinkages and scenario projections
Enfors			x	3	Focused primarily on farmer perceptions and local knowledge, and these contributions were checked against official development statistics and trends in the region
Franklin			x	3	Elicited key system drivers from stakeholders; modeled in an integrated agent-based model
Fredstrom		x		2	Participatory process drawing from local knowledge
Garteizgogeascoa			x	3	The participatory process elicited knowledge from different perspectives (including experts and non-experts)
Gaube			x	3	Integrated modeling process aimed to scientifically integrate diverse factors and to support local stakeholders' "strategic orientation process"
Gibon	x			1	Scientific knowledge only; integrating multiple disciplines
Gourguet		x		2	Used stakeholder perceptions to develop qualitative models of system feedbacks
Gray			x	3	Local expert workshops were used to develop the fuzzy cognitive map that served as an input to the model
Hanspach			x	3	Expert knowledge for village assessment, participatory workshops with diverse stakeholders for regional analysis, and then combined in a mapping exercise

Harmáčková			x	3	The transdisciplinary process involved both participants and researchers in a co-creation process
Hashimoto	x			1	The analysis focused on simulation models and scientific knowledge
Henriques	x			1	Participatory workshops were used to elicit key drivers; invitees were all experts from various disciplines
Huber			x	3	Scientific knowledge was used to develop an agent-based model, with local stakeholder workshops contributing to the development of quantitative and spatially-explicit scenarios for land use and tourism development
Iwaniec			x	3	Scenario development explicitly framed as a collaboration between practitioner and academic stakeholders
Jiren		x		2	Focused on multistakeholder workshops, providing a platform for divergent aspirations to deliberate together
Jiren		x		2	The participatory process primarily drew from local organizations and stakeholders
Kamei	x			1	Primarily drawn from studies and scientific/social scientific knowledge via an expert panel who helped validate and refine the scenarios
Kankam			x	3	Involved diverse knowledge holders throughout various stages of the process; e.g., local knowledge in scenario development and participatory mapping; experts throughout and to do GIS mapping
Karner			x	3	Regional stakeholders developed explorative land use scenarios in a workshop, which was combined with socio-economic and biophysical data
Kebede	x			1	Expert-led scenario development; stakeholder evaluation and evaluation; expert revisions and remodeling
Lacitignola	x			1	Developing a simulation model
Langmead	x			1	Scientific knowledge in the modeling process
Le	x			1	Simulation model only
Liu	x			1	Scientific data focusing on system dynamic and cellular automata modeling

Malinga			x	3	Scenarios developed through participatory workshops only; scientific assessment to evaluate ecosystem services important under each scenario
Manuschevich	x			1	Focused primarily on analyzing three policy scenarios according to simulation models.
Martinez-Fernandez			x	3	Proposed processes involve simulation models alongside participatory processes
Martinez-Sastre			x	3	The participatory process involved scientists, local stakeholders, and local administrators
Merrie	x			1	Academic exercise only
Mistry			x	3	Develops scenarios through a participatory process with indigenous communities and national-level stakeholders before validating them against studies and literature
Mitchell			x	3	Brought together key informants, scientists, and organizational representatives in a focal workshop
Newell			x	3	Local governance and community knowledge used to develop storylines; incorporated into an integrated assessment model informed by scientific knowledge
Norman	x			1	Developing a simulation model using the SLEUTH urban growth model
Onaindia		x		2	Scenarios developed through citizen participation only
Palacios-Agundez			x	3	Scenarios developed through a participatory process with diverse participants including experts and linked with Millennium Assessment scenarios which drew from quantitative models
Palacios-Agundez			x	3	Evaluated scenarios developed by Onaindia et al. (2015) with spatially explicit land use models informed by scientific knowledge
Palomo		x		2	Local participatory knowledge was primary
Pereira			x	3	Diverse participants are involved in the participatory process, including scientists, artists, etc.
Planque			x	3	The participatory process involved diverse participants, including representatives of the fishing industry,

					NGOs, researchers from various disciplines, etc.
Plieninger			x	3	Scenarios developed through a combination of background literature review, several scientific studies in the region, and workshops with local actors
Poonacha			x	3	The purpose of transformative scenario planning is to generate a shared understanding of the system among actors; workshops brought together diverse stakeholders including government, experts, artists, etc.
Qui			x	3	Developing simulation model using Agro-IBIS; used to model participatory scenarios
Raudsepp-Hearne			x	3	Participatory process, breakout groups included scientists, representatives of the specific theme (seeds), facilitators, artists, etc.
Ravera			x	3	Triangulated data from scientific research and participatory processes
Rawluk		x		2	Focus on participation among people in a context to develop value-based scenarios
Ruiz-Mallen		x		2	Focused on community-level participatory workshops to generate and validate scenarios
Sahroui			x	3	Companion modeling brought together scientists and stakeholder knowledge
Saito	x			1	Scenarios developed through expert workshops
Sellberg			x	3	Workshops involved diverse experts, stakeholders, etc.
Shoyama	x			1	Scientific knowledge only
Song	x			1	Focused primarily on scientific knowledge to develop a simulation model
Termansen	x			1	Engaged with local users to conduct choice experiments that fed into the simulation model; still under the framework of scientific knowledge
Thompson			x	3	Co-designed scenario process to increase the range of viewpoints and expertise in the scenario development process
Zavalloni			x	3	Local stakeholders involved in participatory workshops that generated the models
Zia	x			1	Scientific knowledge only

Lead author	Drivers			Score	Rationale
	Top (1)	Bottom (2)	Cross (3)		
Allan	x			1	Downscaled SSPs (which are structural socio-economic global scenarios) to local scale to discuss implications; primarily top-down
Andreotti		x		2	Forecasting focused on the game, which revolves around individual land-use decisions and collaboration
Baggio			x*	3	Consider changing social sharing and cooperation networks and resource availability (top-down). Interactions manifest through a network, so drivers are both top-down and bottom-up.
Bennett	x			1	Scenarios focused on external stressors impacting coastal communities
Bohensky	x			1	Focused primarily on top-down drivers (global development and Australian development) and then analyzed consequences on the Great Barrier Reef
Bohensky	x			1	Scenario focused on climate change and technology; focused on unpredictable elements that act upon the system
Bohnet			x	3	Considers both bottom-up actions like changing agricultural practices, and top-down trends such as urbanization. All are considered under the same framework.
Booth			x	3	Qualitative scenarios from Carpenter et al incorporate both bottom-up and top-down drivers. Biophysical modeling contextualizes these drivers further.
Brown	x			1	Focus on internal sensitivities to external drivers to evaluate robust response options
Bruley			x	3	The participatory game focused on how individual activities (bottom-up) work within the context of top-down climatic/socio-economic drivers. Backcasting then focused on the individual human agency to achieve desired outcomes.
Brunner			x	3	Scenarios used to compare sectoral policy actions that attenuate the negative regional implications of global pressures
Bush			x	3	Scenarios based on two management approaches (bottom-up), evaluated against a range of structural conditions (political, ecological, etc.)
Butler			x	3	Scenarios are a 2x2 matrix of exogenous drivers; identified strategies that are 'no regrets' options, both incremental and

					transformative; considered linkages
Carpenter			x	3	Considers how social/environmental processes (including management) within the Yahara watershed interact with external/global drivers of change
Daconto	x			1	The scenario process considered a wide range of controllable and controllable drivers. Ultimately integrated on centralization of governance and management imposed by central government and the balance of influence between Sherpa and outside investors; both were drivers that stakeholders did not feel they had control over
Dada			x	3	Scenarios focused primarily on top-down drivers that generate press and pulse events; analyzed within the PPD framework which integrates with bottom-up change.
de Chazal			x	3	Links structural conditions (e.g., scenario-based ecosystem change stimulus) with scenarios of land use change at each of the study sites (e.g., renewal of current declining agricultural practices)
Enfors	x			1	Scenarios focus on important uncertainties and feedback processes that affect different development trajectories
Franklin	x			1	Primary drivers of change considered in the scenarios focus on critical uncertainties exogenous to the management system
Fredstrom		x		2	The Manoa method based on future seeds focuses on bottom-up drivers of change. Causal layered analysis contextualized scenarios according to underlying worldviews/myths.
Garteizgogeascoa	x			1	Primarily focused on external drivers as boundary conditions for discussing possible futures (pollution, population growth, etc.)
Gaube			x	3	Explicitly frame the scenario analysis as defining possible future trajectories depending on both external (framework conditions) and internal (local/regional policies, preferences of individual agents) factors.
Gibon			x	3	The model focuses on detailed, hierarchically-nested social-ecological interactions; tests the implications of policy scenarios of land use against those scenarios
Gourguet	x			1	Created system dynamics model of the

					system of interests; tested implications of perturbation scenarios (Structural)
Gray			x*	3	Variables in FCM range from bottom-up (conservation education) to top-down (bushmeat market value, unplanned wildfires). No clear distinction.
Hanspach			x	3	Scenario development did not explicitly focus on both bottom-up and top-down drivers, though discussion revealed how both were considered and influenced scenario outcomes
Harmáčková		x		2	Scenarios based on values held by different stakeholders and the different actions taken; evaluated for their impacts on nature and quality of life
Hashimoto	x			1	Scenario analysis focuses on how future land use patterns vary depending on two external drivers (local natural capital and demographic trends).
Henriques	x			1	4 core socio-economic scenarios focus on external drivers (material consumption and long-term resilience/sustainability). Scenarios are contextualized using drivers and pressures from DPSIR, which are external.
Huber	x			1	Water supply: demand implications considered under external drivers (socio-economic and climate change)
Iwaniec			x	3	Scenarios explicitly integrate strategic (bottom-up) with explorative techniques to imagine positive scenario visions
Jiren			x	3	Critical uncertainties were focused on top-down drivers, but Three Horizons Framework was used to discuss bottom-up (strategic) changes
Jiren			x	3	Process for developing scenarios focused on both top-down and bottom-up drivers, as framed more around controllability and uncertainty and analyzed through feedbacks in a causal loop diagram; included agricultural techniques (potentially bottom-up) alongside land distribution
Kamei	x			1	Translates global SSPs to Japanese built environment; focuses primarily on top-down socio-economic pathways
Kankam		x		2	Analyzes the supply of cultural ecosystem services under different policy scenarios
Karner		x		2	Scenarios emerge from land use transition rules; all scenarios incorporate various

					aspects of land use and management to allow subsequent quantification of multiple ecosystem services and biodiversity indicators. up of land use;
Kebede			x	3	Scenarios combine downscaled SSPs and four distinct adaptation policy trajectories; explicitly aim to demonstrate the value of cross-level scenarios
Lacitignola	x			1	The model characterizes the interplay of tourists, quality of ecosystem goods and services, and capital. Unclear whether top-down or bottom-up, but largely treated as structural drivers of which stakeholders do not have control
Langmead	x			1	Scenarios focused on the primary approach to governance and main values driving society; analyzed for broad structural implications (social, economic, etc.)
Le		x		2	Evaluating social-ecological implications of land use policies; system simulated as a multi-agent system
Liu	x			1	Explicitly couple a top-down system dynamics with a bottom-up cellular automaton model to simulate future land use patterns; incorporates mostly top-down drivers and interactions
Malinga	x			1	Scenarios characterize general social and biophysical changes in the region and their effect on land use; the most uncertain and important drivers used to form starting points of scenarios
Manuschevich		x		2	Scenarios are alternative land use policy scenarios that diverge from business as usual
Martinez-Fernandez	x			1	Scenarios characterizing exogenous drivers are used to explore available management and planning options in a combined scenario (top-down) and policy assessment
Martinez-Sastre	x			1	Scenarios made up of land use change, framed as exogenous changes that are analyzed for their implications on ecosystem services
Merrie	x			1	Scenarios characterize broad structural conditions (i.e., collapsed vs. sustained or connected vs. fragmented).
Mistry	x			1	Scenarios link global scale structural change to local scale structural change
Mitchell			x	3	Developed scenarios from biophysical and social drivers. These were largely structural conditions, including the local community

					(e.g., social capital). The scenarios uniquely consider governance influences.
Newell		x		2	Scenarios primarily consider community development plans and their outcomes
Norman	x			1	Scenarios considered top-down drivers (primarily urbanization/population) as 3 scenarios; current trends, conservation, megapolis
Onaindia	x			1	Scenarios based on global drivers from the Millennium Ecosystem Assessment, focusing on governmental, economic, and socio-political drivers
Palacios-Agundez			x	3	Soft multi-level drivers; compiled list of drivers includes both top-down (global demographic trends) and bottom-up (participatory governance)
Palacios-Agundez			x	1	Focused on making scenarios from Onaindia et al. (2015) locally relevant by analyzing implications for ecosystem services supply, demand, and trade-offs
Palomo	x			1	Drivers were technology, participation, climate change, and migration, which are top-down drivers of change (for the context).
Pereira		x		2	Radically different visions of the future produced using 'seeds' in the present that emerge as mainstream in the future
Planque	x			1	Characterizes different futures for the marine SES based on different 'perspectives' on the future of fisheries management... Resulting scenarios focus primarily on top-down drivers (fisheries production, effects of climate warming, etc.)
Plieninger			x	3	Includes global-level drivers (structural) such as the type of economy and local-level drivers (agency) such as consumption patterns and preferences
Poonacha	x			1	Primary drivers of change for scenario construction are 'appropriate institutions' and 'collaborative action'. Unclear whether these are framed as structural conditions of agency; assumed they set the context for individual agency.
Qui	x			1	4 scenarios of Yahara Watershed are considered top-down structural constraints, under which the nine ecosystem services were modeled
Raudsepp-		x		2	The seeds method is used to explore

Hearne					bottom-up (transformed) futures.
Ravera			x	3	Exploratory exercise to depict visions of the future; climate scenarios developed to develop top-down boundary conditions, deliberative focus group for backcasting; systematically link top-down changes and backcasting exercise
Rawluk		x		2	Scenarios defined by different values regarding human-nature interactions
Ruiz-Mallen	x			1	Scenarios define climatic, policy, and socio-economic horizons to 2030; used as a tool to discuss local adaptation options
Sahroui			x	3	Focused on land use planning scenarios and their impacts on landscape/multi-species connectivity
Saito	x			1	Scenarios developed based on key top-down drivers (climate change, depopulation, etc.) and their implications on ecosystem services and wellbeing
Sellberg		x		2	Seeds method to develop scenarios, which create bottom-up narrative scenarios
Shoyama		x		2	Land use scenarios developed from intensive/extensive land use interventions, considering biophysical and socioeconomic factors
Song		x		2	Scenarios driven by actor actions to preserve wetlands (scenario 1 - current maintenance; scenario 2 - development acceleration; etc.)
Termansen			x	3	Integrates behavioral models (bottom-up) with broader system dynamics modeling.
Thompson	x			1	Scenarios as drivers of land use change, differentially altering potential land use pathways, and affect conservation priorities
Zavalloni		x		2	Scenarios based on approaches to land allocation
Zia		x		2	Focus on implications of conservation management scenarios on several social and environmental outcomes

Lead author	Social-ecological complexity			Score	RATIONALE
	Scenarios and outcomes linear (1)	Outcomes emergent (2)	Scenarios emergent (3)		
Allan		x		2	Use qualitative scenarios to explore interdependencies and interactions across key themes (land, climate, etc.). The Shared Socioeconomic Pathways framework sets conditions for these scenarios.
Andreotti	x			1	Participatory forecasting focused on farm decisions to adopt specific agricultural practices, which generate landscape scenarios; backcasting focused on strategies to achieve a desirable future. Scenarios are 'what ifs' for exploring farmer choices.
Baggio		x		2	Explore implications of scenarios (changes in resource abundance/distribution due to climate, shifting cultural practices, etc.), including structural properties of cooperation and sharing networks
Bennett	x			1	Scenarios are business as usual, worst case, and best case; discussion focuses on elaborating implications of these scenarios and discussing adaptation options
Bohensky		x		2	Scenarios simply 2x2 matrix; interactions and emergent outcomes regarding well-being and environmental sustainability explored with more detail
Bohensky	x			1	Four scenarios from a 2x2 matrix; the aim was to integrate knowledge through scenario development; implications not explored with significant complexity
Bohnet		x		2	Scenarios reflect a social-ecological framework that views 'landscape' as a concept that brings together diverse social-ecological interactions; implications of these scenarios are modelled and explored in more detail (trade-offs)
Booth			x	3	Use qualitative storylines to develop land use change scenarios; translate as inputs into quantitative models that are spatially explicit, temporally continuous, and consider various biophysical outcomes (e.g., nutrient application, climate, etc.)

Brown	x			1	Scenarios based on 2x2 matrix; used to develop robust response options reflection single, double, triple loop learning; scenario outcomes not considered emergent
Bruley		x		2	Scenarios developed through backcasting approach; were explored to identify NCA that contribute to the objectives and capacity of ecosystems to supply them
Brunner		x		2	Scenarios of global change are press and pulse outcomes to test resilience (e.g., green growth, local sustainability, etc.); test outcomes that emerge from the interaction of policy strategies with scenarios.
Bush		x		2	Two relatively simple scenarios were analyzed using an integrated assessment of linkages/feedbacks between four key social-ecological dynamics
Butler		x		2	2x2 matrix scenarios created 4 scenarios; considered diverse drivers and whether they were systemic or proximate; used simple scenarios to inform the identification of 'no-regrets' actions and linkages
Carpenter			x	3	Diverse drivers of change and implications translated into qualitative narrative storylines; while interactions and emergent outcomes are not analyzed systemically, outcomes are not determined from a 2x2 matrix and are thus emergent from participants' understanding of the complexity
Daconto	x			1	2x2 matrix method where the future emerges at the intersection of two drivers of change. Implications elaborated qualitatively but without explicit consideration of complexity and emergence.
Dada			x	3	The generic scenario framework shows outcomes as emerging from the interactions of press-pulse events, human dynamics/institutions, and ecosystem structures/functions
de Chazal		x		2	Two simple scenarios of prospective land use; implications analyzed as complex interactions across ecosystem services

Enfors		x		2	Scenarios are combinations of different states for multiple drivers of change; implications detailed including impact on the effectiveness of small-scale water storage
Franklin		x		2	Scenarios as combinations of six critical uncertainties; implications analyzed in an agent-based model
Fredstrom			x	3	Used Manoa method and future 'seeds'; scenarios emergent from systemic interactions resulting from mainstreamed seeds
Garteizgogeascoa	x			1	Scenarios as 2x2 matrix; combinations of different drivers of change; translated into narratives; implications contrasted with local stakeholder visions but no obvious lens on complexity and emergence
Gaube			x	3	Scenarios simulated based on interactions of external framework conditions, local/regional policies, and individual agent preferences
Gibon		x		2	Tested the implications of 'what if' policy/socio-economic scenarios for their outcomes on the landscape
Gourguet		x		2	A qualitative model of system feedbacks tested for implications of perturbation scenarios
Gray			x	3	Scenarios as stable states of the social-ecological system emerging from interactions in FCM
Hanspach			x	3	Scenario outcomes are depicted as emerging from historical conditions, external framework, and internal dynamics
Harmáčková			x	3	Scenarios emerge from different values held by diverse actors in the context and interactions in the Three Horizons Framework
Hashimoto		x		2	Exploratory scenarios based on contrasting levels of reliance on domestic natural capital and demographic change; analyze for complex implications on land use patterns, biodiversity, and ecosystem services
Henriques		x		2	Scenarios developed from two axes of change; consumption patterns and governance system; implications explored through the causal chain (DPSIR)

Huber		x		2	Six future scenarios are defined from combinations of land use, tourism, and climate change. Implications of these scenarios are modeled in an agent-based model, in which both water fluxes and socioeconomic actors are represented by agents that interact and create complex feedback loops
Iwaniec		x		2	Scenarios are defined according to key themes, goals, and visions for change; outcomes are elaborated via modeling, strategic actions, etc.
Jiren		x		2	Scenarios developed from 2x2 matrix; discussed Three Horizons for a preferred scenario
Jiren			x	3	Scenarios developed from causal loop diagrams and critical uncertainties
Kamei	x			1	Scenarios downscaled from SSPs; outcomes detailed but linear
Kankam		x		2	Land use land change scenarios developed from stakeholder dialogues. Their implications on cultural ecosystem services are richer and hint toward emergent complexity.
Karner			x	3	Scenarios emerge from interactions of global/European storylines and land use transition rules that generate different spatially-explicit scenarios including land use and management
Kebede			x	3	Scenario contexts emerge from combinations of RCP-SSP. adaptation policy trajectories bundled under different socio-economic outcomes
Lacitignola			x	3	Scenarios emerge from the model of interactions between ecosystem goods and services, capital, and tourism; according to adjustments of a bifurcation parameter
Langmead		x		2	Implications of narrative change in socio-economic variables analyzed for more complex/emergent outcomes (e.g., the direction of change in each of the Driver sectors and activities)
Le		x		2	Policy intervention scenarios analyzed for implications in a multi-agent system model
Liu		x		2	Four scenarios along two axes are tested for implications in a complex future land use simulation model (system dynamics and bottom-up cellular automata)

Malinga		x		2	Narrative scenarios analyzed for implications on ecosystem services
Manuschevich		x		2	Scenarios are land use alternatives to business-as-usual; evaluated according to their outcomes on the landscape, including erosion, carbon stock, and wood production.
Martinez-Fernandez		x		2	Scenario analysis looks at vulnerabilities of a complex social-ecological system to exogenous drivers
Martinez-Sastre		x		2	Four plausible scenarios analyzed for emergent outcomes on ecosystem services and trade-offs; conflicts among stakeholders
Merrie			x	3	Method of science fiction prototyping used to address two limitations of other scenario methods: 1) incorporating non-linear change and 2) involving co-evolutionary dynamics of integrated social-ecological systems
Mistry		x		2	Four-axis framework was used to develop local scenarios; implications analyzed in detail and linked to scenarios at higher scales (national, international)
Mitchell		x		2	Two scenarios generated from highest importance/uncertainty drivers; implications analyzed based on the system model of multiple social and ecological drivers
Newell		x		2	Implications of community development scenarios modeled in a system model. The model analyzed community development scenarios (and associated density) against outcomes and relationships between them, such as walkability, social diversity, etc.
Norman		x		2	SLEUTH model used to simulate land use implications of three socio-economic trends; SLEUTH model outcomes emerge from neighborhood rules
Onaindia	x			1	Qualitative storylines explore some interactions, but were largely linear
Palacios-Agundez		x		2	Scenarios start from two primary drivers of change; developed further by making assumptions about how these drivers influence others. Scenarios were then analyzed for implications on ecosystem service provision and wellbeing

Palacios-Agundez		x		2	Analyzed the land use implications and trade-offs of the qualitative storylines in Onaindia et al. (2015)
Palomo		x		2	Scenarios developed from different combinations of multiple drivers; analyzed for implications on ecosystem services and human wellbeing
Pereira			x	3	Futures considered emergent from seeds of Good Anthropocenes. Futures wheels exercise and Three Horizons exercises are qualitative but consider complex interactions and trade-offs
Planque	x			1	Storyline scenarios are relatively simple depictions of the future from multiple perspectives on the marine SES.
Plieninger		x		2	Possible combinations of two drivers generated four scenarios; participants selected the two most relevant scenarios; scenarios elaborated and analyzed for implications on ecosystem services and quality of life
Poonacha	x			1	Four scenarios developed from two drivers of change on two axes; implications explored (threats/opportunities); not analyzed with significant complexity
Qui		x		2	Simulation of nine ecosystem services under four contrasting scenarios
Raudsepp-Hearne			x	3	The seeds method seeks to develop futures as emergent from complex interactions (e.g., seeds in futures wheels and interactions)
Ravera			x	3	Exploratory exercise captured conflicting visions of the future, combined with a climate scenario to conduct a backcasting exercise; Each scenario and component overlapped to conceptual model (system diagram) to infer future trends of changes in vulnerability indicators performance
Rawluk	x			1	Combinations of values underpinned the scenarios; analyzed in more detail for associated management actions
Ruiz-Mallen	x			1	Two drivers of change were used to develop four scenarios; used to frame a discussion about local adaptation options
Sahroui		x		2	Scenarios developed from a discrete number of drivers; outcomes on landscape connectivity modeled
Saito		x		2	Scenarios developed from two drivers;

					implications on changes to natural capital and ecosystem services analyzed in detail
Sellberg			x	3	The seeds method seeks to develop futures as emergent from complex interactions (e.g., seeds in futures wheels and interactions)
Shoyama			x	3	Land use scenarios emerge from intensive/extensive land use interventions, and interacting biophysical and socioeconomic factors
Song		x		2	Three scenarios: current state, development, and restoration are analyzed using a system dynamics model spatial simulation, and landscape simulation
Termansen		x		2	The integrated model was used to analyze the implications of different scenarios of single-farm payment
Thompson		x		2	Scenario matrix (2x2) translated into quantitative inputs; analyzed in the dynamic cellular land change model
Zavalloni		x		2	Analyze land use, public good levels, and welfare deriving from agricultural production in three different scenarios
Zia		x		2	Explore five management scenarios against the hypothesis that conservation-oriented scenarios generate higher value for higher scales and mixed or balanced management scenarios generate higher value for local scales

Lead author	Spatial scale			Score	Rationale
	Single, social (1)	Single, biophysical (2)	Cross/ multi-scale (3)		
Allan			x	3	Coastal Bangladesh; integrates socioeconomic/biophysical elements across multiple scales
Andreotti		x		2	Agroforestry system in Nicaragua
Baggio	x			1	Focus on three Arctic communities
Bennett	x			2	Two coastal fishing communities in Thailand
Bohensky			x	3	Great Barrier Reef; considers both global and regional development (soft linkages)
Bohensky			x	3	Milne Bay Province, Papua New Guinea; analytical framework includes stakeholder knowledge of exogenous (global) and endogenous (regional) scales (soft linkages)
Bohnet		x		2	Focus on two contrasting landscapes in the Wet Tropics
Booth		x		2	The Yahara River watershed in south-central Wisconsin, USA
Brown		x		2	3 different case studies: Argentinian coastal management in an estuary; Colombian in a biodiverse region of the Pacific coast; Mexican case in the forest management area
Bruley	x			1	Two municipalities in the central French alps
Brunner		x		2	Valley in the Swiss alps; implications of global drivers on local context (dealt with under 'drivers')
Bush			x	3	Considers multiple spatial scales throughout the discussion of scenarios
Butler		x		2	Province containing two islands in Indonesia; characterize global climate change as part of a multi-scale social-ecological system
Carpenter			x	3	Watershed scale; soft linkages to others through qualitative storylines
Daconto	x			1	2 towns in Australia - Mossman, and Julatten - and their surrounding landscape
Dada			x	3	National park; analytical framework includes exogenous (global) drivers linked to drivers at the park scale
de Chazal		x		2	Study sites are locations in the central French alps

Enfors	x			1	Smallholder farming community, development trajectory of the region; focused on local level scenarios
Franklin		x		2	Kenai River, Alaska
Fredstrom	x			1	Climate change scenarios for a Swedish municipality
Garteizgogeascoa		x		2	Peruvian MSES tied to the Humboldt Current Upwelling System (HCUS)
Gaube	x			1	Municipality in Upper Austria
Gibon	x			1	Group of four neighboring villages
Gourguet		x		2	Normand-Breton Gulf in NW France
Gray	x			1	Village-level study
Hanspach			x	3	Aggregated across several village scales; framework used to analyze integrates across scales
Harmáčková		x		2	Three protected areas in Czechia; scenarios focus on a local scale; discussion discusses implications across scales (e.g., local action vs higher scale regulations)
Hashimoto		x		2	Noto peninsula of Japan.
Henriques	x			1	England and Wales
Huber		x		2	the Long-Term Socio-Ecological Research (LTSER) site ‘Mazia/Matsch valley’, in the Province of Bolzano/Bozen, South Tyrol, Italy (Fig. 1). The catchment has an area of 91.6 km2, with elevations ranging from about 1200m a.s.l. to 3725 m a.s.l.
Iwaniec	x			1	Central Arizona-Pheonix Long-term Ecological Research metropolitan region
Jiren	x			1	Zambezi region of Namibia
Jiren	x			1	Jimma zone, Oromia regional state, southwestern Ethiopia
Kamei	x			1	National scale; ensure consistency with global SSPs
Kankam		x		2	The coastal landscape in southwestern Ghana
Karner			x	3	Regional agricultural scale; Explicit methodology adopted to select a common global storyline, develop 3 contrasting narrative storylines for land use; interactions across considered
Kebede			x	3	Explicitly multi-scale approach; three deltas in West Africa and South Asia in the context of global change
Lacitignola	x			1	Marine protected area
Langmead		x		2	Northwestern Black Sea shelf

Le		x		2	Watershed
Liu	x			1	National (China)
Malinga			x	3	Soft linkages across scales, with a focus on regional (social)
Manuschevich		x		2	The Araucania region in south-central Chile; includes the coastal area, central valley, and part of the Andes mountains
Martinez-Fernandez		x		2	Oceanic island
Martinez-Sastre		x		2	Mediterranean cultural landscape; Eastern Sierra Morena; boundaries defined through a combination of socioeconomic and biophysical considerations; focused at a specific scale
Merrie		x		2	Global ocean scenarios
Mistry			x	3	Multi-scalar scenarios; hard linkages through matrix characterizing feedbacks; national scale as a mediator
Mitchell		x		2	Australian Alps; explicitly landscape scale
Newell	x			1	District of Squamish, British Columbia; focused on implications of community development outcomes locally
Norman		x		2	Santa Cruz Watershed
Onaindia			x	3	Storylines based on global scenarios from the MEA, loosely consider the global change in the context of the Biscay area
Palacios-Agundez			x	3	Coherence across scales achieved by downscaling MEA
Palacios-Agundez			x	3	Storylines based on global scenarios from the MEA, loosely consider the global change in the context of the Biscay area
Palomo			x	3	Soft link across global to local scales
Pereira			x	3	Focuses on southern Africa; soft linkages across scales in narratives
Planque			x	3	The Barents Sea; different perspectives incorporated into the multiperspective scenarios considered different spatial scales
Plieninger	x			1	Biosphere reserve, focusing on two municipalities; the focus is on local scale drivers and actions
Poonacha	x			1	City of Bangalore
Qui		x		2	Yahara Watershed
Raudsepp-Hearne	x			1	Northern Sweden
Ravera			x	3	Esteli, semi-arid plateau in northern Nicaragua; conceptual model included cross-scale interactions

Rawluk	x			1	Victoria, Australia
Ruiz-Mallen			x	3	Community-level; discusses multiple policy scales
Sahroui	x			1	Metropolitan area of Bordeaux
Saito	x			1	National-scale
Sellberg	x			1	Stockholm city; Seeds methodology helped understand more cross-scale dynamics
Shoyama	x			1	National scale
Song		x		2	Songdo wetlands
Termansen	x			1	National park
Thompson			x	3	Multiple scales; state, county, town, watershed
Zavalloni		x		2	Hill/mountain area in Bologna, Italy
Zia			x	3	Explicitly analyzing cross-scale trade-offs in Ruaha National Park, Tanzania (local vs national/international)

Lead author	Temporal scale			Score	Rationale
	Single, short-term (1)	Single, long-term (2)	Linked, fast and slow (3)		
Allan		x		1	2050 and 2100
Andreotti		x		2	Vision focused on the ideal situation in 2040
Baggio				X	None provided
Bennett				X	None specified
Bohensky		x		2	2100
Bohensky		x		2	2040
Bohnet	x			1	Approximately 20 years
Booth		x		2	2014 to 2070
Brown	x			1	For reference, the future was defined as being over the next 20 years (or 'one human generation').
Bruley			x	3	Focus on desired future in 2040 and strategies and levers for reaching it over time.
Brunner	x			1	2034
Bush				X	None provided
Butler			x	3	Scenarios to 2090; backcasting to link short term
Carpenter		x		2	6 decades to the year 2070
Daconto		x		2	25 years
Dada				X	None specified
de Chazal	x			1	2030
Enfors	x			1	to the year 2030 (1 decade)
Franklin				X	None specified
Fredstrom		x		2	2050
Garteizgogeascoa	x			1	20-year period
Gaube		x		2	30-year simulation period from 2006
Gibon	x			1	5-year time step for the ABM; baseline 2003 and horizon at 2030
Gourguet				X	None specified
Gray				X	None provided
Hanspach		x		2	30 years
Harmáčková				X	None specified
Hashimoto		x		2	2050
Henriques		x		2	2050
Huber		x		2	period of 2015 to 2050
Iwaniec			x	3	Considered 5, 20, and long (2060 or 2100) term
Jiren	x			1	in the next 20 years.
Jiren	x			1	20-year time frame

Kamei				X	None specified
Kankam				X	None
Karner	x			1	2030
Kebede			x	3	Assessment and comparison of implications of change in three delta sin short/medium term (2050) and long term (2100)
Lacitignola				x	None specified
Langmead		x		2	25-year time horizon
Le	x			1	20 years
Liu			x	3	Demonstrate 2010-2050 in 4, 10-year intervals
Malinga	x			1	2030
Manuschevich	x			1	2030
Martinez-Fernandez	x			1	2012-2025
Martinez-Sastre	x			1	2030
Merrie		x		2	2050 and 2070
Mistry	x			1	2030
Mitchell	x			1	future state in 2030.
Newell	x			1	2036
Norman		x		2	2050
Onaindia		x		2	2050
Palacios-Agundez		x		2	2050
Palacios-Agundez		x		2	2050
Palomo	x			1	2035
Pereira		x		3	No single time horizon was stated though scenarios include mention of long-term horizons (2318)
Planque			x	3	Different perspectives incorporated into the multiperspective scenarios incorporated into multiperspective scenarios; loosely linked
Plieninger		x		2	2040
Poonacha	x			1	2030
Qui		x		2	2070
Raudsepp-Hearne		x		2	100-year time horizon
Ravera		x		2	2050
Rawluk				x	None
Ruiz-Mallen	x			1	2030
Sahroui	x			1	15-year time horizon

Saito		x		2	2050
Sellberg				x	None specified
Shoyama		x		2	2050
Song	x			1	2030
Termansen				x	None specified
Thompson		x		2	2050
Zavalloni				x	None specified
Zia				x	None specified

Appendix E

Round 1 and 2 interview protocols

<u>Round 1 Interviews</u>

<u>Part A: Participant information</u>

1. How would you describe your expertise in the Red River Basin?
2. What is your current role and with what organization?

<u>Part B: Scenarios Exogenous change</u>

3. *What do you think are the **most important and uncertain external social future developments** influencing governance and management of the Red River Basin in the coming 30 years (to 2050)? Brainstorm and choose 3, using prompts on the Miro board if needed.
4. *What do you think are the **most important and uncertain external ECOLOGICAL/ ENVIRONMENTAL future developments** influencing governance and management of the Red River Basin in the coming 30 years? Brainstorm and choose 3, using prompts on the Miro board if needed.

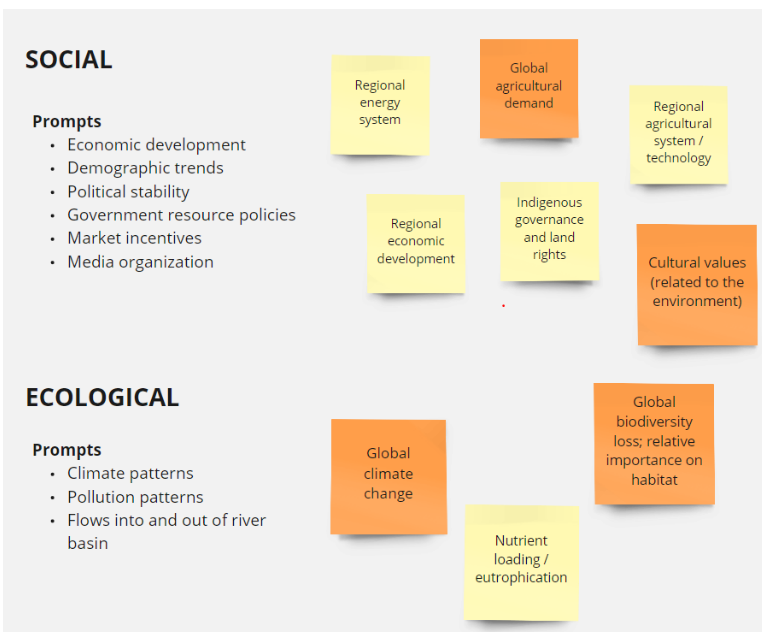

Figure E-1: Screenshot of Miro template after one interview. The virtual sticky notes captured the most important and uncertain future developments discussed.

5. *What **possible mutually exclusive end states** can you imagine for each of these social and ecological future developments in 30 years?

Cultural values	Global agricultural demand	Global climate change	Global biodiversity loss
Shift away from animal-based meat products toward plant-based	Relative advantage of upper Great Plains as a reliable food producer when subjected to more climate stress		
Status quo	1) climate relatively benign; relatively advantage		
	2) climate impacts extreme, relative disadvantage		

Figure E-2: Screenshot of Miro template used to question 5. The future developments from questions 3 and 4 were put in the top row, with mutually exclusive end states discussed in the rows below.

Part C: Resilience

Defining resilience

We often hear the term ‘resilience’ understood and interpreted in many ways, all describing strategies to cope with change and avoid transitioning to an undesirable state.

In our research we define resilience broadly to include all of these: the ability to withstand disturbance, the ability to recover from a disturbance, and to adapt and improve following a disturbance.

Resilience to what?

Resilience is usually determined in relation to a form of disturbance, some sort of long-term stressor or shock. In initial framings of this study, we were interested in resilience to increasing climate variability and change, primarily in the form of shocks like floods and droughts but also long-term stressors associated with changing seasonality and weather patterns.

6. What do you think are the most important impacts of existing and future climate variability in the Red River Basin (i.e., increasing frequency and severity of extreme floods and droughts)?

Resilience over what time frame?

We are looking at mid-century scenarios to 2050 in order to see how present-day resilience-building efforts will serve the Red River Basin of 2050.

Resilience in the Red River Basin

7. What does a resilient future look like to you?
8. What (potentially innovative) practices or projects are being pursued in the RRB that may contribute to resilience, in your view?
9. What features of the Red River Basin need to change to achieve this future?
10. What features need to be preserved to achieve this future? In other words, what existing aspects of the

RRB contribute to resilience?

Optional questions (if not responded to, the responses to questions 8 – 11 will suffice):

11. *What do you think are the **most important and uncertain ECOLOGICAL/ENVIRONMENTAL future developments** relevant to resilience to climate variability in the Red River Basin in the coming 30 years? Brainstorm and then choose 3, using prompts if needed.
12. *What do you think are the **most important and uncertain SOCIAL future developments** relevant to resilience to climate variability in the Red River Basin in the coming 30 years? Brainstorm and then choose 3, using prompts if needed.

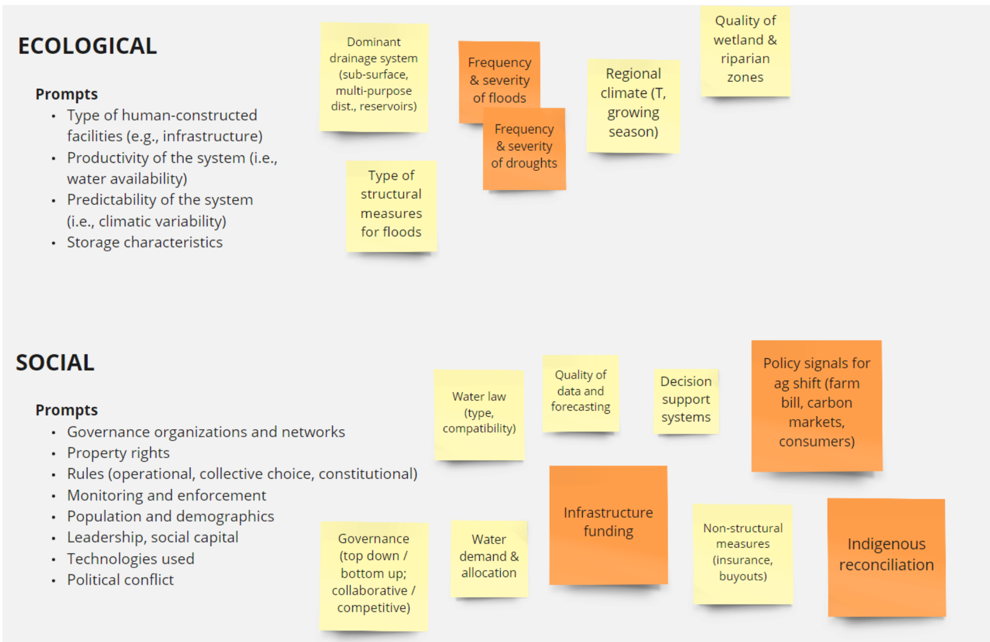

Figure E-3: Screenshot of completed Miro template to support questions 11 and 12. The virtual sticky notes captured the key variables associated with resilience.

13. *What **possible end states** can you imagine for each of these social and ecological future developments in 30 years (if time)?

Climate risk	Policy signals for ag shift (farm bill, carbon markets, consumers)	Indigenous reconciliation	Infrastructure funding
Physical risk overwhelms institutional adaptive capacity; tax revenues plummet; etc..	Net-zero emissions from ag costed (externalities)		Hard, large
Physical risks within current coping capacity; proactive risk management via climate resilience investments	Regenerative ag benefits monetized		Soft, decentralized
	Status quo		

Figure E-4: Screenshot of Miro template to support question 13. The variables from questions 11 and 12 were put in the top row, with mutually exclusive end states discussed in the rows below.

Closing script

14. Can you recommend any other participants I should talk to? For each suggested participant ask for contact information or ask the interview if they would be willing to forward an invitation on my behalf.

Thank you so much for your responses to these questions. You will receive a thank you letter and eGift card shortly. With your permission I may contact you for the purposes of clarification, validation, and elaboration of your interview up to 3 weeks from today and once all stage 1 interviews are complete, I will send you a summary of the synthesis of stage 1 for your feedback. With your permission you may hear from me with an invitation for a follow up interview and/or workshop.

Thank you very much for participating in this study.

<u>Round 2 interviews</u>

<u>Participant information</u>

15. How would you describe your expertise in the Red River Basin?
16. What is your current role and with what organization?

Describe the interview purpose

The method we are using to model these long-term scenarios is called cross-impact balances. This method describes the future as combinations of multiple end-states for different future developments. In round 1 interviews, we developed a list of multiple future social and environmental developments relevant for efforts to build resilience to climate variability and change in the Red River Basin. We determine multiple possible end states for each of those future developments in 2050. We also generated a list of interventions for resilience [describe how these are incorporated in the model; TBD based on the type of data collected in round 1 interviews].

In this interview, I will ask you a series of questions pertaining to your expertise on [insert relevant expertise]. The purpose of these questions is to determine the “influence judgments” between different end states of each uncertainty.

Do you have any questions?

<u>STEP 1: Direct influences between social and environmental developments</u>

The first step is determining <u>direct influences</u> between social and environmental developments identified in round 1 interviews. I will share a Miro board on my screen now to help us do so using a conceptual map. *share Miro board* We are going to draw arrows of <u>direct influence</u> between the future developments on this screen.

17. *Does future development X <u>directly influence</u> future development Y? [Repeat systematically one-by-one through each combination of social or ecological developments]

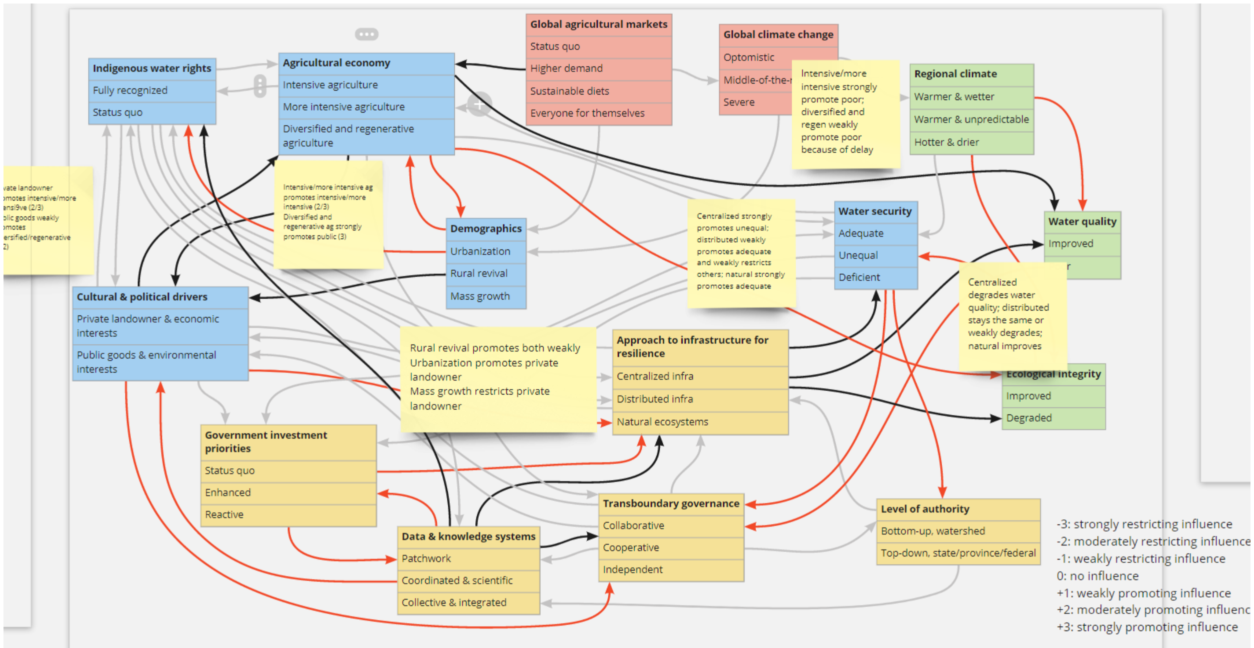

Figure E-5: Screenshot of the Miro template after one of the interviews. The red arrows in the network diagram indicate the judgment sections that were both uncertain and relevant to the interviewee's expertise. The light yellow sticky notes were filled out by the interviewer as the interviewee shared their rationale for a direction and strength of the influence.

STEP 2: Influence judgements between states of social and environmental developments

In step 2, we are going to determine influence judgments between the mutually exclusive states of the future developments that we determined are directly related in step 1 These influence judgements are integers (i.e., 1, 2, 3) ranging as follows:

- -3: strongly restricting influence
- -2: moderately restricting influence
- -1: weakly restricting influence
- 0: no influence
- +1: weakly promoting influence
- +2: moderately promoting influence
- +3: strongly promoting influence

Moving one-by-one through each square of the matrix depicted in the Miro board that is relevant for each , ask the following:

18. *Suppose the only piece of information given about the future of the Red River Basin is that future development X has the state x_i. Would you expect the direct influence of X on future development Y to be a hint that scenario factor Y has the state y_i (positive points), or as a hint that scenario factor Y does not have the state y_i (negative points)?

Example for clarity. Say two factors determined in step 1 interviews are A) **climate change** and B) **economic development**. Step 1 interviews will also determine factor states – i.e., 2 to 4 mutually exclusive possible end-states for each factor. For example, A) **climate change** could be *severe* (RCP8.5), *high* (RCP4.5) or *moderate* (RCP2.6), and B) **economic development** could be *growing*, *stagnant*, or *declining*. Question 3 asks experts to relate factor states to one another. So, in the wording of question 4 above, "suppose the only piece of information given about the future of the Red River Basin is that **climate change** is ***severe (RCP8.5)***. Would you expect the direct influence of **climate change** on **economic development** to be a hint that **economic development** is ***declining***, or as a hint that **economic development** is ***not declining***?

19. *What is the scale of that influence (-3 to +3)?

Example for clarity. Following from the example above, interviewees will be asked to rate the degree of influence according to a Likert scale from -3 to +3. For example, if **climate change** is ***severe (RCP8.5)*** and the expert indicates they expect this to be a hint that **economic development** is ***declining***, they will be then asked to rate this relationship as -1, -2, or -3.

<u>Step 3: Influence judgements between resilience interventions</u>

For each of the interventions for resilience, either:

20. *Repeat questions 3 and 4 for the components of the matrix relevant for resilience.

AND/OR

Imagine a future in which this resilience intervention is scaled and mainstream.

21. Which end states do you think would be impacted (promoted or discouraged) by this resilience intervention?
22. (optional) How do you think different end states would impact this resilience intervention?

More details for clarity: In step 1 interviews, participants identified innovative practices being pursued in the Red River Basin that may contribute to resilience, what features of the Red River Basin need to change to become resilient, and what features need to be preserved to become resilient. These will be represented in the CIB model as <u>either</u> alternative states for future developments in the CIB matrix <u>or</u> as external perturbations to the CIB matrix. For the former, these alternative factor states will be related to the others through influence judgements (-3 to +3) by repeating <u>questions 3 and 4 above</u>. For the latter, experts will be asked <u>questions 7 and 8</u>, which indicate which factor states would inform a perturbation/intervention analysis.

Closing

Thank you so much for your responses to these questions. You will receive a thank you letter and eGift card shortly. With your permission I may contact you for the purposes of clarification, validation, and elaboration of your interview up to 3 weeks from today and once all stage 2 interviews are complete, I will send you a summary of the synthesis of stage 2 interviews for your feedback.

In this study I am gathering a variety of perspectives. If there are major differences between your judgements today and those of others, I may invite you to a short workshop with other interviewees to discuss them, with your permission. With your permission you may hear from me with an invitation to later stages of the study

Thank you very much for participating in this study.

Appendix F

Influence judgments in cross-impact matrix

The tables below are judgment sections that summarize the influence judgments. In a judgment section, the variants in the row influence the variants in the column. The influence judgments are promoting (+) or inhibiting (-) on a scale of weak (1), moderate (2), or strong (3). According to the conventions of the CIB method, a row in a judgment section must sum to zero. The 'rationale' column summarizes the justification for the influence judgments in the row, as stated by interviews and/or in literature.

The primary sources of data for the influence judgments were the round 1 and 2 interviews. The 'supported by' column indicates the degree to which interviewee statements clearly supported the rationale for a given section. The check (✓) indicates that statements from at least two interviewees in round 1 interviews and/or at least one (expert) interviewee from round 2 interviewees support the rationale for the row. The question mark (?) indicates that interviewee statements may support the rationale for the row, but there remained a lack of clarity of disagreement among interviewees. The cross (✖) indicates that interviewees did not offer statements about the row.

Literature was used to triangulate interviewee responses. Thus, the 'supported by' column also indicates whether literature supported the rationale offered by interviewees. The check (✓) indicates that at least one literature source clearly validated the stated rationale. The question mark (?) indicates that literature may validate the stated rationale, but there remained a lack of clarity (e.g., considering context-specific factors in the Red River Basin). The cross (✖) indicates that literature did not validate the interviewee claims (e.g., because no literature was available).

The uncertain influence judgments were subject to a sensitivity analysis. In the 'sensitivity analysis' column, any non-zero influence judgments that are not subject to sensitivity analysis were marked 'none'. Any non-zero influence judgments that are uncertain (i.e., due to lack of support from interviews and/or literature) were marked according to which type of sensitivity analysis they are subject to. Type I addresses new relationships not included in the baseline, Type II involves adjustments of the scores for certain non-zero relationships in the baseline, and Type III addresses combinations of different sensitivities. Appendix G describes the protocol for the sensitivity analysis in detail.

		Global climate change			Rationale	Supported by		Sensitivity analysis
		Optimistic	Moderate	Severe		Literature	Interviews	
Global ag markets	Status quo	-1	2	-1	Status quo' global agricultural markets are associated with the shared socioeconomic pathway (SSP) that does not deviate significantly from historical trends (SSP2). SSP 2 is associated with moderate challenges with mitigation. Thus, 'status quo' agricultural markets influence global climate change toward a moderate outcome and restrict both optimistic and severe outcomes.	✓	N/A	None
	Higher demand	-3	1	2	Higher demand' global agricultural markets reflect the SSP describing a fossil-fuel driven economy (SSP5), which is associated with high challenges with mitigation. Thus, 'higher demand' agricultural markets influence global climate change toward a moderate or severe outcome and restrict an optimistic outcome.	✓	N/A	None
	Sustainable diets	3	-1	-2	Sustainable diets' global agricultural markets reflect the SSP that is a sustainable future (SSP1), which is associated with low challenges with mitigation. Thus, 'sustainable diets' agricultural markets influence global climate change toward an optimistic outcome and restrict both moderate and severe outcomes.	✓	N/A	None
	Everyone for themselves	-3	1	2	Everyone for themselves' agricultural markets reflect the SSP that is a highly fragmented future (SSP3)m which is associated with high challenges with mitigation. Thus, 'everyone for themselves' global agricultural markets influence global climate change to a moderate or severe outcome and restricts an optimistic outcome.	✓	N/A	None

		Rural ag economy			Rationale	Supported by		Sensitivity analysis
		Intensive ag	Diversified & regenerative			Literature	Interviews	
Global ag markets	Status quo	3	-3		Status quo' global agricultural markets are associated with the shared socioeconomic pathway (SSP) that does not deviate significantly from historical trends (SSP2). SSP 2 is associated with moderate challenges with mitigation. Thus, 'status quo' agricultural markets influence global climate change toward a moderate outcome and restrict both optimistic and severe outcomes.	✓	✓	None
	Higher demand	3	-3		Higher demand' global agricultural markets reflect the SSP describing a fossil-fuel driven economy (SSP5), which is associated with high challenges with mitigation. Thus, 'higher demand' agricultural markets influence global climate change toward a moderate or severe outcome and restrict an optimistic outcome.	✓	✓	None
	Sustainable diets	-2	2		**Rationale 1:** Sustainable diets' global agricultural markets reflect the SSP that is a sustainable future (SSP1), which is associated with low challenges with mitigation. Thus, 'sustainable diets' agricultural markets influence global climate change toward an optimistic outcome and restrict both moderate and severe outcomes.	✓	?	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		2	-2		**Rationale 2:** Existing intensive multinationals would capture new demand presented by international market pressure.	✓	?	
	Everyone for themselves	-2	2		**Rationale 1:** Everyone for themselves' agricultural markets reflect the SSP that is a highly fragmented future (SSP3)m which is associated with high challenges with mitigation. Thus, 'everyone for themselves' global agricultural markets influence global climate change to a moderate or severe outcome and restricts an optimistic outcome.	?	?	**Excluded from baseline. Type I sensitivity analysis of both rationale 1 and 2.**
		2	-2		**Rationale 2:** Greater pressure to produce for domestic self-sufficiency increases pressure to intensify			

		Regional demographics			Rationale	Supported by		Sensitivity analysis
		Urbanization	Rural revival	Mass growth		Literature	Interviews	
Global climate change	Optimistic	1	1	-2	Optimistic climate change scenarios influence demographics away from mass growth, as climate change impacts will be less, and fewer people are motivated to migrate.	✓	✓	None
	Moderate	0	0	0	Influence too uncertain. Could be trends in any direction.	-	-	N/A
	Severe	-1	-2	3	Severe climate change scenarios result in significant climate change impacts, influencing people to migrate to regions of relative climate security like the Red River Basin.	✓	✓	None

		Regional climate			Rationale	Supported by		Sensitivity analysis
		Warmer wetter	Warmer extreme	Hotter drier		Literature	Interviews	
Global climate change	Optimistic	2	1	-3	Optimistic global climate scenarios lead to some degree of warming by 2050 due to locked in emissions but avoid major and more extreme climatic shift. Increasing temperature leads to increased atmospheric moisture content, which increases average annual precipitation.	✓	✓	None
	Moderate	-3	2	1	Moderate global climate scenarios influence the regional climate toward a more extreme and unpredictable temperature & precipitation regime in the RRB. Higher chance of heat waves, heavy precipitation events, etc. Moderate global climate scenarios influence away from warmer & wetter outcomes as climate shifts outside of normal range of variability. Still potential to have more extreme hot and dry scenarios.	✓	✓	None
	Severe	-3	1	2	Severe global climate change outcomes influence the regional climate of the RRB toward a hotter and drier scenario. This will occur particularly if climatic tipping points are crossed and/or storm tracks shift. Potential still to have a hotter climate with more extreme variability (i.e., avoiding severe drought outcomes).	✓	✓	None

	Reg. cultural & political	Rationale	Supported by	Sensitivity analysis

		drivers						
		Private	Public			Literature	Interviews	
Regional demographics	Urbanization	-2	2		**Rationale 1:** Urban politics tend toward more progressive politics, which often emphasize environmental issues. Fewer farmers with traditionally greater focus on private landowner and economic interests.	✓	✓	**Excluded from baseline. Type I sensitivity analysis of rationale 1 and 2.**
		2	-2		**Rationale 2:** Urbanization takes more people out of rural areas, so people will not bear witness or mitigate land degradation, reinforcing a paradigm of private landowner and economic interests.	✓	✓	
	Rural revival	2	-2		**Rationale 1:** Rural revival brings more city dwellers closer to the agricultural economy, so they will empathize more with challenges of growing food on private land and adopt private landowner & economic interests. Assumed influence to public goods rural demographic change would be minor in comparison.	✓	✓	**Excluded from baseline. Type I sensitivity analysis of rationale 1 and 2.**
		-2	2		**Rationale 2:** Rural citizens tend to act more on environmental stewardship as they are closer to nature. More rural citizens will bring more people into this culture, moderately promoting public goods and environmental interests.	✓	✓	
	Mass growth	0	0		Mass growth may influence both private and public values, depending on the demographic characteristics of those migrating to the region.	-	-	N/A

	Rural ag economy			Rationale	Supported by		Sensitivity analysis
	Intensive	Diversified &			Literature	Interviews	

		ag	regenerative ag					
Regional demographics	Urbanization	3	-3		Urbanization leaves fewer people in rural areas with diverse skills for the labour force, further entrenching existing intensive economic system. High urbanization rates encroach on agricultural land, intensifying land that already exists as ag. Assumed increased urban demand would not push for greater diversification.	✓	✓	Supported by interviews and literature.
	Rural revival	-2	2		Rural revival brings more people with diverse skills to rural areas, offering opportunities for diversified economy. More people in rural areas to buy local products will increase demand for more diverse products. Assumption that there is no increase in competition for land for housing, etc.	?	✓	**Excluded from baseline. Type I sensitivity analysis.** *Uncertainty regarding whether this relationship holds under 21st century conditions (e.g., automation).*
	Mass growth	-2	2		**Rationale 1:** Mass growth will bring more people with diverse skills and needs to both urban and rural areas, offering opportunity and demand for diversified economy.	?	✓	**Excluded from baseline. Type I sensitivity analysis for rationale 1 and 2.**
		1	-1		**Rationale 2:** Questions remain about how many people and where they are housed, and associated implications on land pressure. Potential weak link to more intensive as available ag land is pressured to produce more.			

	Water security		Supported by	Sensitivity analysis

		Adequate	Unequal	Deficient	Rationale	Literature	Interviews	
Regional demographics	Urbanization	-1	2	-1	Urbanization reduces rural water demand but puts pressure on existing urban water resources, potentially driving unequal outcomes between rural and urban areas	✓	✓	None
	Rural revival	-2	1	1	Challenge with rural outmigration tied to associated agricultural activity. Potential for unequal or deficient outcomes.	✓	✓	None
	Mass growth	-3	1	2	Pop growth in both rural and urban areas increases demand and associated economic activity across the board, strongly increasing the risk of deficiency	✓	✓	None

		Gov investment priorities			Rationale	Supported by		Sensitivity analysis
		Status quo	Flexible	Reactive		Literature	Interviews	
Regional demographics	Urbanization	-1	-1	2	Sparse populations in rural areas have challenges attracting government funds (i.e., more investment per person, so disincentive for government involvement), potentially contributing to a reactive approach.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Rural revival	0	0	0	No direct influence	-	-	N/A
	Mass growth	0	0	0	No direct influence	-	-	N/A

	Rural ag economy	Rationale	Supported by	Sensitivity analysis

		Intensive ag	Diversified regenerative			Literature	Interviews	
Reg cultural & politics	Private	3	-3		Private landowner and economic interests reinforce existing intensive agriculture or motivate more intensive agriculture, limiting regenerative agriculture or diversification due to longer-term, more uncertain economic benefits.	✓	✓	None.
	Public	-2	2		Environmental values moderately promote regenerative/organic agriculture for its sustainability benefits. For example, if people are paying farmers for wetland restoration and ecosystem benefits, or if farmers choose to take action themselves due to their own value system.	✓	✓	None.

		Transboundary governance			Rationale	Supported by		Sensitivity analysis
		Collaborative	Cooperative	Independent		Literature	Interviews	
Reg cultural & politics	Private	-3	1	2	Private cultural values impede collaborative decision making, as diverse interests and needs are evaluated against profit maximization and individual land owner priorities.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Public	2	1	-3	Public cultural values influence a shift away from highly independent decision making, as public goods are shared and require greater collaboration or cooperation to meaningfully address.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**

	Infra resilience			Rationale	Supported by		Sensitivity analysis
	Centralized	Distributed infra	Natural		Literature	Interviews	

Reg cultural & politics	Private	3	-1	-2	Private values influence uptake of centralized or distributed infrastructure, which are highly managed and can offer near-term economic gains. Disincentive to preserve wetlands if they are not compensated equal to agricultural profits. Possible restricting of distributed as would require many landowners to contribute a portion of productive land.	✓	✓	None.
	Public	-3	1	2	Public values influence natural or distributed infrastructure outcomes, since they offer clearer benefits to the environment (e.g., valuing ecosystem services)	✓	✓	None.

		Government investment approach			Rationale	Supported by		Sensitivity analysis
		Conventional	Enhanced	Reactive		Literature	Interviews	
Reg cultural & politics	Private	1	-3	2	Private economic & landowner interests have a moderate positive influence on reactive and status quo approach. Across the basin, landowners are highly involved in local and regional government and if they believe there is nothing wrong with the way things are then they will want to stay the same (i.e., status quo and reactive).	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Public	-3	2	1	Public goods and environmental interests have a moderate positive influence on the enhanced approach, but would also weakly promote reactive because emergency measures may always be needed and depend primarily on other factors.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**

	Indigenous water rights			Rationale	Supported by		Sensitivity analysis
	Fully	Status			Literature	Interviews	

		recognized	quo					
Reg cultural & politics	Private	-2	2		Private landowner and economic interests driving decision making would negatively influence further recognition of Indigenous values and water rights, reinforcing the status quo.	✓	✓	None.
	Public	2	-2		Public goods and environmental interests are more compatible with Indigenous relationships to the land, so would moderately influence further recognition of Indigenous values and water rights.	✓	✓	None.

		Regional demographics			Rationale	Supported by		Sensitivity analysis
		Urbanization	Rural revival	Mass growth		Literature	Interviews	
Rural ag economy	Intensive ag	2	-2	0	Intensive agriculture leads to more centralization, with agglomeration in larger farming organizations. This trend has caused the existing trend of urbanization over the last century. Assumed no direct influence on mass growth	✓	✓	None.
	Diversified & regen ag	-3	3	0	Diversification would strongly promote rural revival and reduce urbanization, because there will be more amenities and diverse jobs available. Assumed no direct influence on mass growth.	✓	✓	None.

	Reg. cultural & political drivers			Rationale	Supported by		Sensitivity analysis
	Private	Public			Literature	Interviews	

Rural ag economy	Intensive ag	3	-3		Intensive agriculture tends to be necessarily more extractive to get a return on your investment. When agriculture has a more hierarchical structure, there is conventionally less interest in the labour and inputs that goes into food and more interest in private landowner and economic interests. This is a reciprocal, self-reinforcing relationship.	✓	✓	None.
	Diversified & regen ag	-2	2		The relationship between the type of rural economy and cultural values was weak historically (i.e., influenced primarily by other factors), but this link may be stronger now. Farmers values are oriented toward wanting to do something about climate change, sustainability, etc. but currently do not see an economically viable pathway.	✓	✓	None.

		Water availability			Rationale	Supported by		Sensitivity analysis
		Adequate	Unequal	Deficient		Literature	Interviews	
Rural ag economy	Intensive ag	-2	1	1	Intensive agriculture has significant water demand if driven by irrigation, and in the RRB agriculture is prioritized over other sectors potentially driving inequalities. Also, intensive agriculture perpetuates a drainage culture that moves water off the landscape and downstream quickly, potentially reducing water availability in times of scarcity.	✓	✓	None.
	Diversified & regen ag	3	-1	-2	Diversified and regenerative agriculture distributes water demands across different products and sectors. Also, regenerative agriculture includes perennial crops and improves soil health, which retains more moisture across the landscape.	✓	✓	None.

		Water quality		Rationale	Supported by		Sensitivity analysis
		Improved	Poor		Literature	Interviews	
ag ec	Intensive ag	-3	3	Intensive agriculture influences water quality to be poor due	✓	✓	None.

				to chemical and nutrient inputs onto the landscape that are washed into water bodies.			
	Diversified & regen ag	1	-1	Shift toward diversified & regenerative agriculture improves water quality due to decreased nutrients and chemical inputs. Additionally, improved soil health obtained through regenerative agricultural practices is expected to reduce erosion, improve water retention, etc. Some evidence that improved crop diversity would also reduce nitrogen and phosphorous leaching. Improvement to water quality has a slow response time, so significant improvements may not be seen on the landscape before 2050, even if practices changed quickly in the 2020s.	✓	✓	None.

		Ecological integrity			Rationale	Supported by		Sensitivity analysis
		High	Low			Literature	Interviews	
Rural ag economy	Intensive ag	-3	3		Intensive agriculture promotes ecological degradation primarily due to land disturbance and pollution.	✓	✓	None.
	Diversified & regen ag	3	-3		Regenerative agriculture promotes higher ecological integrity due to improvement of ecosystem services and promotion of biodiversity and wildlife habitat.	✓	✓	None.

	Infra resilience			Rationale	Supported by		Sensitivity analysis
	Centralized	Distributed infra	Natural		Literature	Interviews	

Rural ag economy	Intensive ag	1	1	-2	Intensive agriculture influences approach to infra resilience to be centralized or distributed, as it requires drainage systems that are highly managed and controlled.	?	✓	**Excluded from baseline. Type I sensitivity analysis.** *In addition to lack of validation in literature, aspects of this influence are indirect and reinforce the relationship between cultural & political drivers and the approach to infrastructure for resilience.*
	Diversified & regen ag	-2	1	1	Diversified and regenerative ag economy influences approach to infra resilience to be natural or distributed to service a wider range of economic needs.	✗	✓	**Excluded from baseline. Type I sensitivity analysis.** *In addition to lack of validation in literature, aspects of this influence are indirect and reinforce the relationship between cultural & political drivers and the approach to infrastructure for resilience.*

		Rural ag economy			Rationale	Supported by		Sensitivity analysis
		Intensive ag	Diversified & regenerative ag			Literature	Interviews	
Water availability	Adequate	2	-2		**Rationale 1:** Adequate water availability allows for continuation of status quo (intensive) or opportunities to become more water intensive. No influence to shift toward a more regenerative agricultural system.	✗	✗	**Excluded from baseline. Type I sensitivity analysis of rationale 1 and 2**
		1	-1		**Rationale 2:** Adequate water availability allows for continuation of status quo (intensive) or opportunities to become more water intensive. No influence to shift toward a more regenerative agricultural system.	✗	✗	
	Unequal	-1	1		**Rationale 1:** Unequal water availability may reduce viability of intensive agriculture, particularly if it requires irrigation. Potential incentive to shift toward diversification/regenerative ag.	?	✓	**Excluded from baseline. Type I sensitivity analysis of rationale 1 and 2.**

		2	-2		**Rationale 2:** Unequal water availability results in some closure of smaller farms, resulting in further consolidation in intensive agriculture. Only weakly promoting more intensive agriculture as water allocations may be restricted.	✗	✓	
	Deficient	-2	2		**Rationale 1:** Intensive agriculture is only possible with sufficient water availability, including irrigation under drought scenarios. Deficiency reduces the viability of this type of system and may influence a shift in the system toward regenerative ag.	?	✓	**Excluded from baseline. Type I sensitivity analysis of rationale 1 and 2.**
		3	-3		**Rationale 2:** Deficient water availability leads to mass closures of smaller farms, dramatically consolidating and entrenching the intensive agriculture system.	✗	✓	

		Transboundary governance			Rationale	Supported by		Sensitivity analysis
		Collaborative	Cooperative	Independent		Literature	Interviews	
Water availability	Adequate	2	1	-3	**Rationale 1:** Adequate water availability encourages meaningful collaborative or cooperative relationships between jurisdictions.	✗	✓	**Excluded from baseline. Type I sensitivity analysis of rationale 1 and 2.**
		-3	1	2	**Rationale 2:** Adequate water security offers no incentive for jurisdictions to work together, so it would inhibit collaboration and promote independence. There is always some degree of cooperation.	✗	✓	
	Unequal	-1	-1	2	**Rationale 1:** Unequal water availability strains collaborative and cooperative governance arrangements, as jurisdictions attempt to protect their own resources, at the expense of others.	✓	✓	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		1	1	-2	**Rationale 2:** Unequal outcomes would bring people together to solve issues collectively, driving	✗	✓	

					Rationale	Literature	Interviews	Sensitivity analysis
					collaboration or cooperation.			
	Deficient	-2	-1	3	**Rationale 1:** Deficient water availability creates conflict and breaks down cooperation and collaboration.	✓	✓	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		2	1	-3	**Rationale 2:** Deficiency would drive a collaborative approach. After a single event, people might move toward an independent approach, but chronic deficiency over time would bring jurisdictions together.	✗	✓	

		Gov investment priorities			Rationale	Supported by		Sensitivity analysis
		Conventional	Flexible	Reactive		Literature	Interviews	
Water availability	Adequate	2	-1	-1	Adequate water availability reinforces a conventional government investment approach, as there is no incentive to pivot toward other approaches.	✗	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Unequal	1	-3	2	Unequal water availability would promote a reactive or status quo approach, because of the need for crisis management. Government would only be motivated to adopt an enhanced approach if the lack of availability is chronic and money must pour into the system.	✗	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Deficient	-3	2	1	Chronic deficiency would force governments to react with an enhanced approach. Still reactive approach would coexist because of need to support near-term issues.	✗	✓	**Excluded from baseline. Type I sensitivity analysis.**

	Authority			Rationale	Supported by		Sensitivity analysis
	Local	Top-down			Literature	Interviews	

Water availability	Adequate	2	-2		Adequate water availability encourages local, bottom-up governance	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Unequal	-2	2		Unequal water availability causes conflict, encouraging more top-down, command-and-control governance	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Deficient	-2	2		Deficient water availability causes loss, damage, and conflict, encouraging "states of emergency" and top-down, command-and-control governance.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**

		Approach to infra for resilience			Rationale	Supported by		Sensitivity analysis
		Centralized	Distributed	Natural		Literature	Interviews	
Indigenous water rights	Fully recognized	-3	1	2	Fully recognized Indigenous water rights and more prominent Indigenous values would positively influence an approach to infrastructure for resilience that prioritizes natural ecosystems and a whole-system (or distributed) approach. Additionally, it would promote a shift *away* from a centralized system, which results in winners and losers and conventionally protects urban areas and prominent economic sectors over Indigenous land and communities.	✓	✓	None.
	Status quo	2	1	-3	Continued status quo (meaning lack of) role of Indigenous values and water rights in decision making would moderately reinforce the centralized system and significantly de-prioritize natural ecosystems. These were assumed based on the inverse of the rationale articulated above.	×	×	**Excluded from baseline. Type I sensitivity analysis.**

	Cultural & political drivers			Rationale	Supported by		Sensitivity analysis
	Private	Public			Literature	Interviews	

					Rationale	Literature	Interviews	Sensitivity analysis
Indigenous water rights	Fully recognized	-3	3		Fully recognized Indigenous water rights would imply more prominent Indigenous values in the culture and politics driving decision making. This would hint toward a culture that prioritizes public goods and the environment over private landowner and economic interests when required, as this better reflects Indigenous relationships to the land.	✓	✓	None.
	Status quo	2	-2		Inverse of rationale above. Status quo (meaning lack of) role of Indigenous values and water rights in water-related decision making moderately reinforces the existing support for private landowner and economic interests.	✓	✓	None.

		Rural economy			Rationale	Supported by		Sensitivity analysis
		Intensive	Diversified & regenerative			Literature	Interviews	
Indigenous water rights	Fully recognized	-2	2		Resource intensity and ecological degradation driven by intensive agriculture is generally not compatible with an Indigenous worldview. Fully recognized Indigenous land and water rights would moderately influence a shift toward a diversified and regenerative agricultural economy.	✓	✓	None.
	Status quo	0	0		No direct influence.	-	-	

		Data & Knowledge Systems			Rationale	Supported by		Sensitivity analysis
		Patchwork	Coordinated & scientific	Collaborative & integrated		Literature	Interviews	
Indigenous water rights	Fully recognized	0	-3	3	Fully recognized Indigenous values and water rights would strongly influence preference for a collaborative and integrated data and knowledge system over a coordinated & scientific knoweldge system, due to the strengthened role of Indigenous and local knowledge holders in decision making.	✓	✓	None.

					Assumed no influence on patchwork data collection, because it would be influenced by other factors.			
	Status quo	0	2	-2	The status quo moderately influences preference for coordinated & scientific data and knowledge systems and restricts collaborative & integrated knowledge systems, because Indigenous and local knowledge holders' role in decision making is not prevalent. Assumed no influence on patchwork data collection, because it would be influenced by other factors.	✓	?	None.

		Transboundary governance			Rationale	Supported by		Sensitivity analysis
		Collaborative	Cooperative	Independent		Literature	Interviews	
Indigenous water rights	Fully recognized	3	-1	-2	Fully recognized Indigenous water rights would require high degrees of collaboration to resolve challenges associated with allocation, etc.	✓	✓	None.
	Status quo	-2	1	1	Status quo governance lacks common goals and meaningful involvement of Indigenous communities in governance and decision making. Status quo reflects historical exclusion of Indigenous communities from transboundary decision making.	✓	✓	None.

	Water security			Rationale	Supported by		Sensitivity analysis
	Adequate	Unequal	Deficient		Literature	Interviews	

Regional climate	Warmer & wetter	3	-1	-2	Warmer and wetter climate promotes adequate water availability, as extremes are manageable and within the range of variability buffered by existing infrastructure.	✓	✓	None.
	Warmer & extreme	-3	2	1	Warmer & extreme climate encourages promotes unequal availability over time and space due to hydroclimatic uncertainty beyond extremes buffered by existing infrastructure.	✓	✓	None.
	Hotter & drier	-3	1	2	Hotter & drier climate encourages deficient water availability.	✓	✓	None.

		Water quality			Rationale	Supported by		Sensitivity analysis
		Improved	Poor			Literature	Interviews	
Regional climate	Warmer & wetter	-2	2		**Rationale 1:** An abundance of water would flush contaminants into water bodies, both during snowmelt and rainfall events. This would increase the load of contaminants in the Red River system.	✓	✓	**Excluded from baseline. Type I sensitivity analysis with both rationale 1 and 2.**
		1	-1		**Rationale 2:** An abundance of water would flush contaminants into water bodies, but it would also reduce their concentration and residence time, which would slightly improve the water quality.	✓	✓	
	Warmer & extreme	-3	3		More extreme variability would flush more contaminants into water bodies during peak flow events. Any buildup of contaminants on the landscape during low-flow or drought events would also be flushed into the system. This would increase the load of contaminants in the Red River system.	✓	✓	None.
	Hotter & drier	-2	2		**Rationale 1:** A hotter and drier climate sees less water on the surface, which means poorer quality in terms of temperature, concentration of contaminants, etc. Even under a hotter & drier scenario there will still be rainfall, and because the Prairies are continental these rainfall events will likely be more extreme.	✓	✓	**Rationale 1 included in baseline. Type II sensitivity of rationale 2.**
	Hotter & drier	1	-1		**Rationale 2:** A hotter and drier reduces landscape runoff, so less contaminants are drawn into the Red River system.	✓	✓	

	Ecological integrity	Rationale	Supported by	Sensitivity analysis

		High	Low			Literature	Interviews	
Regional climate	Warmer & wetter	1	-1		Overall, a warmer & wetter climate would improve ecological integrity because you're increasing ecological activity by adding more moisture to the environment and avoiding severe dry spells. This influence is weak because it is tempered by the higher temperature, which changes the type of organisms that will thrive in the ecosystem.	?	✓	**Excluded from baseline. Type I sensitivity analysis.** *Uncertainty remains regarding whether a warmer & wetter climate would improve ecological integrity (e.g., by introducing more moisture and biological activity) or would decrease ecological integrity due to warmer temperatures that shift the climate regime away from its "natural state".*
	Warmer & extreme	-1	1		Warmer & more extreme variability reduces ecological integrity, because the ecosystems are always trying to bounce back from the more recent dry spells. This influence is weak because it is tempered by the positive role of disturbance in facilitating ecological activity.	✓	✓	None.
	Hotter & drier	-2	2		Hotter & drier climate promotes low ecological integrity because availability of water is a key indicator of survivability as ecosystems are constantly recovering from severe dry periods. Also, the temperature regime is extended beyond organisms' preferred range.	✓	✓	None.

		Ecological integrity			Rationale	Supported by		Sensitivity analysis
		High	Low			Literature	Interviews	
Water quality	Improved	3	-3		Improved water quality improves ecological integrity, for example as eutrophication and algal blooms are diminished due to reduced nutrient loading.	✓	✓	None.
	Poor	-3	3		Poor water quality exacerbates ecological degradation. For example, nutrient loading contributes to eutrophication and algal blooms and poor water quality affects benthic integrity.	✓	✓	None.

	Water quality			Rationale	Supported by		Sensitivity analysis
	Improved	Poor			Literature	Interviews	

Ecological integrity	High	2	-2		Higher ecological integrity improves the capacity of the system to naturally capture and treat contaminants. Lower risk of algal blooms, etc.	✓	✓	None.
	Low	-2	2		Inverse rationale as above	✓	✓	None.

		Water quality			Rationale	Supported by		Sensitivity analysis
		Improved	Poor			Literature	Interviews	
Transboundary governance	Collaborative	3	-3		A collaborative approach with common goal and understanding among jurisdictions would significantly improve water quality by resolving the upstream-downstream dynamic.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Cooperative	1	-1		Cooperation between institutions helps negotiate between multiple interests in efforts to improve water quality. Still limited by locked-in perspectives and individual goals limit significant improvements.	?	✓	**Excluded from baseline. Type I sensitivity analysis.** *Uncertainty due to history of cooperative commitments to improving water quality yet there is a lack of evidence that they have improved water quality.*
	Independent	-2	2		Tension and locked-in perspectives between jurisdictions restrict improvement to water quality, because it is difficult to motivate voluntary commitments	×	✓	**Excluded from baseline. Type I sensitivity analysis.** *Uncertainty due to history of cooperative commitments to improving water quality yet there is a lack of evidence that they have improved water quality.*

	Data systems		Supported by	Sensitivity

		Patchwork	Coordinated and scientific	Collective & integrated	Rationale	Literature	Interviews	analysis
Transboundary gov	Collaborative	-3	1	2	Collaborative governance meaningfully engages with all jurisdictions and perspectives at all levels, including Indigenous. Would be conducive environment for a more integrated and collective approach to data and modelling.	✓	✓	None.
	Cooperative	1	2	-3	Cooperative governance still driven by independent goals, encouraging coordinated/scientific for better data coverage, but lacks common goals and Indigenous engagement for truly collective/integrated.	✓	✓	None.
	Independent	3	-1	-2	Independent governance strongly influences a patchwork approach, as each jurisdiction pursues data collection independently. Lack of structure for coordination or collective action.	✓	✓	None.

		Infra resilience			Rationale	Supported by		Sensitivity analysis
		Centralized	Distributed infra	Natural		Literature	Interviews	
Transboundary gov	Collaborative	-2	1	1	Collaborative governance supports approaches that benefit the whole system, rather than individual needs. Positive influence toward distributed and natural approaches as demonstrated by existing bottom-up initiatives.	×	✓	**Excluded from baseline. Type I sensitivity analysis**
	Cooperative	0	0	0	Cooperative governance would support all three types, so no direct influence to any.	×	✓	None.
	Independent	2	-1	-1	Independent governance encourages centralized infra, as it helps secure individual needs (e.g., major diversions), sometimes at the expense of the whole.	✓	✓	None.

		Authority			Rationale	Supported by		Sensitivity analysis
		Local	Top-down			Literature	Interviews	
Transboundary gov	Collaborative	3	-3		Collaborative governance connects bottom-up initiatives to a larger whole, empowering learning, etc.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Cooperative	0	0		No clear direct influence	-	-	None.
	Independent	-3	3		Independent governance creates potential for conflict/tensions that lead to more top-down control.	?	✓	**Excluded from baseline. Type I sensitivity analysis.**

		Indigenous water rights			Rationale	Supported by		Sensitivity analysis
		Fully recognized	Status quo			Literature	Interviews	
Transboundary gov	Collaborative	2	-2		Assumption that transboundary governance that meaningfully includes Indigenous communities and leaders in decision making would have a weak to moderate influence on Indigenous values and water rights becoming more prominent.	✓	✓	None.
	Cooperative	0	0		No direct influence.	-	-	None.
	Independent	0	0		No direct influence.	-	-	None.

		Gov investment priorities			Rationale	Supported by		Sensitivity analysis
		Conventional	Enhanced	Reactive		Literature	Interviews	
Data systems	Patchwork	1	-2	1	Lack of (updated) information makes governments more reactive or lets them fall back on proven solutions with value that is proven and easy-to-understand.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Coordinated and scientific	1	2	-2	More coordinated scientific data also reveals cost of inaction (reactive). While more holistic scientific data may clarify the value of both status quo and flexible investments, it may not reveal the hidden costs of status quo options.	✓	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Collective & integrated	-1	3	-2	More holistic approach to data collection helps reveal cost of inaction (i.e., the reactive investment approach) and the	×	✓	**Excluded from baseline. Type I sensitivity analysis.**

					hidden costs of status quo investments. This would encourage a shift toward more flexible options.			

		Infra resilience			Rationale	Supported by		Sensitivity analysis
		Centralized	Distributed infra	Natural		Literature	Interviews	
Data systems	Patchwork	3	-2	-1	**Rationale 1:** If data systems are patchwork, decision makers will not know what is happening on the landscape and try to "control" uncertainty and resort to conventional investments in centralized infrastructure. Assumption that distributed infrastructure is more restricted than natural.	✓	✓	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		3	-1	-2	**Rationale 2:** Same as rationale 1, but assumed that distributed infrastructure is more restricted than natural.	✓	✓	
	Coordinated and scientific	-3	2	1	Coordinated and scientific data systems help see the systems as a whole, enabling a distributed, watershed-based approach to managing water. Relying on natural ecosystems also involved some degree of control, which may also be enabled by coordinated and scientific data systems.	✓	✓	None.
	Collective & integrated	-3	1	2	Collective and integrated data system enables design and coordination of a distributed system. Because local and Indigenous knowledges are also included, would more strongly support natural ecosystems approach. Also, reveals hidden costs of centralized system (e.g., diverting problems elsewhere; downstream impacts).	✓	✓	None.

		Water quality			Rationale	Supported by		Sensitivity analysis
		Improved	Poor			Literature	Interviews	
Data & knowledge	Patchwork	-1	1		Data & knowledge systems allow for targeted water quality interventions. Patchwork data systems contribute to lack of knowledge regarding where and what interventions will work.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Cooperative & scientific	1	-1		Cooperative & scientific data and knowledge system allow for targeted interventions to improve water quality.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Collective & integrated	1	-1		Collective & integrated data and knowledge system allow for targeted interventions to improve water quality.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**

		Indigenous water rights			Rationale	Supported by		Sensitivity analysis
		Fully recognized	Status quo			Literature	Interviews	
Data & knowledge system	Patchwork	0	0		No direct influence.	-	-	None.
	Coordinated & scientific	0	0		No direct influence.	-	-	None.
	Collective & integrated	1	-1		Collective and integrated data and knowledge would include Indigenous voices, contributing to further empowerment of Indigenous interests in water-related decision making. This interaction is reciprocal, and stronger in the opposite direction.	✓	✓	None.

		Transboundary			Rationale	Supported by		Sensitivity analysis
		Collaborative	Cooperative	Independent		Literature	Interviews	
Data & knowledge system	Patchwork	-1	-1	2	Lack of data acts as a key barrier to more cooperative and collaborative forms of governance.	✓	?	None.
	Coordinated & scientific	0	0	0	No direct influence.	-	-	None.
	Collective & integrated	2	-1	-1	A collective & integrated data and knowledge system would reinforce a collaborative governance approach. This interaction is reciprocal and stronger in the opposite direction.	✓	?	None.

		Data systems				Supported by		
		Patchwork	Coordinated and scientific	Collective & integrated	Rationale	Literature	Interviews	Sensitivity analysis
Gov investment approach	Conventional	1	2	-2	Status quo investment priorities encourage either patchwork systems (as currently exist) or investment in coordinated/scientific data systems required to calculate status quo ROIs, etc.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Enhanced	-3	1	2	Flexible investment priorities encourage coordinated or collective data systems, as it encourages a more proactive approach and investment in soft infrastructure	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Reactive	3	-1	-2	Reactive investment priorities encourages a patchwork data system, as the alternatives require a longer-term, pro-active view	×	✓	**Type I sensitivity analysis.**

		Infra resilience			Rationale	Supported by		Sensitivity analysis
		Centralized	Distributed infra	Natural		Literature	Interviews	
Gov investment approach	Conventional	3	-1	-2	Status quo government investment priorities encourage centralized infra systems, as large-scale, centralized systems cater to traditional investment tools/assessment techniques and do not similarly value other forms of investment **Included all stated influence judgments in this section in prototype 0.**	✓	✓	None.
	Enhanced	-3	2	1	**Rationale 1:** Flexible government investment priorities encourage distributed and natural systems, as these systems may be more economically efficient than centralized but difficult to finance under status quo priorities. Assumption that distributed will be more strongly promoted than natural infrastructure.	✓	✓	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		-3	1	2	**Rationale 2:** Same as rationale 1. Assumption that natural will be natural more strongly than distributed infrastructure.			
	Reactive	3	-2	-1	**Rationale 1:** Reactive investment priorities reinforce centralized infra systems; difficult to move toward alternatives like distributed/natural. Assumption that distributed is more strongly restricted than natural.	×	✓	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		3	-1	-2	**Rationale 2:** Same as rationale 1. Assumption that natural is more strongly restricted than distributed.			

		Water security			Rationale	Supported by		Sensitivity analysis
		Adequate	Unequal	Deficient		Literature	Interviews	
Infra resilience	Centralized	3	-1	-2	**Rationale 1:** Centralized infrastructure protects against major deficiency like the 1930s drought or worse, but storing water and redirecting it as needed during flood events. Centralized infrastructure avoids devastating outcomes from either floods or droughts and balances out unequal competition.	✓	✓	**Excluded from baseline. Type III sensitivity analysis of rationales 1,2, and 3 (i.e., rationale 1 for influence of centralized, distributed, and natural on water security in combination, etc.)**
		-3	2	1	**Rationale 2:** Centralized infra systems push problems elsewhere, perpetuating unequal access. Uncontrolled drainage reduces resilience to drought/low-flow periods, promoting deficient outcomes.	✓	✓	
		-3	2	1	**Rationale 3:** Centralized infrastructure systems promotes unequal security because there will be winners and losers. Uncontrolled drainage reduces resilience to drought/low-flow periods.	✓	✓	
	Distributed infra	-1	2	-1	**Rationale 1:** Distributed infrastructure would provide some buffer against extremes but would ultimately promote an unequal outcome because it wouldn't have enough capacity for peak extremes.	?	✓	**Excluded from baseline. Type III sensitivity analysis of rationales 1,2, and 3 (i.e., rationale 1 for influence of centralized, distributed, and natural on water security in combination, etc.)**
		3	-2	-1	**Rationale 2:** Distributed infra systems retain water on the land where it is needed, helping reduce unequal access (problem not pushed away) and improving resilience to low-flow	?	✓	
		2	-1	-1	**Rationale 3:** Distributed system would weakly or moderately improve water security, as it reduces landscape runoff.	✓	✓	
	Natural	-3	1	2	**Rationale 1:** We know nature gives us ecosystem services and some resilience to drought through flood storage. However, it would lead to deficient water availability as it wouldn't handle the peaks.	?	✓	**Excluded from baseline. Type III sensitivity analysis of rationales 1,2, and 3 (i.e., rationale 1 for influence of centralized, distributed, and natural on water security in combination, etc.)**
		-2	1	1	**Rationale 2:** Natural ecosystems inhibit adequacy because hydroclimatic variability exceeds natural capacity to buffer.	?	✓	
		3	-1	-2	**Rationale 3:** Natural infra systems retain water on the land and built an even stronger natural	✓	✓	

					buffer to low flow by improving capacity of soil to retain moisture. Many things would have to change for this to be in place by 2050, but if it were that would strongly promote adequate. The system has been so modified, so if you were able to restore some ecosystem functions that would be positive.			

		Water quality			Rationale	Supported by		Sensitivity analysis
		Improved	Poor			Literature	Interviews	
Infra resilience	Centralized	-2	2		Centralized infra perpetuates uncontrolled drainage culture, which causes contaminants to migrate more easily from land to waterways.	✓	✓	None.
	Distributed infra	2	-2		Distributed infra helps retain water where it lands, reducing upstream-downstream runoff. Ability to optimize the system to meet various water quantity and quality objectives.	✓	✓	None.
	Natural	2	-2		**Rationale 1:** Wetlands and habitat provide water purification service.	?	✓	**Rationale 1 included in baseline. Type II sensitivity analysis of rationale 2.**
		-1	1		**Rationale 2:** Natural systems may not perform their functions, e.g., due to context-specific factors, such as whether the nutrient loading reaches a critical threshold beyond which the wetland cannot handle, or if a wetland is not managed to ensure plants that release nutrient uptake back into the system are removed seasonally.			

		Ecological integrity			Rationale	Supported by		Sensitivity analysis
		High	Low			Literature	Interviews	
Infra resilience	Centralized	-2	2		Centralized systems negatively impact ecological inteigrty by disrupting natural flows and draining wetlands. Inter-basin transfers risk introducing new potentially harmful biota to the Red River Basin system.	✓	✓	None.
	Distributed infra	-1	1		Distributed infrastructure creates opportunities to restore natural flow regimes and for habitat to develop around ponds. and reduce degradation from centralized infra systems. However, this influence is tempered by lack of priority to restore and	?	✓	**Excluded from baseline. Type I sensitivity analysis.**

					protect diverse natural habitats, including different types of natural wetlands, etc. Also, reduces ecological integrity because there are more interventions on more landscape.			
	Natural	2	-2		Natural ecosystem approach directly improves ecological integrity by prioritizing habitat restoration and associated ecosystem goods and services.	✓	✓	None.

		Data systems			Rationale	Supported by		Sensitivity analysis
		Patchwork	Coordinated scientific	Collective integrated		Literature	Interviews	
Authority	Local	1	-2	1	Local, bottom-up authority encourages collective and integrated data systems as local/Indigenous/scientific knowledge is utilized as needed to solve local challenges (e.g., via citizen science). Potential for patchwork due to lack of top-down coordination.	✓	✓	None.
	Top-down	1	1	-2	Top-down authority encourages coordinated, scientific data to diagnose top-down solutions or patchwork data due to reluctance to disclose data.	✓	✓	None.

		Infra resilience			Rationale	Supported by		Sensitivity analysis
		Centralized	Distributed infra	Natural		Literature	Interviews	
Authority	Local	-3	2	1	Local, bottom-up authority encourages natural and distributed infra, as water is managed where it lands and local stakeholders are aware of ecosystem services of distributed or natural systems.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**
	Top-down	2	1	-3	Top-down authority includes centralized infra, as it is more conducive to a command-and-control approach. Highly managed distributed system may also be compatible with a distributed system.	×	✓	**Excluded from baseline. Type I sensitivity analysis.**

Appendix G

Sensitivity analysis

The influence judgments described in Appendix F were subject to a detailed sensitivity analysis. First, prototype 0 includes only the influence judgments that are 1) not subject to sensitivity analysis (i.e., are not uncertain), or 2) are the better supported rationale (i.e., by interviews and literature) for judgment sections subject to type II sensitivity analysis (i.e., adjustments to non-zero influence judgments). All remaining judgment sections were uncertain and were zeroed, including those subjected to type I (i.e., introductions of new influence judgments) or type III (i.e., combinations of sensitivities). The cross-impact matrix for Prototype 0 is depicted in Figure G-1.

	A1 a b c d	A2 a b c	B1 a b c	B2 a b	B3 a c	B4 a b c	B5 a b	C1 a b c	C2 a b	C3 a b	D1 a b c	D2 a b c	D3 a b c	D4 a b c	D5 a b
A1 Gl. ag. markets															
a - Status quo		-1 2 -1	0 0 0	0 0	3 -3	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Higher demand		-3 1 2	0 0 0	0 0	3 -3	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
c - Sustainable diets		3 -1 -2	0 0 0	0 0	-2 2	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
d - Everyone for themselves		-3 1 2	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
A2 Gl. climate change															
a - Optimistic	0 0 0 0		1 1 -2	0 0	0 0	0 0 0	0 0	2 1 -3	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Moderate	0 0 0 0		0 0 0	0 0	0 0	0 0 0	0 0	-3 2 1	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
c - Severe	0 0 0 0		-1 -2 3	0 0	0 0	0 0 0	0 0	-3 1 2	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
B1 Demographics															
a - Urbanization	0 0 0 0	0 0 0		0 0	3 -3	-1 2 -1	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Rural revival	0 0 0 0	0 0 0		0 0	0 0	-2 1 1	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
c - Mass growth	0 0 0 0	0 0 0		0 0	0 0	-3 1 2	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
B2 Culture/politics															
a - Private	0 0 0 0	0 0 0	0 0 0		3 -3	0 0 0	-2 2	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	3 -1 -2	0 0
b - Public	0 0 0 0	0 0 0	0 0 0		-2 2	0 0 0	2 -2	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	-3 1 2	0 0
B3 Rural economy															
a - Intensive ag	0 0 0 0	0 0 0	2 -2 0	3 -3		-2 1 1	0 0	0 0 0	-3 3	-3 3	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Regenerative ag	0 0 0 0	0 0 0	-3 3 0	-2 2		3 -1 -2	0 0	0 0 0	1 -1	3 -3	0 0 0	0 0 0	0 0 0	0 0 0	0 0
B4 Water availability															
a - Adequate	0 0 0 0	0 0 0	0 0 0	0 0	0 0		0 0	0 0 0	0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Unequal	0 0 0 0	0 0 0	0 0 0	0 0	0 0		0 0	0 0 0	0 0	0 0	-1 -1 2	0 0 0	0 0 0	0 0 0	0 0
c - Deficient	0 0 0 0	0 0 0	0 0 0	0 0	0 0		0 0	0 0 0	0 0	0 0	-2 -1 3	0 0 0	0 0 0	0 0 0	0 0
B5 Indigenous water rights															
a - Fully recognized	0 0 0 0	0 0 0	0 0 0	-3 3	-2 2	0 0 0		0 0 0	0 0	0 0	3 -1 -2	0 -3 3	0 0 0	-3 1 2	0 0
b - Status quo	0 0 0 0	0 0 0	0 0 0	2 -2	0 0	0 0 0		0 0 0	0 0	0 0	-2 1 1	0 2 -2	0 0 0	0 0 0	0 0
C1 Regional climate															
a - Warmer & wetter	0 0 0 0	0 0 0	0 0 0	0 0	0 0	3 -1 -2	0 0		0 0	0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Warmer & extreme	0 0 0 0	0 0 0	0 0 0	0 0	0 0	-3 2 1	0 0		-3 3	-1 1	0 0 0	0 0 0	0 0 0	0 0 0	0 0
c - Hotter & drier	0 0 0 0	0 0 0	0 0 0	0 0	0 0	-3 1 2	0 0		-2 2	-2 2	0 0 0	0 0 0	0 0 0	0 0 0	0 0
C2 Water quality															
a - Improved	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0		3 -3	0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Poor	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0		-3 3	0 0 0	0 0 0	0 0 0	0 0 0	0 0
C3 Ecological integrity															
a - High	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	2 -2		0 0 0	0 0 0	0 0 0	0 0 0	0 0
b - Low	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	-2 2		0 0 0	0 0 0	0 0 0	0 0 0	0 0
D1 Transboundary gov.															
a - Collaborative	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	2 -2	0 0 0	0 0	0 0		-3 1 2	0 0 0	0 0 0	0 0
b - Cooperative	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0		1 2 -3	0 0 0	0 0 0	0 0
c - Independent	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0		3 -1 -2	0 0 0	2 -1 -1	0 0
D2 Data & knowledge syst.															
a - Patchwork	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	-1 -1 2		0 0 0	3 -2 -1	0 0
b - Coordinated & scientific	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0		0 0 0	-3 2 1	0 0
c - Collective & integrated	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	1 -1	0 0 0	0 0	0 0	2 -1 -1		0 0 0	-3 1 2	0 0
D3 Gov. investment approach															
a - Conventional	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0		3 -1 -2	0 0
b - Enhanced	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0		-3 2 1	0 0
c - Reactive	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	0 0 0		3 -2 -1	0 0
D4 Infra resilience															
a - Centralized	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	-2 2	-2 2	0 0 0	0 0 0	0 0 0		0 0
b - Distributed	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	2 -2	0 0	0 0 0	0 0 0	0 0 0		0 0
c - Natural	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	2 -2	2 -2	0 0 0	0 0 0	0 0 0		0 0
D5 Level of authority															
a - Bottom-up	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	1 -2 1	0 0 0	0 0 0	
b - Top-down	0 0 0 0	0 0 0	0 0 0	0 0	0 0	0 0 0	0 0	0 0 0	0 0	0 0	0 0 0	1 1 -2	0 0 0	0 0 0	

Figure G-1: Summary of prototypes in sensitivity analysis

Prototype 0a, 0b, and 0c are differentiated by a Type III sensitivity on the influence of the ‘approach to infrastructure for resilience’ on ‘water availability’. This Type III sensitivity was structured into three versions of the judgment section, all of which were voiced by multiple participants but none of which could be validated with literature. Prototypes 1 (a, b, c) and 2 (a, b, c) include maximally diverse combinations of Type I and II sensitivity analyses as depicted in Figure G-2, where prototype 2 (a, b, c) both further augments the scope of uncertainty covered in prototypes 1 (a, b, c). Thus, the sensitivity analysis produced nine prototypes of the model. However, only the six prototypes of 1 (a, b, c) and 2 (a, b, c) were analyzed. Prototypes 0a, 0b, and 0c were not analyzed further: the results would not be meaningful given the number of uncertain judgment sections that were zeroed. A detailed description of which influence judgments were changed from prototype 0 are summarized in Table G-1.

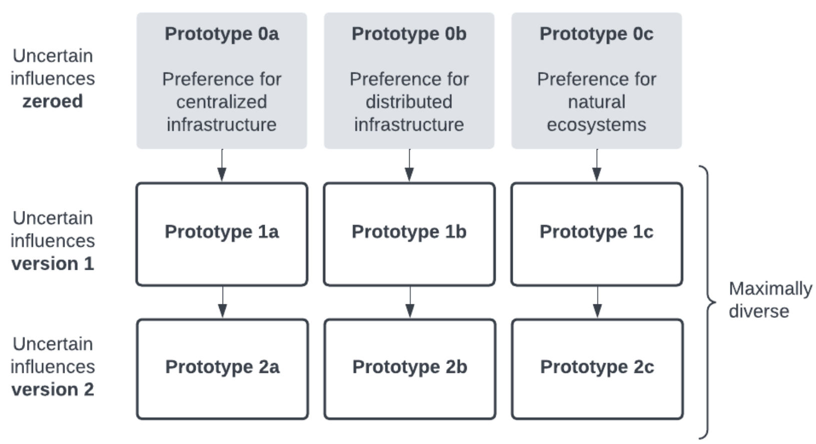

Figure G-2: Summary of prototypes in sensitivity analysis

Table G-1: Detailed description of each prototype with associated changes from prototype 0

Prototype		Purpose	Changes from prototype 0	Adequate	Unequal	Deficient
0	a	Evaluate the Type III sensitivity analysis of the influence of ‘approach to infrastructure for resilience’ on ‘water availability’ with the assumption that centralized infrastructure is most effective for improving water availability.	Centralized	3	-2	-1
			Distributed	-1	2	-1
			Natural	-2	-1	3
	b	Type III sensitivity analysis of the influence of ‘approach to infrastructure for resilience’ on ‘water availability’ with the assumption that distributed infrastructure is most effective for improving water availability.	Centralized	-1	2	-1
			Distributed	2	-1	-1
			Natural	-2	2	0
	c	Type III sensitivity analysis of the influence of ‘approach to infrastructure for resilience’ on ‘water availability’ with the assumption that natural ecosystems are most effective for improving water availability.	Centralized	-1	2	-1
			Distributed	2	-1	-1
			Natural	3	-2	-1

1	a b c	Evaluate all Type I and II sensitivities.	See tables below

Transboundary governance → Water quality

	Improved	Poor
Collaborative	3	-3
Cooperative	1	-1
Independent	-2	2

Transboundary governance → Approach to infra for resilience

	Centralized	Distributed	Natural
Collaborative	-2	1	1
Cooperative	0	0	0

Transboundary governance → Level of authority

	Bottom-up	Top-down
Collaborative	3	-3
Cooperative	0	0
Independent	-3	3

Data systems → Government investment approach

	Conventional	Enhanced	Reactive
Patchwork	1	-2	1
Coordinated & scientific	1	2	-3
Collective & integrated	-1	3	-2

Data systems → Water quality

	Improved	Poor
Patchwork	-1	1
Cooperative & scientific	1	-1
Collective & integrated	1	-1

Government investment approach → Data system

	Patchwork	Coordinated & scientific	Collective & integrated
Conventional	1	2	-2
Enhanced	-3	1	2
Reactive	3	-1	-2

Approach to infra for resilience → Ecological integrity

	High	Low
Distributed	-1	1

Authority → Approach to infra for resilience

	Centralized	Distributed	Natural
Bottom-up	-3	2	1
Top-down	2	1	-3

2	a b c	Evaluate alternative rationales for Type I and II sensitivities.

Global agricultural markets → Rural economy

	Intensive agriculture	Diversified & regenerative agriculture
Everyone for themselves	2	-2

Regional climate → Water quality

	Improved	Poor
Warmer & wetter	1	-1
Hotter & drier	1	-1

Water availability → Rural economy

	Intensive agriculture	Diversified & regenerative agriculture
Adequate	1	-1
Unequal	2	-2
Deficient	3	-3

Demographics → Cultural and political drivers

	Private	Public
Urbanization	2	-2
Rural revival	-2	2
Mass growth	0	0

Demographics → Rural economy

	Intensive agriculture	Diversified & regenerative agriculture
Mass growth	1	-1

Approach to infra → Water quality

	Improved	Poor
Natural	-1	1

Approach to infra → Ecological integrity

	High	Low
Distributed	1	-1

Data systems → Approach to infra for resilience

	Centralized	Distributed	Natural
Patchwork	3	-1	-2

Government investment approach → Approach to infra for resilience

	Centralized	Distributed	Natural
Enhanced	-3	1	2
Reactive	3	-1	-2

Appendix H

Scenario tableau of robust scenarios

<table>
<tr><td>Scenario #</td><td>3</td><td>1</td><td>10</td><td>9</td><td>12</td><td>6</td><td>5</td><td>4</td><td>17</td><td>11</td><td>2</td><td>7</td><td>8</td><td>15</td><td>16</td><td>13</td><td>14</td></tr>
<tr><td>Global ag markets</td><td colspan="5">Status quo</td><td colspan="6">Sustainable diets</td><td colspan="3">Higher demand</td><td>Everyone for them</td><td>Higher demand</td><td>Everyone for them</td></tr>
<tr><td>Global climate change</td><td colspan="5">Moderate</td><td colspan="6">Optimistic</td><td colspan="6">Severe</td></tr>
<tr><td>Demographics</td><td colspan="9">Urbanization</td><td colspan="2">Rural revival</td><td colspan="6">Mass growth</td></tr>
<tr><td>Culture & politics</td><td>Private</td><td colspan="4">Public</td><td colspan="5">Private</td><td>Public</td><td colspan="2">Private</td><td colspan="4">Public</td></tr>
<tr><td>Rural economy</td><td colspan="8">Intensive agriculture</td><td colspan="3">Regenerative agriculture and diversification</td><td colspan="6">Intensive agriculture</td></tr>
<tr><td>Water availability</td><td colspan="6">Unequal</td><td colspan="5">Adequate</td><td>Unequal</td><td colspan="5">Deficient</td></tr>
<tr><td>Indigenous water rights</td><td>Status quo</td><td colspan="4">Fully recognized</td><td colspan="5">Status quo</td><td>Fully recognized</td><td colspan="2">Status quo</td><td colspan="4">Fully recognized</td></tr>
<tr><td>Regional climate</td><td colspan="5">Warmer & extreme unpredictability</td><td colspan="6">Warmer & wetter</td><td colspan="6">Hotter & drier</td></tr>
<tr><td>Water quality</td><td colspan="3">Poor</td><td colspan="2">Improved</td><td colspan="2">Poor</td><td>Improved</td><td>Poor</td><td colspan="2">Improved</td><td colspan="4">Poor</td><td colspan="2">Improved</td></tr>
<tr><td>Ecological integrity</td><td colspan="3">Low</td><td colspan="2">High</td><td colspan="2">Low</td><td>High</td><td>Low</td><td colspan="2">High</td><td colspan="4">Low</td><td colspan="2">High</td></tr>
<tr><td>Transboundary governance</td><td>Independent</td><td colspan="4">Collaborative</td><td>Independent</td><td colspan="2">Cooperative</td><td>Independent</td><td>Cooperative</td><td>Collaborative</td><td colspan="2">Independent</td><td colspan="4">Collaborative</td></tr>
<tr><td>Data & knowledge</td><td>Patchwork</td><td colspan="4">Collective & integrated</td><td>Patchwork</td><td colspan="2">Coordinated & scientific</td><td>Patchwork</td><td>Coordinated & scientific</td><td>Collective & integrated</td><td>Patchwork</td><td>Coordinated & scientific</td><td colspan="4">Collective & integrated</td></tr>
<tr><td>Government investment</td><td colspan="6">Reactive</td><td colspan="4">Conventional</td><td>Enhanced</td><td>Reactive</td><td colspan="5">Enhanced</td></tr>
<tr><td>Infrastructure for resilience</td><td>Centralized</td><td>Distributed</td><td colspan="2">Natural</td><td>Distributed</td><td>Centralized</td><td colspan="2">Distributed</td><td>Centralized</td><td>Distributed</td><td>Natural</td><td>Centralized</td><td>Distributed</td><td colspan="4">Natural</td></tr>
<tr><td>Level of authority</td><td>Top-down</td><td colspan="4">Bottom-up</td><td>Top-down</td><td colspan="2">Bottom-up</td><td>Top-down</td><td colspan="2">Bottom-up</td><td colspan="2">Top-down</td><td colspan="4">Bottom-up</td></tr>
</table>

Figure H-1: The scenario tableau depicts the eight scenarios that are robust to at least two versions (a, b, c) of both prototypes 1 AND 2, in addition to nine additional scenarios that are robust to all three versions (a, b, c) or prototype 1 OR 2. The original eight robust scenarios are highlighted in yellow at the top of the tableau.

Appendix I

Debrief workshop protocol

Presentation of study results

Breakout session 1

Explanation in full group:

Thank you for your attention during that presentation! We are now ready to move on to our first breakout session.

The purpose of this breakout session is to explore your assumptions about the future of the Red River Basin through the process of ranking the scenarios I just showed you according to their: 1) desirability, and 2) plausibility.

In this breakout, you will split into breakout groups of 4 to 5 participants. Each group will be joined by a facilitator. You will have access to the 4 to 6 distinct scenarios, each with a scenario 'narrative' and a landscape sketch.

Your group will be given [X] minutes to:

1. **Rank X scenarios from most to least desirable**
2. **Rank X scenarios from most to least plausible**

Please keep in mind:

- Facilitator will be present to facilitate and will use a Miro board to assist, which is a virtual equivalent of a flipchart and sticky notes
- If you are not finished ranking based on desirability after ~15-20 minutes that is okay. Your facilitator will move your group to the plausibility ranking.
- Don't simply state a ranking, discuss the reasons why you chose certain scenarios as more or less desirable/plausible than others in as much detail as possible. Your facilitator may ask follow up questions to find out this *why*.
- Like I said earlier on, this exercise is not about coming up with the "right" ranking (it may not exist!) but about exploring the future and our assumptions. The process may surface very different opinions or desires about the future, and may expose trade-offs between different goals. Try to be curious, respectful, and open to other perspectives.

Be prepared to choose one person to report back your reflections on the exercise. The report back will focus on interesting assumptions and themes that surfaced, not on your final ranking of the scenarios.

With that, I will send you off to breakout rooms.

In breakout rooms:

Facilitator explains the exercise again and shares their screen with a Miro board. The Miro board will depict the 4-6 scenarios with brief descriptions. Facilitators and participants will have access to longer descriptions presented in the introduction if they need them.

Participants try to rank scenarios from most to least desirable and facilitator will use numerical indicators to follow discussion (or move scenarios around on the board). Facilitators will ask follow-up questions as needed to find out the rationale behind rankings. Participants may agree on the ranking, but it is perfectly fine if they do not (e.g., there could be two scenarios ranked 'most desirable' by different participants).

Figure I-1: Miro board for Breakout session #1

<u>*Report back in full group:*</u>

Breakout rooms are closed and participants return to the main Zoom room.

I will now ask a representative from each group to give a 1 to 2 minute summary of the main themes and insights from your group. Don't't worry about the ranking itself, just broader insights. One of our facilitators is going to time you and stop you at 2 minutes.

Thank you so much for your engagement in this part of the session. We will now take a short [5-10] minute break, so see you back at X:XX.

---- BREAK ----

Breakout session 2

Explanation in full group:

We are now moving into our second breakout session. The purpose of this breakout is to connect these long term scenarios to actions we are taking to build resilience in the present.

During our interviews, I asked participants for examples of initiatives that are happening now that they think will contribute to a resilient future. I have gathered some together here.

During your breakout session, your facilitator will lead you through the following steps:

1. **Choose one example from the preloaded stickies on the Miro board.**
2. **Discuss as a group which scenarios that initiative is promoting, *and why*. In other words, which scenarios become MORE likely by pursuing this initiative?** For example, if I was interested in building a large piece of grey infrastructure, I might start looking for scenarios with 'centralized infrastructure' as the dominant approach to infrastructure for resilience, and see what kind of scenarios are associated with that.
3. **Discuss as a group which scenarios that initiative is inhibiting, *and why*. In other words, which scenarios become LESS likely by pursuing this initiative?**
4. **Choose another example from the list of initiatives and report step 2 (if time)**

In breakout rooms:

Facilitator explains the exercise briefly again and shares their Miro board with pre-loaded sticky notes of 'initiatives'. Participants decide on an initiative to start with. Facilitator then moves that sticky over to the Miro board of scenarios and leads participants through discussing which scenarios that initiative is promoting versus inhibiting, and why.

(if time) With 5 minutes remaining, the facilitator stops the exercises and asks the group to discuss: ***What does this exercise tell us about our near-term efforts to build resilience in the RRB?***

Figure I-2: Miro board for breakout session #2

(if time) Debrief in full group:

Each group please take a minute to share which initiative you chose and any insights from you discussion about which scenarios it is promoting and inhibiting. One of our facilitators is going to time you and stop you at 2 minutes.

Full group debrief

We have two questions that will discuss for the remainder of our time together:

- Did this process of scenario development and discussion change the way you think about the future of the RRB? Why or why not? How?
- What are the implications of this discussion for the way we "build resilience" in the present?

Closing

Appendix J

Influence judgments changed for strategy assessment

The table below summarizes the influence judgments that were changed for the strategy assessment, as differentiated from prototype 1 (a, b, c).

Table J-1: Influence judgments that were changed for the strategy assessment

<table>
<tr><th>Prototype</th><th>Version</th><th>Purpose</th><th>Rationale</th><th>Judgment sections</th></tr>
<tr><td>3</td><td>a
b
c</td><td>To evaluate collaborative response to drought</td><td>The most direct influence that evaluates a collaborative response to drought is to adjust the influence of water availability on transboundary governance. In this strategy, deficient or unequal water availability promotes – rather than restricts – collaborative and cooperative governance. Additionally, the assumption that deficient or unequal water availability promotes top-down centralization of authority was removed to avoid contradicting these positive outcomes.</td><td>Water availability → Transboundary governance
<table>
<tr><th></th><th>Collaborative</th><th>Cooperative</th><th>Independent</th></tr>
<tr><td>Adequate</td><td>-3</td><td>1</td><td>2</td></tr>
<tr><td>Unequal</td><td>1</td><td>1</td><td>-2</td></tr>
<tr><td>Deficient</td><td>2</td><td>1</td><td>-3</td></tr>
</table>
Water availability → Level of authority
<table>
<tr><th></th><th>Bottom-up</th><th>Top-down</th></tr>
<tr><td>Adequate</td><td>0</td><td>0</td></tr>
<tr><td>Unequal</td><td>0</td><td>0</td></tr>
<tr><td>Deficient</td><td>0</td><td>0</td></tr>
</table></td></tr>
<tr><td>4</td><td>a
b
c</td><td>To evaluate implications of a true market for ecological goods and services</td><td>Under a true market for ecological goods and services, both private and public interests would promote a diversified and regenerative agricultural economy, because the additional ecological goods and services offered by regenerative agriculture would be valued in the economy. Also, the restricting influence of private interests on distributed and natural infrastructure approaches would flip to promoting influences, as landowners would benefit from the value of the ecological goods and services offered by these approaches.</td><td>Cultural & political drivers → Rural economy
<table>
<tr><th></th><th>Intensive agriculture</th><th>Diversified & regenerative agriculture</th></tr>
<tr><td>Private</td><td>-2</td><td>2</td></tr>
<tr><td>Public</td><td>-3</td><td>3</td></tr>
</table>
Cultural & political drivers → Approach to infra for resilience
<table>
<tr><th></th><th>Centralized</th><th>Distributed</th><th>Natural</th></tr>
<tr><td>Private</td><td>-3</td><td>1</td><td>2</td></tr>
<tr><td>Public</td><td>-2</td><td>-1</td><td>3</td></tr>
</table></td></tr>
</table>

<table>
<tr>
<td>5</td>
<td>a
b
c</td>
<td>To evaluate the implications of effective demand management on water availability</td>
<td>Effective demand management reduces water demand, thereby reducing anthropogenic pressures on water availability. The two anthropogenic influences on water availability in the model are water use from the rural economy and demographics. The influence of intensive agriculture on water availability was zeroed to reflect no significant influence, whereas regenerative agriculture improves water availability as the soil quality improves its water storage capacity. The influence of water availability on the state of the rural economy was also zeroed, because demand management would no longer be a source of selectivity for the economy.</td>
<td>Rural economy → Water availability
<table>
<tr><th></th><th>Adequate</th><th>Unequal</th><th>Deficient</th></tr>
<tr><td>Intensive agriculture</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Diversified & regenerative agriculture</td><td>3</td><td>-1</td><td>-2</td></tr>
</table>
Water availability → Rural economy
<table>
<tr><th></th><th>Intensive agriculture</th><th>Diversified & regenerative agriculture</th></tr>
<tr><td>Adequate</td><td>0</td><td>0</td></tr>
<tr><td>Unequal</td><td>0</td><td>0</td></tr>
<tr><td>Deficient</td><td>0</td><td>0</td></tr>
</table>
Demographics → Water availability
<table>
<tr><th></th><th>Adequate</th><th>Unequal</th><th>Deficient</th></tr>
<tr><td>Urbanization</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Rural revival</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>Mass growth</td><td>0</td><td>0</td><td>0</td></tr>
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Appendix K

Scenario narratives

Scenario 1: Friends in environmental crisis

In 2050, more inclusive water governance and management isn't enough to improve resilience in the RRB. At a global scale, global greenhouse gas emissions stabilize and the RRB experiences a gradual increase of average annual temperature and a more extreme and unpredictable climate, with floods and droughts more likely within the same year. Global agricultural markets are stable, reinforcing the existing intensive agricultural system. The urbanization trend continues.

Despite continued reliance on intensive agriculture, the culture and politics driving decision making about water prioritize public goods and environmental interests over private landowner and economic interests when required. This creates an enabling environment for full recognition of Indigenous water rights, which reinforces the protection of the environment for its inherent cultural & social value, and promotes meaningful inclusion of Indigenous interests and knowledge in decision making.

In response, transboundary governance of the RRB becomes highly collaborative, as municipal, state, provincial, Indigenous, and federal governance entities all meaningfully collaborate on shared goals. Data collection is organized and shared across jurisdictions through a basin-wide forum that brings together scientific, local, and Indigenous data and knowledge. Despite improved collaboration, the government investment approach is reactive, focusing on emergency support and insurance rather than maintenance and preventative measures. Still, bottom-up initiatives drive a distributed approach to infrastructure for resilience, buffering hydroclimatic variability with a system of ponds and controlled tile drainage and using large-scale infrastructure only if required.

Despite these efforts, socio-economic trends like intensive agriculture and urbanization drive unequal water availability leading to seasonal competition for water across sectors and demographics. Water quality remains poor and ecological integrity is low.

Scenario 2: Everyone's paradise

In 2050, people and nature in the RRB are in harmony. The world has transitioned to a low-carbon economy and people around the world shift toward more sustainable diets. As a result, the climate of the RRB remains relatively stable, experiencing only a slight increase of average annual temperature while climate variability remains within recent historical ranges. To meet the stringent environmental standards on the global agricultural market, the economy of the RRB diversifies and shifts toward regenerative agricultural practices that nourish soil health and ecological integrity.

This economic diversification is accompanied by a reversal of the urbanization trend, leading to a revival of the rural population and cultural life. Additionally, the culture and politics driving decision making about water in the basin prioritize public goods and environmental interests over private landowner and economic interests when required. The enabling environment offered by this socio-economic transformation leads to full recognition of Indigenous water rights.

In response, transboundary governance becomes more collaborative and inclusive, as municipal, state, provincial, Indigenous, and federal governance entities all meaningfully collaborate on shared goals. Data collection is organized and shared across jurisdictions through a basin-wide forum that brings together scientific, local, and Indigenous data and knowledge. These initiatives are supported by an enhanced government investment approach that includes soft, natural, and gray measures disbursed in smaller increments with more flexible returns. In this future, water managers primarily buffer hydroclimatic variability with natural ecosystems, supplemented by a distributed ponds and controlled tile drainage. Large-scale infrastructure is only used as a last resort.

Together, these shifts lead to a more sustainable landscape in the RRB with adequate water availability for both human and environmental uses, improved water quality in the RRB and Lake Winnipeg, and high ecological integrity.

Scenario 3: Deteriorated status quo

In 2050, the status quo economy and infrastructure approach break down under the pressures of climate change. At a global scale, global greenhouse gas emissions rise and eventually stabilize, leading to a gradual increase of average annual temperature and a more extreme and unpredictable climate in the RRB with floods and droughts more likely within the same year. Global agricultural markets are stable, reinforcing the existing intensive agricultural system. The urbanization trend continues.

A continued reliance on intensive agriculture reinforces a culture and politics driving decision making that prioritizes private landowner and economic interests. These socio-economic factors contribute to a lack of recognition of Indigenous water rights, perpetuating the de-prioritization of Indigenous interests, lack of recognition of inherent cultural and social value of the environment, and exclusion of Indigenous knowledge in decision making.

In this scenario, governance and management of the RRB breaks down. Transboundary governance becomes independent, with entities acting in their own interests without consultation. Data collection is patchy with limited data sharing, reducing the quality of basin-wide models and forecasts. Government investment is reactive, focusing on emergency support and insurance with insufficient spending on maintenance and preventative measures. Hydroclimatic variability is managed primarily with large-scale infrastructure, including reservoirs, diversions, and intra/inter-basin transfers, with continued drainage from landscape, including via uncontrolled tile drainage.

These trends drive unequal water availability leading to seasonal competition for water across sectors and demographics. Additionally, water quality remains poor and ecological integrity is low.

Scenario 4: Some people's paradise

In 2050, the world has transitioned to a low-carbon economy and people around the world shift toward more sustainable diets. As a result, the climate of the RRB remains relatively stable, experiencing only a slight increase of average annual temperature while climate variability remains within recent historical ranges. Despite the stringent environmental standards on the global agricultural market, the RRB maintains its intensive agricultural economy. The urbanization trend continues.

A continued reliance on intensive agriculture reinforces a culture and politics driving decision making that prioritizes private landowner and economic interests. These socio-economic factors contribute to a lack of recognition of Indigenous water rights, perpetuating the de-prioritization of Indigenous interests, lack of recognition of inherent cultural and social value of the environment, and exclusion of Indigenous knowledge in decision making.

In this scenario, governance and management of the RRB follows a middle-of-the-road scenario. Transboundary governance is cooperative, so different jurisdictions discuss their independent goals and interests supported by formal agreements when required. Data and knowledge systems are comprehensive and coordinated, though focused on scientific data and exclude local and Indigenous knowledge. The government investment approach is conventional, focused on gray/hard infrastructure measures with large financial disbursements and clear returns. Still, a bottom-up approach results in a distributed approach to infrastructure for resilience, buffering hydroclimatic variability with a system of ponds and controlled tile drainage and using large-scale infrastructure only if required.

Together, these shifts lead to a more sustainable landscape in the RRB with adequate water availability for both human and environmental uses, improved water quality in the RRB and Lake Winnipeg, and high ecological integrity.

Scenario 7: Severe social-ecological breakdown

In 2050, the world has failed to curb global greenhouse gas emissions, leading to a severe climate change scenario. The result is a hotter & drier climate in the RRB leading to a highly unpredictable climate and significant risk of severe, multi-year or multi-decadal droughts. Additionally, global agricultural demand for conventional products from the RRB is higher, reinforcing the existing intensive agricultural system. Severe climate change impacts around the world lead to mass migration into the RRB, driving population growth in both rural and urban areas.

A continued reliance on intensive agriculture reinforces a culture and politics driving decision making that prioritizes private landowner and economic interests. These socio-economic factors contribute to a lack of recognition of Indigenous water rights, perpetuating the de-prioritization of Indigenous interests, lack of recognition of inherent cultural and social value of the environment, and exclusion of Indigenous knowledge in decision making.

In this scenario, governance and management of the RRB breaks down. Transboundary governance becomes independent, with entities acting in their own interests without consultation. Data collection is patchy with limited data sharing, reducing the quality of basin-wide models and forecasts. Government investment is reactive, focusing on emergency support and insurance with insufficient spending on maintenance and preventative measures. Hydroclimatic variability is managed primarily with centralized large-scale infrastructure, including reservoirs, diversions, and intra/inter-basin transfers, with continued drainage from landscape, including via uncontrolled tile drainage.

Centralized infrastructure prevents chronically deficient water availability but drives unequal water availability leading to competition for water across sectors and demographics, particularly in the face of mass migration to the area. Water quality remains poor and ecological integrity is low.

Appendix L

Quotes from debrief workshop

The following table includes key quotes from debrief indicating participant perspectives on the value of the transdisciplinary scenario exercise.

Table L-1: Key quotes from debrief workshop

Theme	*Quotes*
Making sense of complexity	"I don't think it changed how I thought about the basin, but… the scenario approach is just so effective. It presents a range, and you sort of look at these different gradations along the continuum and I just think it's an excellent, excellent way to consider during complex situations." "… I think I was reminded [of]… the importance of that sustainable development perspective... When thinking about resilience in the Red River Basin it's hard for me to picture or envision resilience in the basin without an acknowledgement of Indigenous rights going forward. It's such a big part of the fabric... So, it's just so key to have the social, environmental, and economic aspects that are brought together… these are hard decisions..."
Surface different perspectives	"For a long time, many in the U.S. have said we need to include more social science... But the truth is our projects often aren't funded to do that and when the budget is tight that's the part that gets dropped off and we really need to do more than that. And I'm trying to get that included in some projects I'm working on and being part of this has influenced some of my thinking on that to try harder on that aspect…" "[We have] done a lot of work on kind of how decision-making is informed by both kind of facts and evidence but also perspectives… Being in these breakout groups is a good reminder that we all have priorities, biases, and just different places from which we're coming to." "I think… there was a lot of enthusiasm for the discussion. These are just short, kind of scratch the surface. I think we could have probably spent hours. I've done a few scenario sessions and certainly the understanding that starts to happen when you get the group together and just sharing, understanding, and seeing the other perspectives." "I don't know necessarily that everybody shares that same vision on how we are to get there and as I said earlier, not only is it different from province to province it's different from country to country." "[It is] reassuring to see that there are these many different variables and many different perspectives in the basin and that… maybe we have some actual authority and power here to change the way our future is shaped."
Affirming the	"I looked at all these faces that all have the same passion. We may see different priorities to reach

value of collaboration	that end goal, but the passion is definitely there for the basin.” “It was kind of a reminder that by bringing people together… around scenarios like this may actually change the way our future is shaped and how we prioritize. Recognition of Indigenous rights… seems to be kind of coming through fairly clearly as a priority for many…” “It reassured me… that we, in the basin, both in the United States and North Dakota and Minnesota and South Dakota part of the basin, we can work together.”