Faculty of Biological and Environmental Sciences
University of Helsinki

THE POWER OF PERSPECTIVES:

DEVELOPING AND IMPLEMENTING INTER AND TRANSDISCIPLINARY METHODS TO ADDRESS WICKED SOCIO-ENVIRONMENTAL PROBLEMS

Kelsey LaMere

DOCTORAL DISSERTATION

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"Like music and art, love of nature is a common language that can transcend political or social boundaries."

—Jimmy Carter

"Never doubt that a small group of thoughtful, committed citizens can change the world; indeed, it is the only thing that ever has."

—Margaret Mead

ABSTRACT

Today, the wicked socio-ecological problems facing the world, like climate change and food security, are far too large-scale and complex for any single institution or academic discipline to address alone. Further, these often-contentious issues affect various stakeholders. Therefore, progress requires socially sensitive solutions that take all relevant parties' knowledge and values into account. Hence, participatory problem-solving approaches, like inter and transdisciplinary science, which invite diverse perspectives into the problem-solving process, are attractive options for combatting wicked problems. By integrating diverse knowledge bases and modes of thinking, these approaches can produce more creative, credible, democratically accountable, and socially acceptable solutions. However, despite the benefits they provide, these approaches must be developed further to ensure they reach their full potential. As such, **chapters I and II** of this thesis aim to promote the incremental advancement of inter and transdisciplinary science on two dimensions:

First, **chapter I** aims to draw attention to the critical process of strengthening communication via cognitive integration. Cognitive integration "bridges the gaps" in understanding between members of diverse problem-solving teams, which eases communication and promotes collaborative work. **Chapter I** uses a paired structural topic modeling and interview analysis approach to identify and describe different perspectives about "risk," a key concept for the operational interdisciplinary team studied. Within this team, diverse perspectives about ideas as fundamental as the definition of risk and potential conflict areas were found, like the idea of quantitative risk analysis. Transparently revealing and describing the differences in perspectives within diverse teams in this way at the beginning of their collaborative work could help facilitate cognitive integration and direct conflict resolution efforts, thereby enabling inter and transdisciplinary teams to begin their work more smoothly and effectively.

The second area for development this thesis aims to address is the lack of peer-reviewed methods in inter and transdisciplinary research. Specifically, **chapter II** describes the development of a new method for mental model elicitation, which is a popular tool within transdisciplinary research. Mental model elicitation is intended to document a participant's causal understanding of a problem system. However, the academic literature rarely

discusses the elicitation process, and those approaches it does describe, direct and indirect elicitation, are likely to either oversimplify the participants' ideas or introduce facilitator bias, respectively. **Chapter II** describes the Rich Elicitation Approach (REA), which combines both approaches in a single framework to maintain the benefits of each while compensating for their shortcomings.

Unlike **chapters I and II**, the final chapter of this thesis, **chapter III**, focuses on a real-world transdisciplinary problem-solving effort. Specifically, **chapter III** reports the outcomes of a problem framing study to understand how climate change may affect salmon and their fishery in the Baltic Sea region and direct fishery management accordingly. **Chapter III** makes use of the REA developed in **chapter II**, as stakeholders' mental models form the basis of this study. By analyzing these models, 15 themes describing the problem, goals for the salmon management considering climate change, and strategies to help achieve those goals were found. Additionally, **chapter III** identified potentially conflicting values and ideas that salmon management may need to address moving forward. Problem framing is only the first step toward addressing the climate change issue for salmon management. Continuing efforts will require the cooperation of diverse problem-solving teams in a contentious management context, which could be facilitated by transparently acknowledging and describing perspective differences, as was done in **chapter I**.

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1 INTRODUCTION

1.1 Addressing Wicking Socio Environmental Problems

Since the mid-20th century, Earth has experienced rapid environmental change (Barnosky et al., 2014) driven by human population growth (Barnosky et al., 2014; Roser et al., 2020) and shifting lifestyles (Barnosky et al., 2016, 2014; Brown et al., 2011). While the technological, economic, and social advancements responsible for these changes have undeniably brought an improved quality of life and even prosperity to multitudes, they have also taken a heavy toll on the environment (Barnosky et al., 2014; Foley et al., 2005). For example, the unsustainable resource use driving the likes of industrial agriculture, fossil fuel consumption, and consumerism has led to familiar, interconnected issues, like pollution (Hayes et al., 2003; Wright et al., 2013), biodiversity loss (Barnosky et al., 2016, 2014, 2011), and climate change (IPCC, 2014). These issues could, in turn, affect society by altering livelihoods, driving conflict, and destabilizing social structures (CNA, 2014, 2007). Further, they are projected to jeopardize such fundamental necessities as air, water, and food, among countless others (Barnosky et al., 2016; CNA, 2014, 2007; Foley et al., 2005; IPCC, 2014). Nevertheless, to continue to support the growing human population, natural resource consumption, and the intertwined social and technological systems supporting it must continue, at least in some form. Thus, humanity is caught in a seemingly inextricable web of so-called “wicked problems” (Rittel and Webber, 1973), characterized by their complexity, uncertainty, lack of simple right or wrong solutions, and unsolvable by traditional methods and modes of thinking (Brown et al., 2010a; Ludwig, 2001; Rittel and Webber, 1973).

These problems must be addressed if we claim to value nature, as we know it today, and the diversity of life that it presently supports, including humans. However, many have argued or implied that the institutions we have tasked with this responsibility, namely our traditional technocratic governance structures and the hierarchical, disciplinary science that supports it, are inadequate to face these challenges (Brown et al., 2010a; Gibbons, 1999; Maasen and Lieven, 2006). Specifically concerning science, this inadequacy stems from 1) waning credibility (Chilvers and Kearnes, 2015; Maasen and Lieven, 2006) and 2) a deficit of the type of holistic knowledge needed to solve[1] modern wicked problems (Brown et al., 2010a; Repko, 2014). These issues are particularly problematic because scientific advice is more critical now than ever, as the diffuse and technical nature of wicked socio-environmental problems requires science to detect, understand, and address them (Lidskog, 2008).

The credibility of science has diminished in recent decades, as its normative cultural authority as society's source for true, trustable knowledge has come into question (Chilvers and Kearnes, 2015; Maasen and Lieven, 2006). This is the result of its perceived lack of objectivity as its advisory role in governance grows (Chilvers and Kearnes, 2015; Maasen and Lieven, 2006), its increasing visibility in a polarizing and politicizing media environment (Dietz, 2013), high profile failures (Wynne, 1992), and tendency to ignore the advice of stakeholders (Linke et al., 2020; Wynne, 1992). A lack of scientific credibility could damage scientific institutions, threaten the well-being of those who benefit from scientific knowledge, and undermine any governance decisions made following its advice (Lidskog, 2008; Linke and Jentoft, 2016; Maasen and Lieven, 2006; Wynne, 1992). The second issue science faces, a knowledge deficit, has developed as wicked problems have rendered the traditional, disciplinary approach to knowledge production, which focuses on basic and experimental studies[2], ineffective (Repko, 2014). This is because a strictly disciplinary approach to problem-solving is likely to focus on a single aspect of the issue and therefore, be blinded to the broader context, thus failing to address it adequately (Repko, 2014). Relying on basic and experimental science too heavily is also problematic, as these approaches are unable to provide the context-specific, practical knowledge needed to address socio-environmental problems (Brown et al., 2010a; Linke et al., 2020; Repko, 2014). Further, a strictly disciplinary scientific approach may dampen creativity and ignore stakeholder knowledge, and values (Repko, 2014), which could limit the solutions developed (Brown et al., 2010a) and threaten their successful implementation (Linke et al., 2020). As such, increasing complexity (or

[1] Wicked problems are rarely "solved" once and for all (Rittel and Webber, 1973). Solving wicked problems is typically an iterative and on-going process of active problem mitigation, adaptation, and management (Rittel and Webber, 1973).

[2] Scientific approaches resembling this description are often referred to as normal science (Kuhn, 1970) or mode 1 knowledge production (Gibbons et al., 1994).

awareness of complexity) and rising doubt about the efficacy of disciplinary problem solving has led to the acknowledgment that no single, homogenous group of experts is capable of addressing large-scale, complex socio-ecological problems alone (Lawrence, 2010; Ludwig, 2001; Repko, 2014).

In recent decades, increased participation in science has come to the fore as a solution for both the credibility and knowledge deficit problems (Lidskog, 2008). Including citizens in the knowledge production process creates a mechanism for accountability by increasing transparency and ensuring societal knowledge and values are represented appropriately (Maasen and Lieven, 2006). Opening knowledge production various scientific disciplines and relevant citizens increases the pool of epistemic and phronetic knowledge available for problem-solving. By collaborating, participants can share the costs and benefits of problem-solving efforts and combine their knowledge and resources (Roberts, 2000). Further, increasing the diversity of participants ensures issues are approached from multiple perspectives, allowing problem solvers to think more creatively and shift their perception of the problem (Bardwell, 1991; Cronin et al., 2011; Cronin and Weingart, 2019; Weingart et al., 2010), which encourages the development of novel alternative solutions (Bardwell, 1991).

Several schools of thought about participation have been developed, each with different perspectives about who should be invited to participate in science, why the need for participation has arisen, and how it should be done (see Lidskog (2008) for differing perspectives on participation). These have shaped the inter and transdisciplinary research (ITDR) approaches of today, which will be the focus of this thesis.

Generally speaking, both inter and transdisciplinary approaches are considered to be synergistic and intended to solve real-world problems by integrating diverse perspectives (Brown et al., 2010a; Huutoniemi et al., 2010; Klein, 2015), where interdisciplinarity focuses on integrating perspectives between scientific disciplines and transdisciplinarity includes the perspectives of extra-scientific participants as well (see sections 2.1 – 2.3).

These characteristics have made ITDR approaches integral to the field of sustainability science (Kates et al., 2001; Lang et al., 2012), which has been developed specifically to safeguard Earth's life support systems, alleviate poverty, and facilitate a transition toward a more sustainable way of life by addressing today's wicked socio-environmental problems (Clark, 2007; Kates et al., 2001). As such, effective ITDR can enable more effective sustainability science.

However, ITDR approaches have a long way to go to reach their full potential. These approaches have been criticized for everything from being challenging to implement, to a lack of robust methodological standards (Brandt et al., 2013; Jahn et al., 2012; Lang et al., 2012; von Wehrden et al., 2017), to their potential to disempower participants (Chilvers and Kearnes, 2015) and create destructive power dynamics (Chilvers and Kearnes, 2015; Lidskog, 2008; Linke and Jentoft, 2016). Any of these issues could inhibit the processes of trust development between science and society, or knowledge production, hence limiting their capacity to solve wicked socio-environmental problems.

1.2 Thesis Goals, Aims, & Questions

In light of the challenges described above, this thesis's first general goal is to take steps toward developing ITDR by enhancing its credibility and capacity for holistic knowledge production in sustainability science. There are innumerable ways to meet this goal. However, this thesis contributes by meeting the following aims: **Chapter I** aims to develop a concrete strategy to ease the process of conducting ITDR by enhancing communication, thereby increasing its efficiency and effectiveness. **Chapter II** aims to create a standardized yet flexible peer-reviewed methodology for mental model elicitation and documentation, a frequently used tool in ITDR. Additionally, this thesis's aims to fulfill the first two aims with ethical considerations in mind, as failure to do so could undermine the credibility and knowledge production capacity of the future ITDR efforts that may employ them. In addition to the goal of improving ITDR, the second goal of this thesis, addressed in **chapter III**, is to use ITDR to begin the process of problem-solving in the context of a real-word wicked socio-ecological problem, fisheries management (Chuenpagdee and Jentoft, 2019a; Jentoft and Chuenpagdee, 2009).

THESIS GOALS, AIMS, & QUESTIONS

Goal 1: Help develop ITDR approaches, which improve the credibility and knowledge production capacity of sustainability science.

Aim 1a: Develop methods to ease the ITDR process by improving communication between participants.

Aim 1b: Create a standardized, yet flexible method for eliciting & documenting mental models.

Aim 1c: Reach aims 1a & 1b while keeping ethical considerations in mind.

Questions 1:

- How could ITDR be developed to better support sustainability science?
- How could communication between participants in ITDR projects be improved?
- How should stakeholders' mental models be elicited & documented?
- How well did the methods this thesis employed work?
- How should research related to these methods proceed?
- How can aims 1a & 1b be achieve ethically, in accordance with ITDR principles?

Goal 2: Begin the process of addressing a real-life wicked problem, fisheries management, in the context of the Baltic salmon fishery.

Aim 2a: Develop a holistic understanding of the probelm.

Aim 2b: Delineate areas of conflict & concensus between stakeholders.

Questions 2:

- How could climate change affect Baltic salmon & their fishery?
- What goal should we set for the fish and fishery considering?
- What actions should we take to reach those goals?
- What areas of concensus & conflict can be found between stakeholders?

Box.1 The goals, aims, and questions addressed in this thesis

Specifically, this thesis frames the problem that climate change may pose for Baltic salmon and their fishery with expert stakeholders. This framing process was conducted to develop a holistic understanding of the problem and areas of conflict and consensus between stakeholders to help guide future fisheries management efforts. This thesis's goals, aims, and the concordant questions it will answer are presented in box 1.

1.3 Thesis Outline

To help the reader better understand these goals, aims, questions, and the value of addressing them, the theoretical framework section of this thesis summary offers a description of ITDR approaches, a brief history of their development, and the societal changes leading to their development. Then, the theoretical framework section describes the foundational schools of thought about participation in science that shaped ITDR and delves deeper into the research gaps that led to the thesis's aims one through three. The theoretical framework section is followed by a methodology section, which describes the methods used throughout this thesis in depth. Next, the results section includes the results of this thesis work relevant to answering the questions stated above. Lastly, the discussion section describes this thesis's specific contributions to ITDR and Baltic salmon management, the limitations of the research, and suggestions for further research related to these topics.

2 THEORETICAL FRAMEWORK

2.1 The Supradisciplinary Approaches

To discuss this thesis work, it is essential to understand what ITDR is first, which is not an altogether straightforward story. Multi, inter, transdisciplinary science are all members of the so-called "supradisciplinary" scientific approaches. However, significant ambiguity about their definitions and their differences still exist within the literature (Huutoniemi et al., 2010; Lawrence, 2010; Maasen et al., 2006; Robinson, 2008; von Wehrden et al., 2019).

To distinguish between the supradisciplinary approaches and understand how they are related, I imagine them as branches on a tree (figure 1). The branch of supradisciplinary approaches adjoins the tree's trunk. The multidisciplinary branch develops first, jutting from the supradisciplinary branch, followed by the interdisciplinary branch. Then, from the interdisciplinarity branch springs the young, green transdisciplinary branch. Although each branch grows and develops in its own direction, the leaves and twigs of both the inter and transdisciplinary branches intermingle and are fed by the same ideological sap. This sap and the intertwined branches represent the overlapping rational and values behind the inter and transdisciplinary approaches and that they are often used together in problem-solving contexts.

Despite ambiguity about these terms, most agree that both inter and transdisciplinary science are synergistic, participatory, and solutions-oriented approaches that integrate diverse perspectives to solve complex problems (Brown et al., 2010a; Huutoniemi et al., 2010; Klein, 2015). Interdisciplinarity is typically focused on integrating perspectives between scientific disciplines, whereas transdisciplinarity

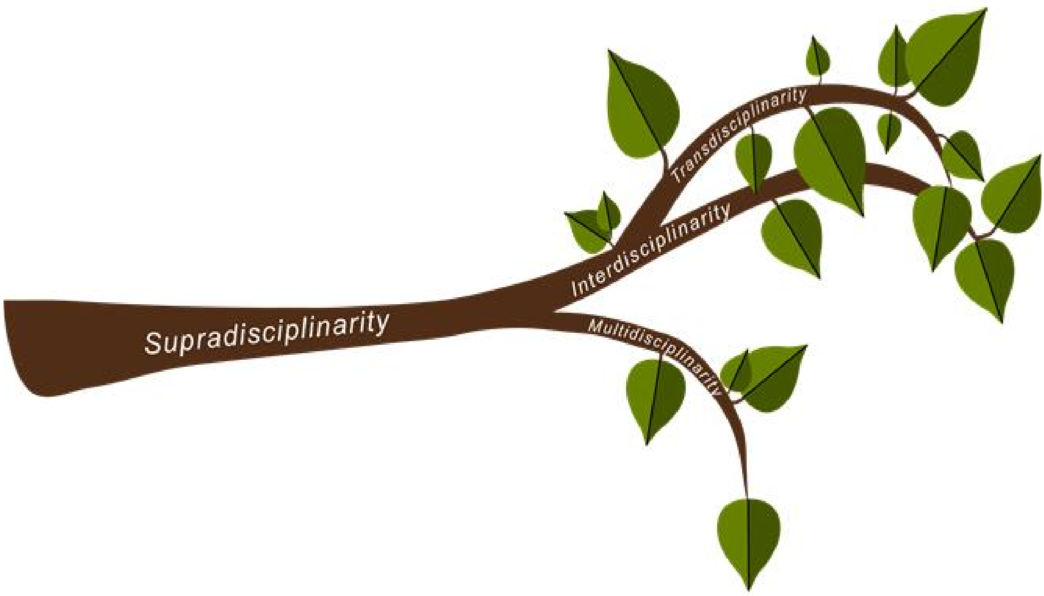

Figure 1. The branch represents my conceptualization of the developmental relationships between multi, inter, and transdisciplinary research. Multi, inter, and transdisciplinarity are all forms of supradisciplinary research. Multidisciplinarity developed first, followed by inter and then transdisciplinarity. While some view inter and transdisciplinarity as closely related, or even consider transidisciplinarity to be a form of interdisciplinarity (Huutoniemi et al., 2010), the characteristics of multidisciplinarity diverge significantly from both (Balsiger, 2004; Huutoniemi et al., 2010).

integrates extra-scientific participants' perspectives as well (Hirsch Hadorn et al., 2008b; Klein, 2015) (see section 2.2). On the other hand, multidisciplinary science is not directed at problem-solving, nor is it participatory (Balsiger, 2004). Further, unlike inter and transdisciplinary projects, multidisciplinary projects are not intended to produce integrated knowledge, as they typically involve members of different scientific disciplines contributing to a common theme by working in parallel or sequentially, rather than creating knowledge together (Huutoniemi et al., 2010). For these reasons, multidisciplinarity is not addressed further in this thesis work. Figure 2 provides a simple schematic of the dichotomies between multi, inter, and transdisciplinary approaches.

2.2 Characterizing Inter & Transdisciplinarity Today

Perhaps, as Klein (2006) suggests, the reason ITDR research is so difficult to define and hold to a single standard is that it is so complex. Nevertheless, this has not stopped the scientific community from ardently trying. In my opinion, one of the most useful of these efforts is Huutoniemi et al. (2010)'s framework for identifying and categorizing interdisciplinary research documents. The framework acknowledges that multiple forms or conceptualizations of interdisciplinarity exist (Huutoniemi et al., 2010) and that it is, therefore, "best understood not as one thing but as a variety of different ways of bridging and confronting the prevailing disciplinary approaches." The framework adopts Miller (1982)'s (Miller, 1982) perspective of interdisciplinarity, which considers it to be a "generic, all-encompassing concept, (which) includes all activities which juxtapose, apply, combine, synthesize, integrate or transcend parts of two or more disciplines." I find this framing particularly useful because it meshes well with my tree metaphor, where transdisciplinarity can be considered and semi-independently developing offshoot off interdisciplinarity. As such, I believe that Huutoniemi et al. (2010)'s framework encompasses interdisciplinarity *and* transdisciplinarity. Hence, her use of the term "interdisciplinarity" is analogous to my use of ITDR. From here on, I will use the term ITDR when discussing Huutoniemi et al. (2010)'s work to maintain clarity.

Huutoniemi et al. (2010) produced their framework by reviewing the literature about or related to ITDR. They identified three primary dimensions on which the authors of these works described the

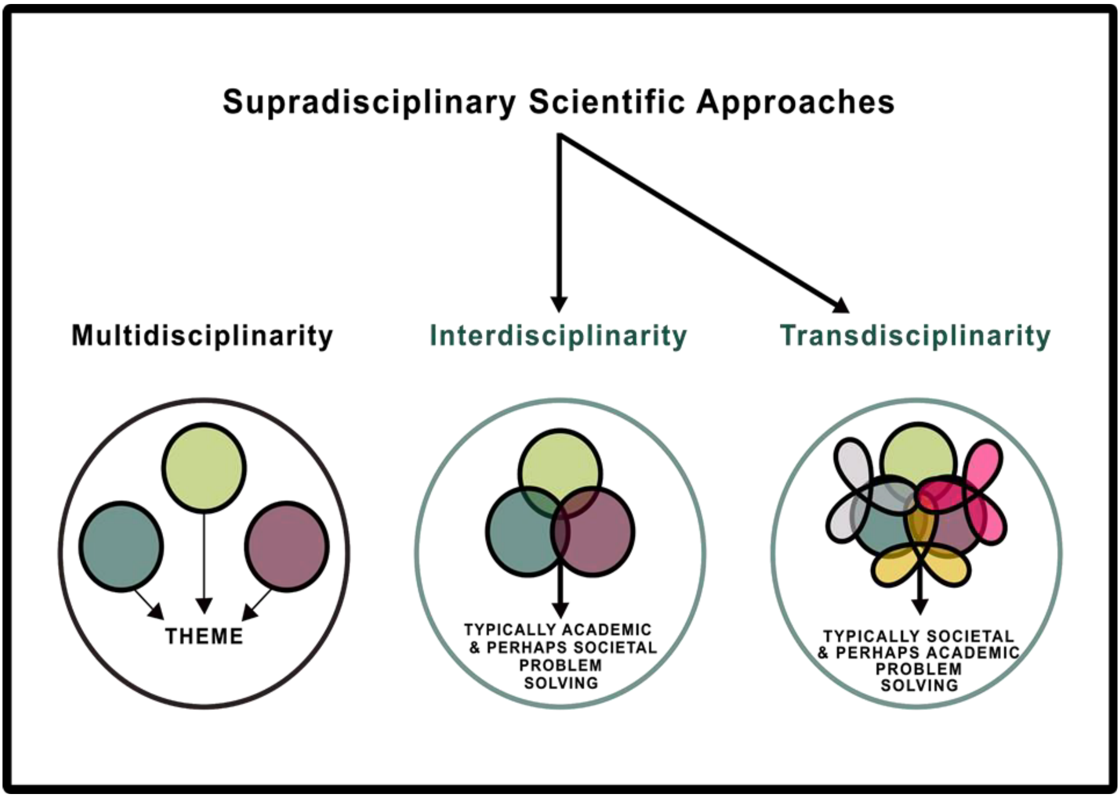

Figure 2. The figure visually describes the differences between supradisciplinary research approaches. Here, the colored shapes represent scientific disciplines (circles) and extra-scientific individuals or groups (three-lobed shape). Each color represents a separate discipline or specialty. In the case of multidisciplinarity, the individual arrows indicate that each discipline contributes individually to a given theme, while inter and transdisciplinarity's single arrows represent the use of integrated knowledge to solve societal or academic problems. The two approaches, inter and transdisciplinary research, circled in blue, will be the focus of this thesis.

concept. These dimensions form the three typologies of ITDR included within the framework. The first two explicitly address the concept of integration, which is the defining characteristic of ITDR interaction, the primary cognitive challenge of ITDR (Jahn et al., 2012), and the most debated aspect of it (Huutoniemi et al., 2010). In essence, the purpose of ITDR is to create a more comprehensive understanding of the problem and perhaps solutions for it, by, for example, actively integrating perspectives, data, theories, and concepts from multiple perspectives (Huutoniemi et al., 2010; Repko, 2014).

The three typologies of ITDR according to Huutoniemi et al. (2010):

1. **Scope -** i.e., how different the fields being integrated are. This typology defines ITDR as either narrow or broad. Narrow efforts are conducted between those with closely related perspectives, like an ecologist and a biologist, and broad efforts are conducted between those with very different perspectives, like a fisheries biologist and lawyer. Naturally, broad integration is likely to be more challenging, as those from highly diverse backgrounds will use very different methodologies, concepts, and theories (Huutoniemi et al., 2010).

2. **Type of Interaction Between Fields -** The second and most complex typology, type of interaction, addresses the role integration plays in an ITDR effort. According to the typology, ITDR activities can be integrated in three primary ways. First, via empirical ITDR, in which the heterogeneous data types produced by different fields are integrated to analyze a particular problem. Second, by methodological ITDR, where methodologies from different fields are integrated to create new knowledge, thus producing a better understanding of an issue. Third, via theoretical ITDR, in which concepts, theories, and models from multiple fields are integrated to understand and analyze a problem jointly.

3. **Goals -** The third typology of ITDR is related to the goals of an ITDR effort. An ITDR project's goals can be either epistemological, instrumental, or a mix of the two. Epistemological goals focus on integrating perspectives to produce a more thorough, holistic understanding of a problem or developing novel approaches to understand it. On the other hand, instrumental goals are geared toward producing societal value – for example, real solutions to real-world problems, commercial products, and the like. ITDR studies with mixed goals, intend to address both instrumental and epistemological issues.

Within Huutoniemi et al. (2010)'s framework, transdisciplinarity specifically could be characterized in the following way:

Scope - Broad. Transdisciplinary efforts incorporate highly diverse individuals ascribing to diverse schools thought from both inside and outside academic institutions.

Type of integration - Theoretical. Transdisciplinarity is geared toward integrating concepts, theories, and ideas to develop unified knowledge. However, empirical and methodological integration may also occur.

Goal - Mixed. Transdisciplinary efforts aim to produce new knowledge or understanding to solve societal problems.

However, because the transdisciplinary discourse has largely evolved in its own direction, separate from interdisciplinarity, I have also included the three overlapping themes Klein (2015) found within the transdisciplinary discourse:

1. **Transcendence -** According to Klein (2015), transdisciplinarity is a recent iteration in the historical quest for the unity of knowledge. As such, transdisciplinarity can be viewed as a critique of the traditional disciplinary approach to knowledge production as it aims to "transcend" their limiting worldviews. Proponents of transdisciplinarity as a transcendent approach to knowledge production would likely believe in an imperative to deeply integrate different perspectives to produce holistic knowledge.

2. **Problem-solving -** Like interdisciplinarity, many view transdisciplinarity as an approach to problem-solving. However, transdisciplinary problem solving emphasizes the use of various methods, concepts, and theories from both inside *and* outside academia. Further, transdisciplinarity's goal is nearly always to creatively address societal problems (Balsiger, 2004; Jahn et al., 2012; Klein, 2015; Lawrence, 2010).

3. **Transgression -** The final theme within the transdisciplinary discourse is the idea of transgression. Transdisciplinarity encourages its practitioners to question conventions and boundaries. For example, transdisciplinary efforts often break the barriers between schools of thought and between institutions by inviting extra-scientific actors into the scientific process (Klein, 2015). Further, transdisciplinarity can be seen as

a statement questioning, for example, narrow, reductionist world-views, traditional ideas about which types of knowledge provide legitimate contributions to science, or the detached role of scientists in society (Klein, 2015).

2.3 A Brief History of Inter & Transdisciplinarity

Next, I will introduce a brief history of the inter and transdisciplinary approaches to help the reader differentiate between the two approaches and improve their understanding of these approaches' place in society over time. It could be said that the ideas and values on which inter and transdisciplinary science were built can trace their origins as far back as ancient Greece (Klein, 2015). However, I will limit the scope of their historical development to the last 100 years. According to Balsiger (2004), the beginnings of the modern supradisciplinary approaches were born of the debate between those dedicated to disciplinarity's merits versus those favoring more holistic scientific approaches circa the late 1920s. This debate likely began or was at least revived, in response to the increasing trend toward specialization and disciplinarity, which occurred during the 19th century (von Wehrden et al., 2019). The budding supradisciplinary approaches were typically driven forward and refined by social scientists or natural scientists working with sociological ideas (Balsiger, 2004). However, World War II-era defense-related projects and their imperative to integrate the knowledge and skills of a diverse array of actors jumpstarted the conceptualization of interdisciplinarity as a problem-solving approach (Klein, 2015). Around the same time (1938), Ludwig von Bertalanffy introduced general systems theory (Bertalanffy, 1950), which encouraged science to leave reductionist thinking behind, in favor of holistic, contextualized approaches for understanding complex phenomena instead. Disciplinary expertise was not enough to understand the world according to this paradigm, and hence, required the integrated knowledge of a variety of experts to produce meaningful results (Balsiger, 2004). In the 1960s, interdisciplinarity entered the knowledge production discourse in academic and political realms (Huutoniemi et al., 2010). Then, in the 1970s, the first text mentioning transdisciplinarity was published (Balsiger, 2004), and the interdisciplinary branch forked into two.

Despite its relatively long history, interdisciplinarity only began to gain legitimacy in academic institutions in the United States in the 1980s after the National Collegiate Honors Society and the fields of women's studies and environmental science endorsed the concept (Repko, 2014). Similarly, transdisciplinarity also took time to gain momentum. The transdisciplinary debate did not begin in earnest until the 1990s (Balsiger, 2004), and by 2004, according to Lawrence (2015), it was still relegated to the status of "buzzword." More than ten years later, in 2015, while transdisciplinarity had gained worldwide recognition, it was not yet considered mainstream (Lawrence, 2015), and as of 2019, von Wehrden et al. (2019) still considered transdisciplinary collaboration rare. However, the real prevalence of either trans or interdisciplinary science is likely still tricky to gauge, due to ambiguity in their definitions.

2.4 Science's Previous Contract with Society

With an outline of the landmark events in the development of ITDR over the last 100 years behind us, it is vital to move on to a more in-depth discussion about what drove their development and rise in popularity. Understanding this context will illuminate important ideals to strive for as these approaches continue to be developed and are applied in socio-environmental problem-solving efforts.

A critical factor in the evolution of ITDR has been the changing relationship between science and society in recent decades. I will refer to this relationship as "science's contract with society," inspired by others' use of the term to signify the paradigm governing societal expectations for the behavior of science and scientists and the value they are expected to produce (Gibbons, 1999; Lidskog, 2008; Maasen et al., 2006).

Previously, the basis of this contract stipulated that science's primary goal was to pursue the kind of true, self-evident knowledge Aristotle referred to as epistême, which is distinct from phronesis, i.e., practical, everyday knowledge (Aristotle, 2003; Linke and Jentoft, 2014). Specifically, this scientific knowledge was to be, as stated by Hirsh Hadorn et al. (2008a), "universal, explanatory, demonstrated to be true by a standard method, teachable and learnable." This knowledge would then be taken up by other professionals, like engineers, to improve society's standard of living and produce plentiful, high-quality goods (Gibbons et al., 1994; Hirsch Hadorn et al., 2008a). The production of such knowledge was expected to be carried out by objective, efficient (Ludwig, 2001) scientists working within their own disciplines and detached from practical life, i.e., the so-called life-world (Hirsch Hadorn et al., 2008a). In return for the steady stream of value-free, unbiased knowledge that science was expected to efficiently and effectively provide, society offered science its autonomy, credibility, and a near-monopoly on knowledge production.

How the process of knowledge production was conducted under this previous contract and why, has been conceptualized and discussed in many different ways, which have often influenced one another and include conceptual similarities. Two of the most notable and most often referred to in the inter and transdisciplinary literature are Thomas Kuhn's "normal science" and Gibbons et al.'s "mode 1 knowledge production." According to Kuhn's *The Structure of Scientific Revolutions* from 1962, science is most productive as a "puzzling-solving" activity, where scientists work within disciplinary groups, which believe in common, implicit paradigms and the rigor of a specific set of tools to study them. An example of a paradigm is the discipline of biology's belief in Darwin's theory of evolution. Under such a paradigm, normal scientists will continue to discover new facts, which have been predicted by the paradigm or support it, thereby incrementally articulating the paradigm further and improving the methods used to study it (Kuhn, 1970).

Kuhn's concept of normal science overlaps with the idea of mode 1 knowledge production, initially introduced in 1994 by Gibbons et al. in their book, the *New Production of Knowledge*. *The Dynamics of Science and Research in Contemporary Society* (also see (Nowotny et al., 2003, 2001). There, mode 1 knowledge production characterizes science as a highly autonomous institution, which, again, operates within specialized disciplines, and is, as alluded to in Kuhn's work, dominated by so-called basic theoretical and experimental science, which does not necessarily begin with a practical goal in mind (Gibbons et al., 1994).

Whether described as normal or mode 1, the type of science that dominated knowledge production under science's previous contract with society tends to be characterized as disciplinary, focused on basic and experimental pursuits, and led by academic scientists.

2.5 Why is Science's Contract with Society Breaking?

Despite the productivity and longevity of this approach (Maasen and Lieven, 2006), some suggest it is no longer sufficient to address modern challenges (Gibbons, 1999; Maasen and Lieven, 2006) and that the time has come to develop a new contract between science and society (Gibbons, 1999). Two commonly cited causes for the degradation of the previous contract are: 1) a loss of scientific credibility, 2) a knowledge deficit, which threatens the efficiency and effectiveness of science.

2.5.1 A Loss of Credibility: Increasing Reliance on Science Threatens Perceived Scientific Objectivity

The credibility afforded to science by its self-imposed distance from societal affairs and perceived objectivity throughout most of the 19th and 20th centuries came under intense scrutiny circa the 1990s (Gibbons, 1999; Lidskog, 2008; Ludwig, 2001; Maasen and Lieven, 2006). Maasen and Lieven (2006) suggest that this diminishing trust was brought about by the emergence of the so-called "knowledge society[3]," which is characterized by its dependence on scientific knowledge and capacity to create it ("GOETE - GOETE Glossary"). Modern society has been recognized as a knowledge society since the 1970s, and this characterization has continued to strengthen thereafter (Stehr and Ruser, 2017). Notably, within a knowledge society, risk co-evolves alongside knowledge (Maasen and Lieven, 2006). For example, once science discovered how to use the combustible remains of ancient plant and animal life as fuel, the risks associated with anthropogenic climate change also increased. Hence, new knowledge propagates new risks. Additionally, new knowledge abolishes ignorance about pre-existing risks. Imagine the improvements in knowledge and technology that made predicting the risk of an asteroid collision possible, or the knowledge that poor sanitation and hygiene increase disease risk. As new knowledge and technology have exposed and created risks, which are often scientific and technical in nature, decision-makers' reliance on science to advise governance has risen (Maasen and Lieven, 2006).

Governance has become further dependent on science because many of

[3] Alternatively described as the "risk society" (Beck, 1992; Maasen and Lieven, 2006).

the threats facing society today, like the wicked problems described in the introduction of this thesis, tend to be difficult to perceive because they are diffuse (Beck, 1992), being delayed in time and distributed in space (Lidskog, 2008). To exemplify this point, consider climate change. It is exceedingly difficult or even impossible for a layperson to perceive changes in precipitation or air temperature over decades, particularly across broad geographic scales. Further, climate change is a complex phenomenon characterized by interconnected social and environmental factors (Grundmann, 2016). This complexity and diffuseness make it difficult to detect change and establish cause and effect relationships (Lidskog, 2008), making it understandably arduous for governance and the citizenry to react to this issue independently. For these reasons, society must trust science now, more than ever, to use its methodological, theoretical, and technological tools to detect wicked problems like these, build knowledge about them, and develop solutions (Chilvers and Kearnes, 2015; Lidskog, 2008).

For these reasons, in the modern knowledge society, science has become more closely tied to governance, exemplified by the scientific knowledge and expertise that have been developed to support nearly every policy domain (Maasen and Lieven, 2006). These changes require scientists to ask more applied and societally relevant questions than previously, necessitating a new type of knowledge production, which cannot rely on basic and experimental science alone (Repko, 2014). The shifting role of science in society may be referred to as the “sciencitization” of politics or the “politicization” of science (Maasen and Lieven, 2006). While opinions diverge about the merits and ethical ramifications of this coupling, for many, it diminishes the perception of scientific objectivity and precipitates a credibility issue (Maasen and Lieven, 2006).

Here, it is worth mentioning that ensuring scientists’ objectivity is seen as vital because it has been characterized as an essential prerequisite for science’s pursuit of the truth. It has been supposed that objectivity, i.e., impartiality and freedom from bias, allows scientists to produce epistemically sound knowledge (Ludwig, 2001; Maasen and Lieven, 2006) divorced from value systems and beliefs. For this reason, science’s historical efforts to create both cognitive and social distance between itself and the institutions of church and state have been seen as a liberation (Maasen and Lieven, 2006). Free from the power and authority of these institutions and therefore, from their beliefs and values as well, science could pursue the truth, thus fulfilling its duty to society under the previous contract.

Despite these assumptions, purely objective science entirely divorced from value systems and ideologies has always been more of an ideal to strive for than a reality (Dietz, 2013; Ludwig, 2001), as the scientists conducting research and creating knowledge can never fully extricate themselves from their perceptions of the world, which are fundamentally informed by their experiences, beliefs, and values (Glynn, 2017; Glynn et al., 2017). However, this concept still appears to be challenging for those who expect objectivity from science (Maasen and Lieven, 2006), which may even include scientists themselves. This conflict may result in the reluctance of scientists and scientific institutions to engage with societal affairs. Nevertheless, the direct involvement of science in such issues, which may be viewed as political, is common today, which appears to bring the discussion of bias or partiality to the fore. Perhaps for some, it goes so far as to make science seem like a political instrument or to make the scientists themselves appear to be interested, political actors (Dietz, 2013). Politicized science objectionable for those who, like Luhmann (1995), believe science and politics should be two distinct and fundamentally different institutions, where the purpose of science is to produce truth, and that of politics is to secure and protect power.

2.5.2 A Loss of Credibility: The Increasing Visibility of Science Decreases Trust

The credibility of science has suffered further blows in the eyes of the citizenry as science has become increasingly visible. This increased visibility has certainly exposed scientific fraud and misconduct, like faked or manipulated data, which have undoubtedly damaged the reputations of science and scientists (Carey, 2015; Chilvers and Kearnes, 2015). While such issues were once primarily dealt with within the confines of academia, now they are publicly dealt with on the internet. For example, in 2015, the New York Times published an article titled “Science, Now Under Scrutiny Itself,” which described the recent uptick in the number of retracted scientific articles due to the rising prevalence of online watchdog blogs and websites like RetractionWatch.com, poliscirumors.com, and PeerPub.com [4] (Carey, 2015). In addition, today, new forms of media enable and encourage the consumption of material aligned with previously held beliefs (Dietz, 2013; O'Neill and Boykoff, 2011), which may do even more widespread damage, as these conditions may lead to increased skepticism and mistrust of science, if it conflicts with consumers' pre-existing views (Dietz, 2013; O'Neill and Boykoff, 2011). Further, mis and disinformation[5] about science are now propagated more efficiently than ever amongst a citizenry who may struggle to recognize it (Scheufele and Krause, 2019). While some misinformation may be the product of innocent naivety, misinformation, disinformation, and uncertainty have often been insidiously leveraged to degrade public trust in science in the service of political (McCright and Dunlap, 2010) and corporate agendas (Oreskes and Conway, 2010). Further, the now more visible process of scientific knowledge creation itself, which is slow, non-linear, and by design characterized by uncertainty and debate between scientists, may appear inconsistent and, therefore, untrustworthy (Dietz, 2013; Ding et al., 2011).

2.5.3 A Loss of Credibility: Scientific Failures & Disregard for Stakeholders Decrease Trust

Perhaps it is unjust that science should lose credibility because the messy, uncertain reality of the process of knowledge production has become more obvious and provides an easy target for those opposing scientific information. However, a loss of credibility is understandable when science comes to erroneous conclusions or develops new technologies with negative consequences for citizens. For example, the development and misuse of technologies such as nuclear power, thalidomide, chemical fertilizers, and chlorofluorocarbons have soured citizens against science (Chilvers and Kearnes, 2015). Such situations are further damaging when citizens have been ignored, despite having relevant information or more effective solutions to share.

A well-known example of such a case, reported and studied by Brian Wynne, concerns the management of nuclear fallout in West Cumbria, UK, from the

[4] Note that these groups appear to be predominantly run by scientists themselves in an effort to make science more credible and accountable.

[5] Misinformation is merely incorrect information, whereas disinformation is intentionally incorrect (Scheufele and Krause, 2019).

Chernobyl disaster in 1986 (Wynne, 1992). There, scientists produced a model for the decay of the radioactive cesium based on incorrect assumptions about the area's soil types. Although local sheep farmers, who were familiar with the soil types in the area, tried to inform the scientists of their mistake, their advice fell on deaf ears. Consequently, radioactivity in the area failed to diminish as expected, and radioactive particles were absorbed by plants, which were ultimately consumed by animals, including the sheep. Adding insult to injury, as they attempted to solve the problem, scientists continued to ignore the sheep farmers' advice about related issues, including appropriate procedures for running field experiments with sheep. The scientists' disregard and arrogance made the farmers feel that they and their knowledge as professionals were being denigrated and threatened. Unsurprisingly, the scientists' credibility plummeted in the farmers' eyes, and therefore, they were unconvinced by subsequent scientific arguments, including the course of the radioactive fallout. Conspiracy theories ensued.

Issues like these are becoming increasingly important as governance has become more reliant on scientific advice (Brown et al., 2010a; Maasen and Lieven, 2006). As science has taken on this new advisory role, it has, in some cases, led to a technocratic style of decision making, which may exclude stakeholders' values and preferences (Linke and Jentoft, 2016, 2014). For example, Linke and Jentoft 2014 and 2016 discuss the European Union's (EU) fishery governance system whose chief regulatory instruments are catch limits called Total Allowable Catches (TACs). Annually, scientists from the International Council for the Exploration of the Seas (ICES) recommend TACs for different fish populations to the European Council based on fish population dynamics research (ICES, 2019; Linke et al., 2020). However, relying on this powerful tool too heavily has led other non-scientist stakeholders to feel alienated from the fisheries governance process (Linke and Jentoft, 2014). Such a narrow approach is also likely inadequate to solve many fisheries-related issues (Linke and Jentoft, 2014). Unfortunately, similar to the case of the West Cumbrian sheep farmers, failure to meaningfully engage with relevant stakeholders has led to mistrust, non-compliance with regulations, conflict, and has delegitimized the fishery governance system (Linke et al., 2020).

Therefore, as science continues in its advisory role, it must take steps to grow into its new position. For example, it must assume the new responsibilities of reflecting on how it influences the course of society and of ensuring that it will best meet the needs of those affected by the decisions made following its advice. Achieving this task will require scientists to develop a solid understanding of societal values and needs (Ignatius et al., 2019), new strategies for building trust with the citizenry, and a perspective, which allows reflection on personal biases and role in the power dynamics involved in the production of knowledge and decision making (Russell, 2010).

2.5.4 A Knowledge & Innovation Deficit: The Old Knowledge Production System is Not Effective in the Context of Modern Wicked Problems

The lack of trust caused by events like those described in Brian Wynne and Linke and Jentoft's is likely to lead to the disregard of scientific advice and undermine any decisions made on its behalf (Linke et al., 2020). Hence, failure to engage with stakeholders is problematic for socio-environmental problem-solving efforts. A lack of engagement is also an issue for these efforts because it may decrease the effectiveness and efficiency of science, particularly in the face of wicked problems.

Effectiveness ensures that the scientific process's desired outcomes are reached, and efficiency ensures it is done systematically without squandering valuable resources (time, money, etcetera). Perhaps under science's previous contract with society, these aims discouraged scientists from interacting with stakeholders and encouraged specialization and science's decomposition into disciplines. The rationale behind this idea could be that groups of scientists working with similar problems, drawing on similar theories, and employing similar methods develop amongst themselves their own culture, language, mode of operation, and shared knowledge base. These commonalities could allow those within the same discipline (i.e., with more similar perspectives) to quickly understand one another, work together, and critique one another's work from a position of understanding (Cronin and Weingart, 2019). Conversely, newcomers from outside the discipline or science altogether may require substantial time to obtain fluency and full understanding of the discipline, as scientific knowledge can often be highly technical and abstract. As such, before this level of mutual understanding develops, for example, at the beginning of an inter or transdisciplinary project, miscommunication and misunderstandings may compromise the efficiency and perhaps the effectiveness of the project (Cronin and Weingart, 2019).

However, modern wicked socio-ecological problems may threaten the efficiency and effectiveness of science to an even greater degree because a traditional disciplinary approach, which was the norm under science's previous contract with society, is arguably incapable of producing the diversity of knowledge and innovation such problems demand (Brown et al., 2010a; Lawrence, 2010; Repko, 2014). According to Repko (2014), a strictly disciplinary approach to problem-solving is likely to focus on a single aspect of the issue and is, therefore, blind to the broader context, thus failing to address the issue adequately. This idea is strengthened by Russell (2010), who eloquently explains that each person's knowledge can only ever be partial, even the knowledge of experts, as it is limited by cognitive capacities and perceptions rooted in individual experience and values. H. Rittel, one of the founders of the wicked problems concept, also recognized the limitations of individuals and experts in wicked problem-solving, stating that the knowledge needed is "*not concentrated in any single head*; for wicked problems there are no specialists" (Rittel, 1972). Further, he acknowledge that the best knowledge for dealing with a wicked problem, likely comes from those who will be affected by the solution, i.e., stakeholders (Rittel, 1972), as they tend to hold vital practical, phronetic knowledge and a strong understanding of the ethical landscape surrounding the problem at hand (Linke and Jentoft, 2014). This was certainly true in the case of the West Cumbrian sheep farmers (Wynne, 1992), and similar conclusions have been drawn in the context of other wicked socio-ecological problems. For further examples, see (Holm et al., 2020) and (Chuenpagdee and Jentoft, 2019b), which discuss the importance of incorporating stakeholder knowledge into the wicked problem of fisheries governance.

In addition to producing a knowledge deficit in the face of wicked problems, remaining in a disciplinary mode, which ignores the perspectives of stakeholders and other scientific actors, may dampen creativity, limiting the solutions developed (Repko, 2014). Collaborative problem solving with a diverse group of participants ensures issues are approached from multiple perspectives, allowing problem solvers to think more creatively and shift their perception of the problem (Bardwell, 1991; Cronin et al., 2011; Cronin and Weingart, 2019; Weingart et al., 2010). This way of thinking, in turn, deepens participants' understanding (Cronin and Weingart, 2019), allowing them to discover novel alternative solutions (Bardwell, 1991). Brown et al. (2010) allude to this idea as well, referring to the importance of the cross-pollination of ideas between a diversity of perspectives and the benefits a rich collective imagination provides for solving wicked problems.

Even within the academic community, the increasing complexity (or awareness of complexity) and scale of socio-environmental problems paired with rising doubt about the efficacy of disciplinary problem solving has led to the acknowledgment that no single, homogenous group of experts is capable of addressing them alone (Lawrence, 2010; Ludwig, 2001; Repko, 2014). Hence, the type of knowledge production science relied upon under its old contract with society is ineffective, as it leads to a knowledge and innovation deficit. This problem necessitates a new contract, open to all society's intellectual resources.

2.6 Participation: The Primary Tenet of a New Contract

As science and society negotiate this new contract, broader participation is emerging as its primary tenet (Brown et al., 2010b; Lidskog, 2008; Maasen and Lieven, 2006). It is important to note here, that in parallel with science, governance is also moving toward greater participation, making efforts to engage citizens more actively in the policy process. For example, see the United Nations' Convention on Access to Information, Public Participation in Decision Making and Access to Justice in Environmental Matters and the EU's Common Fisheries Policy. Interest in broader participation in science and governance extends seamlessly from democratic theory, which upholds public participation and deliberation as core values and essential for societies to address and triumph over difficult problems and situations (Dietz, 2013). Participation brings about these positive results in part because it offers solutions to both the credibility and knowledge deficits, which have degraded science's (and perhaps governance's) prior contract with society.

Participation addresses issues of credibility and trust by ensuring science remains accountable to society, i.e., that it operates in the citizens' best interest and fulfills societal needs appropriately (Chilvers and Kearnes, 2015; Maasen and Lieven, 2006). As active partners, citizens can both audit and contribute to the knowledge production processes to ensure that their values, understandings, and needs are expressed appropriately and taken seriously (Chilvers and Kearnes, 2015; Lidskog, 2008; Maasen and Lieven, 2006). More participatory forms of science and governance also create precedence and a formal space for integrating valuable stakeholder knowledge into scientific and political problem-solving processes (Brown et al., 2010b). These benefits have led science and governance to become increasingly open to broader participation over the last four decades or so (Chilvers and Kearnes, 2015). Indeed, it has become difficult to find any decision-making processes related to science and the environment that are not open to public participation in some way (Chilvers and Kearnes, 2015). While it may be challenging to differentiate participation in science from participation in governance considering their increasing closeness, this thesis focuses primarily on participation in science.

2.6.1 Participatory Approaches

As the idea of broader participation has enjoyed growing support, several schools of thought on the topic have been developed, each with its own ideas about why participation is necessary, who should participate, and how (Lidskog, 2008). Despite these differences, each nevertheless advocates for more inclusive knowledge production strategies, where citizens become active partners, and scientists become more introspective and transparent about their own assumptions, biases, and values (Lidskog, 2008). Here, I describe three alternative schools of thought about participation, which have contributed to modern ITDR: 1) post-normal science, 2) new production of knowledge, and 3) citizen science.

Post- Normal Science

Post-normal science was first described by Jerome Ravetz and Silvio Functowicz in 1990 (Funtowicz and Ravetz, 1990) and developed further in subsequent articles (De Marchi and Ravetz, 1999; Funtowicz and Ravetz, 1993; Ravetz, 1999). This school of thought suggested post-normal science as an alternative to

Thomas Kuhn's normal science (Kuhn, 1970) (see section 2.4). Ravetz and Funtowicz argue that the type of normal, high validity, high-reliability science typically performed in disciplinary, laboratory settings did not provide sufficient knowledge to address modern problems, particularly in decision-making contexts characterized by uncertainty and high decision stakes. They posited that the development of complex techno-scientific problems required better cooperation between scientific disciplines *and* between scientific and extra-scientific actors to solve them. Hence, post-normal science emphasizes the importance of practical, local, and stakeholder knowledge, which can help one to understand a problem and its context better. Extended peer communities could also help ensure knowledge produced for problem-solving efforts remained relevant and of high quality. Lidskog (2003) suggests that although post-normal science invites all relevant persons to participate in science, science remains at the helm of knowledge production. Other participants play a supporting role by enriching scientific knowledge and helping to course-correct if the science goes astray.

New Production of Knowledge

The new production of knowledge was originally introduced in 1994 by Gibbons et al. in their book, the *New Production of Knowledge*. *The Dynamics of Science and Research in Contemporary Society* (also see (Nowotny et al., 2003, 2001)). Within this school of thought, mode 2 knowledge production is juxtaposed with mode 1. Mode 1 is characterized by the existence of science as a highly autonomous institution, which operates within specialized disciplines, and is dominated by basic theoretical and experimental science, which does not necessarily begin with a practical goal in mind (Gibbons et al., 1994). This conception of knowledge production mirrors the expectations of science upheld under science's prior contract with society, as discussed in section 2.4. Mode 2, on the other hand, always begins with the intention of societal applicability and is oriented toward practical problem-solving (Gibbons et al., 1994). Mode 2 is also socially distributed and open to non-scientific knowledge, meaning that people from different scientific or nonscientific backgrounds are invited to participate in the process of knowledge production (Gibbons et al., 1994). However, the new production of knowledge advocates for the inclusion of the highly educated public (i.e., the agora) specifically, which it argues has become increasingly large and diverse since the rise of the knowledge society (Gibbons et al., 1994; Lidskog, 2008). According to Gibbons et al. (1994), mode 2 knowledge production became a necessity as the knowledge society developed, during which time science's normative cultural authority as the producer of reliable knowledge began to decline. To maintain its credibility in the eyes of society, science was required to exchange its autonomy for accountability (see sections 2.5.1 – 2.5.3 for discussion about the declining credibility of science). Hence science's shift away from mode 1 and toward mode 2 knowledge production. By engaging with the agora, science would be made accountable to society, ensuring the production of socially robust and trustable knowledge.

Citizen Science

Lastly, citizen science was founded by Alan Irwin in 1995 with his book, the aptly titled *Citizen Science: A Study of People, Expertise and Sustainable Development* (Irwin, 1995). This conceptualization of participation in science began with criticism of the perspective that citizens would accept science-based decisions if only they could understand it or were better educated about science. Instead, Irwin argues, bridging the gap between science and society is more about helping those with scientific knowledge, and those with context-specific knowledge relate to one another without favoring either. To help, Irwin encourages expanded dialogue and interaction between the two camps and public-centered knowledge production methods. These strategies should encourage scientists to address citizens' concerns and promote the cross-pollination of ideas between groups. As such, knowledge should be woven together by scientists and citizens in tandem, striking an appropriate balance between scientism and populism. Citizen science is particularly relevant now as society transitions toward a peer-to-peer model, in which citizens may become more empowered as decision-makers and knowledge-producers (Wildschut, 2017).

2.7 Developing Inter & Transdisciplinary Problem Solving

Despite the benefits participation provides, some warn that it is not a panacea for solving science's credibility and knowledge deficit issues (Lidskog, 2008; Maasen and Lieven, 2006). If conducted inappropriately, transdisciplinary methods, in particular, may reproduce the same power dynamics between scientists and extra-scientific actors that were present under science's previous contract with society, where the knowledge and values of scientists were dominant (Lidskog, 2008). Along similar lines, transdisciplinary research has the potential to disempower, exclude, and oppress (Chilvers and Kearnes, 2015). For example, it may fail to include or purposely omit legitimate stakeholders (Linke and Jentoft, 2016) or may be used to create the illusion of legitimacy or accountability even if stakeholders were only superficially involved or were not given adequate authority in the process (Linke and Jentoft, 2014; Maasen and Lieven, 2006).

ITDR approaches more generally have also been criticized for incoherent problem framing, generally failing to involve practitioners sufficiently,[6] difficulty in integrating heterogeneous knowledge, producing ambiguous results, and for a lack of standard methods and reproducibility (Brandt et al., 2013; Jahn et al., 2012; Lang et al., 2012; von Wehrden et al., 2017). Any of these may derail the development of trust between science and society or the process of knowledge production itself. As such, if ITDR approaches are to become the keys to unlocking wicked problems that many believe they are, they must be further developed and tested with thoughtful engagement strategies and ethics[7] in mind. These issues precipitated the first goal of this thesis and its attendant aims (see box 1). The following sections (sections 2.7.1-2.8.1) describe the research gaps these aims fulfill in greater detail.

2.7.1 Research Gap 1: Concrete Tools to Improve Communication in ITDR are Limited. A Rapid Tool for Making Implicit Perspectives Explicit Could Facilitate Cognitive Integration.

The challenges ITDR faces are, in part, the result of inefficient and ineffective communication between members of the problem-solving effort (Hall and O'Rourke, 2014; Harris and Lyon, 2013). These communication difficulties occur because although approaching complex problems from multiple perspectives is a powerful tool and a hallmark of ITDR (see section 2.2), perspective differences

[6] In the case of transdisciplinary research specifically.

[7] When I speak about developing approaches with ethics in mind, I am referring to the idea that ITDR must produce credible knowledge for the benefit of society and ensure that, for example, who is allowed to participate, power dynamics, and the values and biases of researchers are not allowed to jeopardize that goal.

can lead to misunderstanding and miscommunication (Cronin et al., 2011; Cronin and Weingart, 2019). Misunderstanding and miscommunication may increase frustration and conflict, which, in turn, decrease the productivity of diverse teams (Cronin et al., 2011; Cronin and Weingart, 2019). More precisely, Cronin and Weingart (2019) explain that when teams include diverse perspectives, the defining feature of inter and transdisciplinary teams, representational gaps (rGaps) (i.e., perceptual gaps), may exist between them. rGaps imply different and perhaps incompatible assumptions between people about a given word, concept, or issue, due to differences in knowledge and experience between individuals or subgroups (Cronin and Weingart, 2019). These differences and assumptions can then "distort the intended meaning of communications" (Cronin and Weingart, 2019). Therefore, when an rGap between individuals or subgroups exists, they are unlikely to understand or learn from one another, and in some cases, the situation may devolve into conflict (Cronin and Weingart, 2019). This is likely why Huutoniemi et al. (2010) found that most of the interdisciplinary research proposals submitted to the Academy of Finland were narrow in scope. The broader in scope a research effort becomes, or put another way, the more diverse the perspectives and fields of thought involved, the more likely significant barriers to communication and interaction become (Huutoniemi et al., 2010). However, maintaining a narrow scope is a suboptimal approach, as it limits the creativity and knowledge interdisciplinary problem-solving efforts can leverage. Further, a narrow scope essentially excludes the possibility of transdisciplinarity, which is broad in scope by nature. Therefore, to make broad scope collaborative problem solving possible, participants must bridge the gaps between their perspectives enough to allow for effective communication and interaction.

Despite these challenges, very few articles provide concrete communications solutions (Wang et al., 2019). However, some useful work to advise communication in ITDR has been done. For example, Wang et al. (2019) recently developed a framework, which includes topics and indicators for successful communication in ITDR. Their conclusions were three-fold:

1. The role of power dynamics among members of an ITDR team should be understood and addressed.

2. Translators, either from within the team (most likely social scientists) or external consultants, should help bridge the perspective of the different team members, make research understandable, and help team members express their interests and concerns.

3. Successful communication in ITDR requires researchers to prioritize interaction and to be open to and dedicated to the process of communication, including incentivizing and prioritizing spending time to develop trust within the group.

Although this framework helps describe what to look out for and what systems should generally put in place to support communication in ITDR, it does not provide the translator or the team itself with readily applicable tools to improve communication.

Cronin and Weingart's (2019) research on the process of cognitive integration also sheds some light on what can be done to improve communication in ITDR. The term cognitive integration describes "the degree to which one can translate between perspectives and thus, understand the intended meaning of what others communicate" (Cronin and Weingart, 2019). Note that cognitive integration is based on improving understanding between those with different perspectives, *not* homogenizing them, which would reduce the team's creativity and innovativeness (Weingart et al., 2010). Cronin and Weingart (2019) report that cognitive integration requires team members to understand one another's perspectives, which is achieved via three interconnected processes. These processes include (1) Enrichment, where team members reciprocally teach and learn about one another's perspectives; (2) Expansion, where team members combine their perspectives to produce new knowledge; and (3) Reconciliation, where conflicting perspectives and their underlying assumptions are addressed and reconciled (Cronin and Weingart, 2019). Cronin and Weingart (2019) go on to explain the importance and process of developing the right social environment to allow cognitive integration to occur, called affective integration. They suggest that cognitive integration is more likely to occur when team members have developed a general fondness for one another and have built trusting and respectful relationships. Fondness, trust, and respect are built through, for example, repeated exposure, positive interactions, and mutual successes (Cronin and Weingart, 2019).

Undoubtedly, many diverse teams can affectively and cognitively integrate successfully on their own their projects. For example, Haapasaari et al. (2012a) describe how this process proceeded within their interdisciplinary project, indicating that shared methodological understanding between the team members provided common ground, which helped them develop their understanding of one another and a shared understanding of their task. However, in some cases, cognitive integration may require facilitation, perhaps from a translator, like Wang, 2019 suggests. The need for facilitation may arise, for example, in particularly complex or challenging circumstances, if the process must be accelerated in the face of stringent deadlines, or if a team is unable to meet regularly in person and engage in enrichment, expansion, and reconciliation on their own.

Chapter I of this thesis aims to address this situation (box 1, aim 1a). Specifically, it aims to begin the development of a method to assist teams with the expansion and reconciliation phases of cognitive integration (Cronin and Weingart, 2019). As discussed above, expansion involves recognizing and learning about the different perspectives within the team. Hence, the new method must be able to make implicit perspectives about key topics explicit. Doing so may also illuminate areas where perspectives conflict within the group, paving the way for dialogue targeted at reconciling these perspectives (Cronin and Weingart, 2019). The method must also be able to be implemented rapidly to address communication difficulties before they subsume the conversation, leading to frustration or the withdrawal of team members into like-minded subgroups. Further, rapid implementation could help cognitive integration proceed more quickly, allowing the team to begin their collaborative work more quickly as well. The new method must also be easily scalable, so the perspectives of large numbers of team members can be analyzed. The method must be scalable because legitimate stakeholders are often left out of ITDR due to the practical difficulties (Linke and Jentoft, 2016), like including a large number of participants (box 1, aim 1c).

Chapter I adapts and tests two candidate methods, interview analysis and topic modeling, for their applicability in this task. Structural topic modeling was the first method chosen because it is a tool that uses algorithms that compute the statistical likelihood of word co-occurrence to identify themes (i.e., topics) rapidly within large bodies of text (Blei, 2012; Roberts et al., 2016). These themes could then be used to identify different perspectives within the group, if we assume that the text data analyzed reflects the participants' perspectives. Interview analysis was the second method chosen because it has long been used to reveal interviewees' perspectives. If either of these methods or both in tandem can effectively reveal perspective differences rapidly for large numbers of participants, this approach could facilitate cognitive integration in diverse teams. **Chapter I** investigates these approaches in the context of an interdisciplinary team at the beginning of their ITDR project. Specifically, the two methodologies are used to illuminate perspective differences about the concept of "risk," a key concept for this team.

2.7.2 Research Gap 2: No standardized, effective, & socially robust methodology for mental model elicitation exists.

As stated above, another challenge ITDR faces is a lack of standardized, peer-reviewed methodologies and guidelines for conducting them ethically (Gray, 2018; Lang et al., 2012; von Wehrden et al., 2019, 2017). It has proven difficult to create standards for these approaches because examples of successful ITDR studies are still rare (von Wehrden et al., 2019), the literature on the topic is fragmented and dispersed (Lang et al., 2012), reporting is poor (Gray et al., 2018), and mistakes and lessons learned that other researchers could benefit from are rarely described (Gray et al., 2018). Further, ITDR requires the development of a diverse array of methodologies to cope with the various problems they seek to solve (von Wehrden et al., 2017). In essence, the problem at hand often shapes the methodology used (von Wehrden et al., 2017), which is understandable and not necessarily to be discouraged. However, an appropriate balance between flexibility and reproducibility must be reached to preserve methodological functioning while maintaining the credibility of ITDR. Sufficient documentation and reporting of new methodological innovations could help. In addition, commonly used methodologies in ITDR that are not problem or project-specific should be improved and standardized.

Chapter II of this thesis focuses on developing a standardized, practical methodology for the elicitation and documentation of stakeholders' mental models, ensuring stakeholders' knowledge is respected and reported accurately (box 1, aims 1b and 1c). Mental model elicitation is a commonly used tool within the field of participatory modeling (PM) (Jones et al., 2011), an increasingly popular toolbox for transdisciplinary problem solving (Smetschka and Gaube, 2020; Voinov et al., 2016; Voinov and Bousquet, 2010).

Also known as cognitive maps, mental models are internal representations of the cause and effect relationships within an external system (Jones et al., 2011; Moray, 1998). Shaped by individual experience, knowledge, and values (Johnson-Laird, 2010, 1983; Jones et al., 2011), a person's mental models assist them in reasoning and navigating the world (Johnson-Laird, 2010; Jones et al., 2011; Nersessian, 2002). In this way, one's mental model about a problem system reflects their perspective of it. Jones et al. (2011) provide a review of the reasons a practitioner might choose to elicit stakeholders' mental models, including:

1. To determine similarities and differences between stakeholders' perspectives to promote communication between them (Abel et al., 1998).

2. To integrate stakeholders' perspectives about an issue to produce a more holistic knowledge base about it (Özesmi and Özesmi, 2004).

3. To produce a synthesized frame of a system to support decision-making (Dray et al., 2006).

4. To facilitate social learning (Pahl-Wostl and Hare, 2004).

5. To identify stakeholder's misconceptions and knowledge gaps (Morgan et al., 2001).

6. To provide socially robust information to support negotiations in complex, uncertain contexts (Kolkman et al., 2005).

For these reasons, mental models provide useful information for a variety of participatory modeling approaches, including problem framing (Haapasaari et al., 2012b), Bayesian belief networks (Haapasaari et al., 2013, 2012b; Meynecke et al., 2017; Smith et al., 2018), fuzzy cognitive maps (Gray et al., 2014, 2015; Olazabal et al., 2018; Özesmi and Özesmi, 2004; Solana-Gutiérrez et al., 2017), conceptual content cognitive maps (Kearney and Kaplan, 1997), and Actors, Resources, Dynamics, and Interactions (ARDI) models (Etienne et al., 2011; Mathevet et al., 2011).

Although many ITDR studies do report the process they used to conduct mental model elicitation (Haapasaari et al., 2012b; Martinez et al., 2018; Olazabal et al., 2018; Solana-Gutiérrez et al., 2017), few report their methodologies in detail, and some neglect to report them altogether. The methodologies or strategies that *are* reported often appear to be ad hoc and tailored to the specific contexts in which they are implemented. The reason behind this is likely partially because, to the best of my knowledge, no standard methodologies or guidelines for mental model elicitation have been developed. For this reason, my colleagues and I developed a guiding, tailorable methodology for mental model elicitation and documentation, which ensures that stakeholder knowledge is portrayed accurately and makes efforts to ensure power is equalized between participants and researchers.

Although no clear guidelines for mental model elicitation and documentation exist, Jones et al. (2011) describe the two broad mental model elicitation styles: direct and indirect elicitation. When mental models are elicited directly, participants, individually or in groups, define the structure of their mental models themselves (Jones et al., 2011). Typically, a facilitator is present to assist them in using visualization tools, which help represent the variables within a system and the connections between them (Dray et al., 2006; Haapasaari et al., 2012b; Özesmi and Özesmi, 2004). The benefits of this approach are twofold. First, this type of engagement with their own mental models can act as a valuable learning experience for participants, allowing them to deeply consider their perspectives (Marcot et al., 2001; Uusitalo, 2007) and exposing, for example, deficiencies in personal knowledge. Second, because each participant is directly involved in the modeling process, direct elicitation helps ensure that representations of their mental models resemble their thoughts as accurately as possible and limits the introduction of a facilitator or analyst's bias (Abel et al., 1998). However, direct elicitation can also lead to unintentional information loss or simplification due to, for example, time constraints or fatigue, either on the part of the facilitator, the participant, or both. Further, participants may struggle to use visualization tools to represent complex causal networks. This loss of holism defeats the goal of ITDR in sustainability science, which is to provide the holistic, complex knowledge required to address wicked problems (see section 2.5.4).

The second style of mental model elicitation, indirect elicitation, relies on textual information, like interview transcripts or questionnaire responses (Jones et al., 2011). Using this information, an analyst builds the stakeholder's model, which may reduce the problems associated with direct elicitation. Hence, indirect elicitation potentially reduces oversimplification or information loss. However, without a participant's direct involvement, more opportunity for an analyst to unintentionally bias the depiction of the stakeholder's model exists, which creates an ethical conundrum because the elicited mental models should remain recognizable to stakeholders and adequately reflect *their* knowledge and values (Agrawal, 1995).

In summary, like all participatory modeling studies, and arguably ITDR efforts more broadly, mental model elicitation should help provide:

1. **Normative value** – which suggests that incorporating stakeholder perspectives into the modeling process increases a model's or its outputs' legitimacy in natural resource management and decision making contexts (Fiorino, 1990; Jones et al., 2009).

2. **Substantive value** – which describes the value synthesizing stakeholder perspectives holds for knowledge base development and the generation of new solutions (Fiorino, 1990; Jones et al., 2009).

3. **Instrumental value** – which indicates the value participatory processes, like mental modeling, may have in strengthening relationships between stakeholders and thereby easing the implementation of subsequent decisions (Fiorino, 1990; Jones et al., 2009).

4. **Educational value** – which suggests that engaging stakeholders in the PM process serves as an educational experience (Voinov et al., 2016; Voinov and Bousquet, 2010).

Considering the shortcomings of both direct and indirect elicitation, a new, standardized method is required to produce representations of mental models that accurately depict stakeholder knowledge and values, as complete as possible, and add normative, substantive, instrumental, and education value to the ITDR research effort.

Chapter II fulfills this research gap by developing a new approach for mental model elicitation, the Rich Elicitation Approach (REA), which combines direct and indirect elicitation methods. By combining these methods, the REA is intended to compensate for the shortcoming of each while merging their strengths to produce accurate, complete depictions of mental models. I found one prior study in the field of cultural anthropology, which used voice recordings following direct elicitation to ensure the concepts vocalized by the stakeholder had been written down (Radonic, 2018), which is similar to the coupling we suggest. However, the REA takes this strategy further, using indirect elicitation not only as a means of verification that all concepts are represented, but also to ensure they are represented as accurately and holistically as well.

The REA was tested in the context of a transdisciplinary effort to address a real-world fisheries management issue (**chapter III**). The implementation of the REA was reported using Gray et al.'s (2018) "4P framework" for reporting participatory studies (Gray et al., 2018), to support the process of methodological development in ITDR.

2.8 Sustainability Science: An Application of Inter & Transdisciplinary Approaches

In addition to addressing the two research gaps described above to improve the ITDR's credibility and capacity for knowledge production, this thesis provides a case study of transdisciplinary problem-solving in the context of sustainability science (**chapter III**).

The characteristics of the ITDR approaches described in sections 2.1 and 2.2 make them ideal for application within sustainability science. The match between sustainability science and ITDR is strong because both sustainability science and the ITDR approaches are defined by problem-solving. The specific problems, sustainability science seeks to solve are, for example, preservation of Earth's life support systems, poverty alleviation, and the transition to a more sustainable way of life (Clark, 2007; Kates et al., 2001). Further, sustainability science is also open to the inclusion of extra-scientific actors and emphasizes the importance of multiple ways of knowing (Kates et al., 2001). Hence, in sustainability science, ITDR:

1. Makes certain all the relevant scientific and practical knowledge available is integrated to allow for a more complete understanding of the problem and the development of solutions.

2. Can be used to address stakeholders' goals, values, and norms, which are necessary to help guide the transition toward sustainability.

3. Encourages collaboration, which is necessary to develop legitimacy, accountability, and ownership of the wicked socio-environmental problems in question (Funtowicz and Ravetz, 1993; Gibbons et al., 1994; Hirsch Hadorn et al., 2008b; Lang et al., 2012).

2.8.1 Research Gap 3: The Potential Effects of Climate Change on Baltic Salmon & the Wider Socio-Ecological System are Unknown. Knowledge about this Topic, Goals for Fishery Management, & Management Strategies Must be Developed Using a Socially Robust ITDR Approach.

As such, the second goal of this thesis is to use ITDR to begin the process of problem-solving in the context of a real-word sustainability challenge and wicked socio-ecological problem, fisheries management (box 1, goal 2). Specifically, this portion of the thesis aimed to develop a holistic understanding of the problem climate change may pose for Baltic salmon (*Salmo salar L.*) their fishery (box 1, aim 2a), and to delineate areas of conflict and consensus between stakeholders (box 1m aim 2b) to help guide future fisheries management efforts.

These are essential issues to address because in the Baltic region, salmon support commercial and recreational fisheries (ICES, 2019), are an integral part of both marine and freshwater ecosystems (ICES, 2019; Ignatius and Haapasaari, 2018; Kulmala et al., 2012), and are deeply rooted in the cultural heritage of many nations bordering the sea (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Kulmala et al., 2012; Leeming, 2005; Lönnrot, 2009). Presently, Baltic salmon stocks are rebounding (Reusch et al., 2018; Romakkaniemi et al., 2003) following steep population declines driven by decades of overfishing, coupled with habitat loss due to dams, and the thiamine deficiency syndrome, M74 (ICES, 2019; Romakkaniemi et al., 2003). Strong management efforts, like the multinational Baltic Salmon Action Plan (SAP) (1997-2010), are largely responsible for the salmon's recovery. However, they are still considered threatened (HELCOM, 2011; ICES, 2019). Therefore, to continue to support Baltic salmon populations as they recover, prompt management action must be taken to address emergent threats.

Climate change may pose one such threat. In the Baltic region, warming is expected to exceed the global average (HELCOM, 2013; Räisänen, 2017) and has affected or is anticipated to affect the physical (Bolle et al., 2015; HELCOM, 2013; Sonnenborg, 2015), biological (Bolle et al., 2015; Engström-Öst et al., 2015; Koster et al., 2005; Niiranen et al., 2013; O'Neill et al., 2017) and social systems (Zandersen et al., 2019) of which salmon are a part, thus precipitating concern. Although the effects climate change has had on Atlantic salmon populations *outside* the Baltic Sea[8] have been studied and documented (Almodóvar et al., 2018; ICES, 2017a; Jonsson et al., 2016; Otero et al., 2014), presently the available literature only draws tentative links between the geographically isolated Baltic populations and climate change. Further, the issue has not yet been addressed directly, nor has it considered the system from a holistic perspective, which is crucial for understanding fisheries systems (De Young et al., 2008). As such, a broader, more complete knowledge base is required to understand and manage the effects climate change may have on the salmon and the system they are embedded within (i.e., the "salmon system.")

In addition to the need for a more complete knowledge base, a second barrier must be navigated before the climate change problem can be

[8] Baltic salmon and Atlantic salmon are the same species. Baltic salmon are simply Atlantic salmon that live out the duration of their lives in the Baltic Sea.

addressed. Mounting a management response to any new information produced will only be possible in the context of a functional fisheries management system. Although Baltic salmon management has experienced previous collaborative successes, like the SAP, it also has a long history of controversy (Ignatius et al., 2019). Currently, due to conflicting stakeholder interests, efforts to establish a new SAP are gridlocked at the European Union (EU) level (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014).

The struggle to establish a new SAP and other salmon management issues appear to stem from two interconnected problems (1) the marginalization of stakeholder groups' values, beliefs, and role in salmon management (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014), and (2) a failure to acknowledge the complex socio-ecological context in which salmon management takes place (Linke and Jentoft, 2014). Although the EU's Common Fisheries Policy (CFP) (Regulation (EU) No 1380/2013) calls for stakeholder involvement in the fisheries management process, efforts have fallen short, causing stakeholders to feel disillusioned and ignored (Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014). Hence, the CFP has been described as reliant on "top-down" control, "unresponsive to local conditions," and is said to lack support from those stakeholders dependent on fish for a living and dedicated to the long-term wellbeing of the ecosystem (Mackinson and Wilson, 2014). Furthermore, the CFP is more reliant on science than any other policy arena in Europe (Schwach et al., 2007), making it a prime example of the "sciencitized" political system described in sections 2.5.1, complete with the attendant credibility and holistic knowledge deficits. Despite these difficulties, research suggests that providing salmon stakeholders with *truly meaningful* opportunities to collaborate from an early stage of the management process would improve outcomes (Haapasaari et al., 2007; Ignatius et al., 2019) by rebuilding trust, and the credibility and legitimacy of the fisheries management process (Mackinson and Wilson, 2014). For these reasons, Baltic salmon management, including efforts to investigate and respond to the problem that climate change may pose, requires a transdisciplinary approach from the outset.

The specific ITDR approach I chose to investigate this issue was problem framing. Problem framing is a crucial first step for solving wicked problems (Bardwell, 1991; Burgman, 2005; Verweij and van Densen, 2010) and is critical for securing cooperation and promoting integration in transdisciplinary problem-solving efforts (Jahn et al., 2012; Lang et al., 2012; Smetschka and Gaube, 2020). The purpose of this approach is to clearly define an issue and its context, including all pertinent social, biological, and physical aspects (Bardwell, 1991; Clark and Stankey, 2006; Haapasaari et al., 2012b; Smetschka and Gaube, 2020). Problem framing is essential because the way a problem is framed, i.e., conceptualized, reflects the knowledge and values of the problem solvers (Bardwell, 1991), and ultimately determines the solution that will be implemented (Bardwell, 1991; Brugnach et al., 2008; Kueffer et al., 2012; Pahl-Wostl, 2007; Rittel and Webber, 1973; Tversky and Kahneman, 1981). For this reason, all relevant stakeholders should be included (Haapasaari et al., 2012b; Ignatius et al., 2019) to ensure the results are legitimate, credible, and cover all available knowledge.

During problem framing, the problem is considered from multiple perspectives (Bardwell, 1991; Brugnach et al., 2008), i.e., frames, which must be synthesized or otherwise taken into account to ensure that proposed solutions are supported by as robust a knowledge base as possible and are as socially acceptable as possible. Further, by investigating a problem from multiple perspectives, problem solvers can:

1. Reduce the chance that important facets of the problem are overlooked (Briggs, 2008; Haapasaari et al., 2012b).

2. Better define what is and what is not possible in a given situation (Bardwell, 1991).

3. Realize new solutions to move past previously perceived roadblocks (Bardwell, 1991).

4. Address the perspective differences underlying conflict over environmental management (Bardwell, 1991; Haapasaari et al., 2012b; Verweij and van Densen, 2010).

3 METHODS

The methods used in each of the three chapters are explained below. Please note that the subheadings indicate the section's relevance to each chapter. Figure 3 graphically summarizes the methods used, data produced, and outcomes produced in all three chapters.

3.1 Participant Selection

*3.1.1 Participant Selection (**Chapter I**)*

The participants included in the study reported in **chapter I** were all members of the WISE project, an interdisciplinary collaboration between Finnish institutions, including the University of Helsinki, Aalto University, the BIOS Research Unit, Tampere University, and the University of Turku. The WISE project's mission is to improve decision making over wicked socio-ecological problems in the Finnish context; see https://wiseproject.fi/en/ for more information. Broadly speaking, the project members, whom I will refer to as "participants," worked primarily in one of four general research areas, including the humanities, future studies, social sciences, and natural sciences. In the study reported in **chapter I**, the participants were divided into two groups 1) those who contributed texts for topic modeling and 2) interviewees. These two groups are distinct because not all participants wished to submit text for the study's topic modeling portion. Additionally, the authors of **chapter I** were members of the WISE project, and while they were not interviewed, they were permitted to contribute texts for the topic modeling portion of the study. Altogether, 19 participants contributed text, and 16 were interviewed.

*3.1.2 Participant Selection (**Chapters II & III**)*

The 11 participants of the salmon-climate change problem framing study (**chapters II and III)** were Finnish and Swedish expert stakeholders of the Baltic salmon fishery with various professional backgrounds. Stakeholders from Finland and Sweden specifically were chosen because the majority of salmon are produced in their rivers, and they jointly receive about 70% of the annual fishing

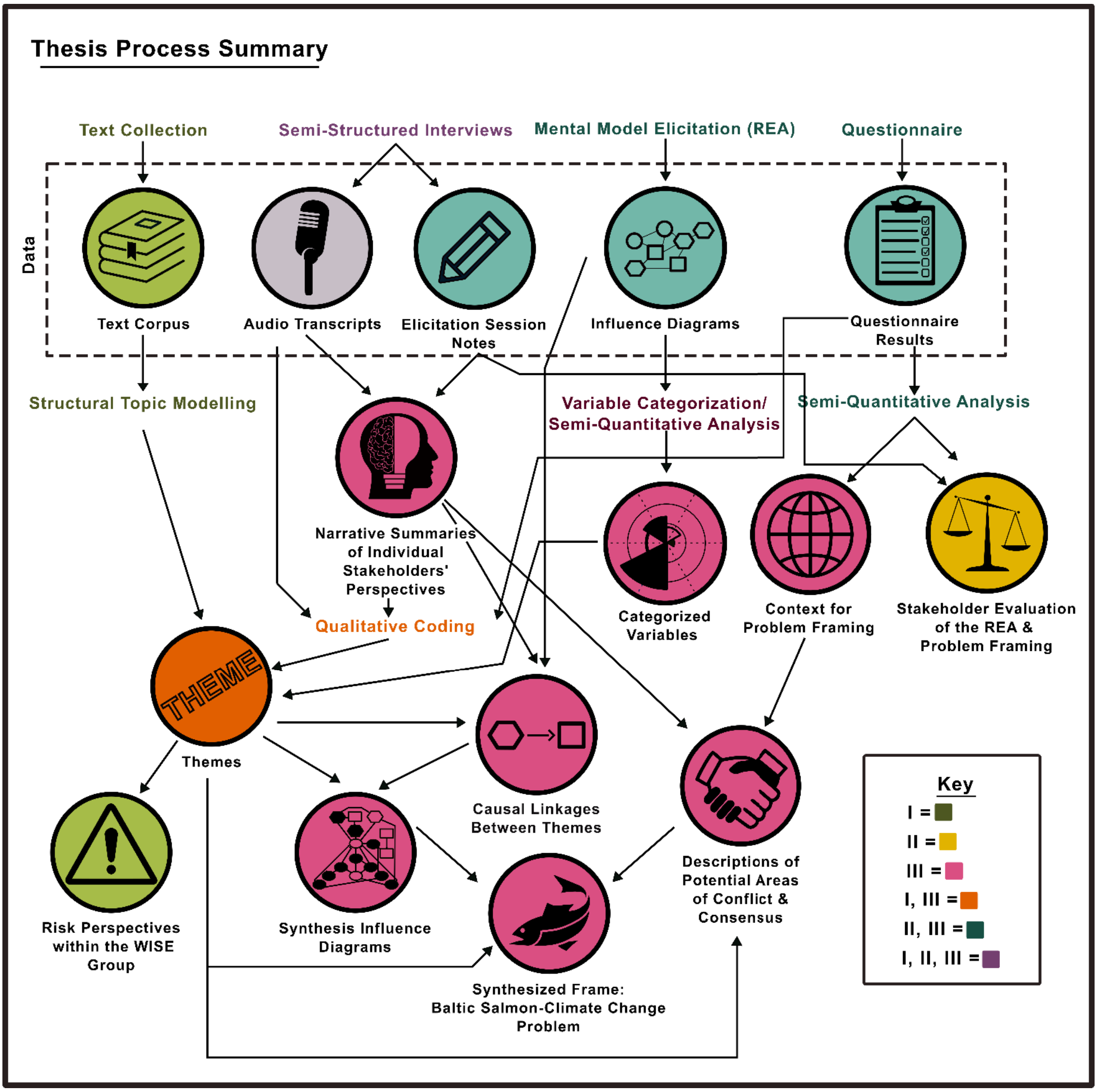

Figure 3. Depicts the relationships (arrows) between the methodologies (colored text) and data (inside the dashed box) used in this thesis, and the outcomes produced. The colors describe which chapters each method, data type, and outcome relates to (see key).

quota (ICES, 2019). Only expert stakeholders were included because they were likely to have the richest understandings of the salmon-climate change problem (Nersessian, 2002). Considerable ambiguity about the terms "expert," "stakeholder," and "expert stakeholder" exists within the scientific community (Krueger et al., 2012). Therefore, I explicitly state the definition of expert stakeholder used in this thesis. Expert stakeholders are those individuals who are both affected by or affect the outcome of Baltic salmon management (Durham et al., 2014) *and* have considerable experience and knowledge about the system (Fazey et al., 2006) through their professional or leisure activities. From here forward, I refer to expert stakeholders simply as stakeholders.

My co-authors and I contacted stakeholders for the problem framing study via snowball sampling (Browne, 2005; Matthews and Ross, 2010a). First, we emailed our professional contacts whom we considered to be expert stakeholders and then asked them to pass on our request for participants to other qualified candidates. All participants in **chapters I – III** are referred to by pseudonyms to protect their privacy, and neither identifiable information about them nor their interview transcripts have been published.

A list of the participants in **chapters I** and **II/III** and relevant demographic information is available in table 1.

3.2 Topic Modeling (Chapter I)

The first method used in **chapter** I to generate a better understanding of risk perspectives within the WISE group was structural topic modeling (STM). STMs form a subgroup of probabilistic topic models (TM) (Roberts et al., 2018, 2016), also known as mixed membership models, which are tools to find themes, i.e., topics, within large collections of data (Blei, 2012). Here, a topic modeling approach was used to find topics within text data, although TMs have been adapted for other types of data, including, for example, images (Blei, 2012).

To analyze data, TMs use unsupervised machine learning algorithms to compute two primary metrics: (1) probability distributions for each word in the corpus, based on the probability of word co-occurrence, which indicate the likelihood that a given word belongs to a given topic; (2) the proportion of each topic within each text in the corpus (Blei, 2012). Hence, each text can contain multiple topics.

Table 1. Summary of Participants in Chapters I – III					
Chapter	**Participation Type**	**Project/Nationality**	**Profession/Discipline**	**Number**	**Total Number**
I	*Contributed Texts*	WISE	Humanities	3	19
		WISE	Future Studies	3	
		WISE	Social Sciences	8	
		WISE	Natural Sciences	5	
	Participated in Interview	WISE	Humanities	3	17
		WISE	Future Studies	3	
		WISE	Social Sciences	8	
		WISE/WINLAND	Natural Sciences	WISE = 1, WINLAND = 1	
II & III	*Participated in Entire Problem-Framing Study*	FI/SE	NGO	FI = 3; SE = 2	11
		FI	Government Ministry	1	
		FI	Transnational Management Agency	1	
		SE	County Management Agency	3	
		SE	University	1	

To illustrate these ideas and describe the topic modeling process, consider a topic model used to analyze a single text, Herman Melville's *Moby Dick.* First, the text must be converted into a readable electronic file format like a .txt file. Then, the text must be “pre-processed” at the analyst’s discretion, meaning, for example, that all words are converted to lowercase, and unnecessary or irrelevant information, like punctuation, numbers, and stop words, is removed (Roberts et al., 2018). Stop words are very common words, which are not relevant to the analysis, like “a,” “and,” “the,” “so,” and etcetera. The analyst may also choose to remove custom stop words that are overly common in their particular corpus (Roberts et al., 2018). If an analyst were considering a collection of journal articles, for example, it might be reasonable to remove words like “table” and “figure.” The analyst can also choose to stem or lemmatize words (Roberts et al., 2018). While both approaches convert words into their basic form, stemming removes word endings (i.e., "running" becomes "run"), whereas lemmatization uses context to identify the root of a word. For example, a lemmatization algorithm would determine the basic form of "meeting" depending on whether it was used as a noun or a verb in a given sentence. The analyst can make additional pre-processing decisions, including the number of letters a word must contain or the number of texts it must appear in to be included in the analysis (Roberts et al., 2018).

Following pre-processing, the analyst must assume the number of topics, *k*, *Moby Dick* contains (Blei, 2012; Roberts et al., 2018)[9]. This decision may require an iterative process, including choosing a *k* value, running the model, and checking the resulting topics for their coherence and comprehensibility. Topic modeling packages may contain statistical functions to help determine an appropriate *k* value; however, the semantic validity and interpretability of the topics are crucial as well (Grimmer and Stewart, 2013). Comparing the exclusivity of words to a topic and their semantic coherence for each *k* value can also help determine an appropriate value. High exclusivity indicates that topics comprised of words that are unique to each topic. High semantic coherence, a proxy for human judgment of topic quality, indicates that the topics are interpretable.

Returning to our example, after investigating, the analyst determines *k* = 15 would be an appropriate choice for *Moby Dick* and runs the model using this *k* value on the pre-processed text. Now let us consider the two most prevalent topics the model finds, where the first comprises 30% of the text and the second, 15%. The remaining 55% of the text is composed of the other 13 themes.

The first topic contains words like "harpoon," "oil," "whale," "struggle," and "boat." The second, "mind," "insane," "rage," "Ahab," "revenge." Now, the analyst must determine what these topics mean using their expertise and domain-specific knowledge. To better understand the topics and the information they contain, they can consult word-clouds, list of words that are the most exclusive to each topic, texts containing the highest proportions of the topic, passages containing high proportions of the topic, etcetera. Despite the helpful clues this information provides, the analyst must be familiar with the texts or the general context surrounding them to make reasonable conclusions about the topics'

[9] Note that Blei (2012) and Roberts et al. (2018) discuss the method, although the *Moby Dick* example is my own, developed to illustrate the idea those articles contain.

meanings. Fortunately, the analyst in this hypothetical example is a scholar of classic American literature and has read *Moby Dick*. As such, the scholar determined the two most prevalent topics represent themes about whaling and madness, respectively. Real topic modeling studies typically include more texts than the analyst can either easily read or distinguish common themes between. However, although the analyst will not have read each text, they must understand the discourse well enough to make informed judgments about what the topics could mean. For example, if the analyst were looking for themes within classic 19^{th}-century American literature, the analyst should ideally be an expert in that subject, although they may not have read every text included in the study.

STMs differ from TMs in that they are designed for use in the social sciences, which tend to be interested in questions related to an article's metadata, including, for example, a text's author, the publication it was printed in, or perhaps, the political affiliation of the publication (Roberts et al., 2016). STMs allow metadata like this to be flexibly incorporated into the analysis process, hence illustrating their effects on topics (Roberts et al., 2016). For example, an STM could be used to observe which authors contributed to which topics and whether those topics were more dominant within the liberal or conservative political discourse.

In the *Moby Dick* example, imagine that the analyst wanted to determine the main themes described in American literature in the 19^{th} century and how their prevalence shifted from the beginning to the end of the century. The analyst would conduct the same process as described above, only with a much larger corpus, including all the notable works of American literature from the 19^{th} century *and* the year they were published (metadata). The analyst would then determine the meanings of each topic and observe the prevalence of the topics during each year.

3.2.1 Elucidating Risk Perspectives Using Structural Topic Modeling

My co-authors and I used an STM approach to define the main ideas (topics) that had influenced the way each member of the WISE group understood risk. Further, my co-authors and I wished to see if the same ideas influenced team members working within the same academic field. As such, to begin the topic modeling process, I requested texts ("text collection" in Figure 3) from each member of the WISE team that they felt had affected their understanding of risk. Altogether, 53 English language texts were received, including books, book chapters, a blog text, a PowerPoint presentation, reports, and journal articles. A complete list of the titles included in this text corpus is included in **chapter I**'s appendix table S1. As metadata for each text, I included a pseudonym representing the WISE team member who had contributed it, which reflected their academic field (humanities, social science, future studies, or natural science.) For example, social scientist 2 (SS2) or future studies scientist 1 (F1).

After collecting this material, I pre-processed the text using the 'stm' R package for structural topic modeling, as described above (Roberts et al., 2018, 2016). A brief description of the pre-processing decisions made is available in table 2. Next, the STM was run for eight topics, *k* = 8. More detailed information about the text pre-processing decisions and *k* value assignment are available in **chapter II.**

After running the model with *k* = 8, the authorship team viewed word clouds, lists of words exclusive to each topic, and considered the texts containing the highest proportions of each topic. With this information, the authorship team interpreted each topic as a group. The group members had plenty of experience with risk as a concept, understood the context of the WISE team, and at least one author had read each text within the corpus.

Table 2. Text Pre-Processing Decisions

Pre-Processing Step	Decision
Convert to all lowercase	Yes
Remove punctuation	Yes
Remove numbers	Yes
Remove common stop words	Yes
Remove custom stop words	Yes[10]
Stemming	No
Lemmatization	No
Required word length	>3 letters
Word must be found in X texts	2-52

3.3 Elucidating Perspectives via Semi-structured Interviews

Data for all three chapters included in this thesis was collected via semi-structured interviews conducted with research participants. The semi-

[10] A full list of custom stop words is available in the appendix of **chapter I.**

structured approach was appropriate for each study because it allows the interviewer(s) to direct the interview using a set of predetermined questions while providing the freedom for interviewees to expound on their ideas and discuss other tangentially relevant ideas (Gill et al., 2008; Matthews and Ross, 2010b). I recorded audio and produced transcripts for each interview in **chapters I – III**.

*3.3.1 Conducting Semi-structured Interviews (**Chapter** I)*

For **chapter I**, interviews were conducted between one member of the WISE team and either one or two interviewers. The interviews included questions about the participant's background, their reasons for contributing specific texts for the STM portion of this research, their basic conceptualization of risk, and essential aspects of the risk assessment cycle, including risk analysis, risk evaluation, risk communication, and uncertainty and probability (ISO, 2018). A full list of questions can be found in the appendix of **chapter I**. However, **chapter I** analyzes the participant's answers to two sets of questions in particular to define the most relevant aspects of their risk perspectives:

1. Risk definition & conceptualization
    a. *What is risk?*
    b. *What does it mean to you?*
2. Risk Analysis
    a. *How can risks you identified be estimated (by you or others)?*
    b. *Which risks do you believe you (or others) could estimate?*
    c. *How would you (or others) proceed with analyzing the risks?*
    d. *Would you (or others) quantify risks? If so, then how?*

The first set of questions was analyzed because these questions were fundamental to understanding each participant's risk perspective, as any differences in their conceptualizations of risk could propagate further differences about related concepts. The interviewers asked the second set of questions, about risk analysis, after requesting that the participants think about a hypothetical winter storm scenario. The scenario was meant to provide participants with some context to make answering the following questions easier and more concrete (see **chapter I**). My co-authors and I chose to analyze this set of questions because the widest gaps in perspective seemed to revolve around risk analysis, particularly quantitative risk analysis.

*3.3.2 Conducting Semi-structured interviews (**Chapters** II & III)*

The semi-structured interviews described as “direct elicitation sessions” in **chapter**s **II** and **III** were conducted between one stakeholder and one interviewer, i.e., facilitator. The questions asked during the elicitation sessions guided the process of direct mental model elicitation. Please note, the interviews described in **chapter**s **II** and **III** were the same. However, **chapter II** focuses on developing a new methodology for mental model elicitation in the context of the salmon-climate change problem, whereas **chapter III** focuses on reporting and synthesizing the results of that elicitation process.

A facilitator asked the stakeholders the following three questions, adapted from those used by (Haapasaari et al., 2012b), to engage their mental models about the salmon-climate change problem:

1. *What variables and causal relationships do you think should be considered when determining the impacts of climate change on Baltic salmon and their associated fishery?*
2. *What goals do you have for salmon and their fishery in the future considering climate change?*
3. *What management strategies or actions can be undertaken to achieve those goals?*

The purpose of the first question was to determine each stakeholder’s understanding of the direct and indirect cause and effect relationships between climate change and whatever aspects of the salmon system they found relevant. The second question was asked to help determine which aspects of the salmon system the stakeholders valued most, which could be used later to find potential areas of consensus between them and help direct the fisheries management process. Lastly, the analyst asked the third question to determine how the goals mentioned above could be reached in a manner that would be acceptable to the stakeholders and to use their knowledge about the system to help generate potential solutions.

The stakeholders reported their answers as influence diagrams (Haapasaari et al., 2012b), which act as representations of the stakeholders’ mental models by displaying the cause and effect relationships between variables within the problem system. Within these diagrams, arrows indicate the direction of the effect (Haapasaari et al., 2012b), and the thickness of the arrows qualitatively

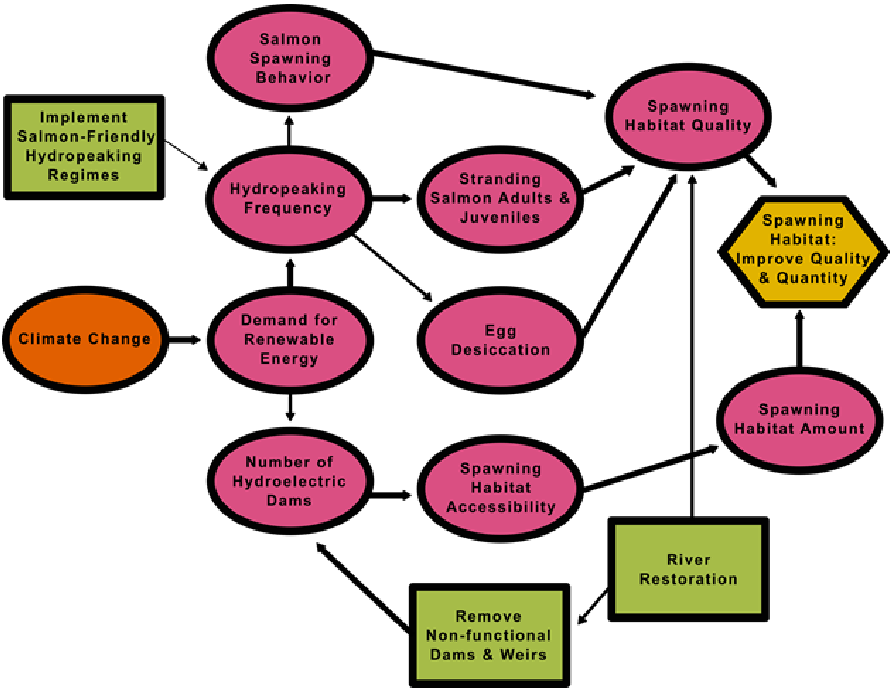

Figure 4. Depicts a hypothetical influence diagram documenting a hypothetical stakeholder's mental model of the effects of climate change on Baltic salmon. Here, pink ovals represent uncertain variables, green squares represent actions, and the yellow hexagon represents a goal. Climate change, an uncertain variable, is presented in orange to help readers orient themselves within the diagram. Line thickness qualitatively represents the stakeholder's uncertainty about the relationship; thicker lines depict more certain relationships.

indicates degrees of belief, i.e., the stakeholder's uncertainty about the relationship (Haapasaari et al., 2012b; Varis and Fraboulet-Jussila, 2002; Varis and Lahtela, 2002). Within the influence diagrams, responses to question 1 were recorded as uncertain variables (ovals), responses to question 2 as goals (also known as utility, loss, or preference of decision nodes (Haapasaari et al., 2012b) (hexagons), and responses to question 3 as actions (rectangles) (often conceptualized as management options (Haapasaari et al., 2012b). See figure 4 for a hypothetical example of an influence diagram.

3.4 Interview Analysis

*3.4.1 Interview Analysis (**Chapter I**)*

The transcripts of the participants' responses to the two sets of interview questions described in section 3.3.1 were coded according to a theory-directed content analysis approach (Hsieh and Shannon, 2005) to identify themes representing different aspects of risk perspective within the group. Theory-directed content analysis is an approach that uses the analysis to validate or extend a prior theory, and which may use aspects of it as an initial coding scheme (Hsieh and Shannon, 2005). Here, my colleagues and I used prior theories or conceptualizations of risk to guide our analysis and identify similar conceptualizations in the team member's interviews. More information about the coding protocol is available in **chapter III**. In conjunction with the themes identified during the topic modeling portion of **chapter I,** these themes were used to display the differences in risk perspective between members of the interdisciplinary team studied.

*3.4.2 Interview Analysis (**Chapters II & III**)*

The interview transcripts used in **chapters II and III** were also coded. However, those transcripts were coded to indicate all uncertain, goal, and action variables and any comments about the mental model elicitation process or direct predictions regarding the salmon-climate change problem. In addition to the coded transcripts, notes (elicitation session notes) were taken on each transcript describing the main themes they contained and the stakeholder's attitudes about those themes and the elicitation process itself. Then, following the protocol for the indirect elicitation portion of the REA processes, any uncertain, goal, or action variables that had been unintentionally left out or overly simplified within the stakeholders' influence diagrams were added back in or adjusted accordingly. Next, these "enhanced" versions of the stakeholders' influence diagrams were sent back to the stakeholders for their approval, following the REA methodology described in **chapter II**.

3.5 Questionnaires (Chapters II & III)

Following the REA's direct elicitation phase, the stakeholders were invited to participate anonymously in an online questionnaire. The questionnaire was designed to provide additional context for problem framing, determine the utility of the problem framing process according to the stakeholders, and provide insight into how the elicitation/problem framing processes could be improved. The full list of questionnaire questions is available in **chapter II**'s appendix.

3.6 Assessing the REA (Chapter II)

To determine the efficacy of the REA approach, I relied on three pieces of information. First, I took note of the number of variables and causal relationships within each stakeholder's influence diagram immediately after direct elicitation and again after indirect elicitation. The number of nodes and variables were used as proxies for the influence diagrams' "realism," which means that an increase in the number of causal relationships should equate to a better representation of the stakeholders' mental model and hence, a reduction in the amount of information lost during the elicitation process. I also consulted the relevant questionnaire responses to gauge the stakeholders' assessment of the substantive, normative, instrumental, and educational value mental model elicitation and collaborative problem framing provide. Lastly, I examined the questionnaire responses and the elicitation session notes to determine how the REA could be improved for future use.

3.7 Synthesizing Perspectives (Chapter III)

Following the mental model elicitation, I harmonized the variables within the stakeholders' influence diagrams, as was done by (Martinez et al., 2018; Olazabal et al., 2018), for example. If, for example, different words were used to represent the same concept, I standardized them to make the stakeholders' influence diagrams more comparable.

Following harmonization, I began synthesizing the stakeholders' perspectives about the salmon-climate change problem, which required several steps. First, I analyzed the stakeholders' perspectives about the salmon-climate change problem qualitatively by developing short narratives to describe each stakeholder's perspective about the issue based on the interview transcripts and the elicitation session notes. Next, I deconstructed the influence diagrams and categorized the variables they contained. The variables were categorized into three hierarchical categories, "1st", "2nd", and "3rd" order, where 1st order represented the narrowest level of categorization, and 3rd order, the broadest. For example, the variable "snow cover" was categorized as follows: 1st order = "snow," 2nd order = "hydrologic cycle," and 3rd order = "physical uncertain variables." Further, because salmon are anadromous and therefore use both riverine and marine habitats during their lives and exhibit a complex life cycle (ICES, 2019), each variable was also categorized by the habitat and life stage it pertained to. Those variables that did not pertain to a habitat or life stage were simple given the label "not applicable" in these categories.

After categorizing the variables, I was able to recognize the most frequently described variables, concepts, and themes among the stakeholders' influence diagrams, which was useful for deducing those that may have been the most important or best understood by the stakeholders.

Next, using a theory-directed content analysis approach, I coded the narrative summaries, categorized variables, and questionnaire results to determine and describe the most common themes across the 11 stakeholders' perspectives. Only those themes discussed by four or more stakeholders were reported in **chapter III**. To display the cause and effect relationships between these themes, I created a synthesized influence diagram, in which the common themes formed the nodes. The causal linkages between themes were determined by examining the stakeholders' influence diagrams and narrative summaries to determine the existence and nature of the relationship between two themes. Lastly, I used the relevant questionnaire responses, frequency of the given answers, and the narrative summaries of individual stakeholder's perspectives to determine and describe potential areas of conflict and consensus that may arise if the salmon-climate change issue were to be formally addressed by fisheries management.

4 RESULTS

4.1 Summary of the Main Results

4.1.1 Topic Modelling & Interview Analysis Methodologies Reveal Diverse Perspectives Within Interdisciplinary Teams

The topic model used in **chapter I** identified eight topics, presented in **chapter I**, table 1. These topics exemplified either (1) the specific types of risks, in the "hazard" sense of the word (hazard-interests), or (2) the stages of the risk management and governance process (process-interest) that interested each participant. For example, those participants contributing texts to the global environmental risks topic, a hazard interest, were interested in large-scale socio-environment risks, like climate change, and their sociopolitical ramifications. Those contributing texts to the quantitative risk analysis topic, a process-interest, on the other hand, were those who, for example, either supported or opposed certain risk analysis methodologies. Interestingly, participants from the same field did not show a clear affinity for the same topics. For example, humanists, natural scientists, and social scientists contributed text to the “global risks” topic. Instead, the topics appeared to more closely depict individuals’ interests (**chapter I**, figure 2).

After observing the specific texts contributing to each topic, a potential conflict between perspectives became apparent. Of the three articles contributing the most text to the quantitative risk analysis topic, we found that one, contributed by NS5, described how a quantitative risk analysis method could be used to manage risk. Whereas those texts contributed by SS1 and SS6 questioned the utility and practice of quantitative analysis methodologies. Hence, exemplifying possibly conflicting opinions about when and why such analysis methods should be used.

The results of the interview analysis portion of the study indicated different perspectives within the group about (1) the meaning of “risk” and (2) risk analysis. Within the WISE group, risk was a flexible concept, whose meaning was often context-dependent. When asked to explicate what risk meant to them, the participants tended to offer definitions that were either (1) probability-based, impact or hazard-based, or a combination of the two and were either (2) qualitative or quantitative (**chapter I**, figure 1). For example, the response "risk equals probability times impacts," would constitute a conceptualization of risk combining both the concepts of impact and probability framed quantitatively. On the other hand, an answer like "risk is a negative external force, like an economic crisis" would indicate a qualitative, impact-based conceptualization of risk.

The members of the WISE group also often described the relationship between risk and the concepts of uncertainty and surprise. However, their understandings of these relationships were often very different. Some described uncertainty as an intrinsic part of risk, whereas others imagined risk and uncertainty as opposites, where risk is calculable, and uncertainty is not necessarily. Similarly, some believed risk is related to known events that occur with some probability, whereas others indicated that risk is also related to entirely unknown, i.e., “black swan” events (Taleb, 2007).

In addition to their alternative viewpoints about the definition of risk, the WISE group members also had differing perspectives about risk analysis (ISO, 2018), which was also clear from the topic modeling results. The first of these differences were found in the approaches described for analyzing risks. Participants tended to describe either quantitative or qualitative approaches based on either data-driven, or imaginative exercises, or a combination of the two (**chapter I**, figure 1). Those that suggested data-driven approaches to risk analysis said that information like, for example, statistical data, expert knowledge, and systems knowledge, could be incorporated into quantitative models or otherwise used to judge risk. Most, but not all, of these data-driven approaches were described as quantitative processes. On the other hand, those who suggested imaginative approaches to risk analysis typically focused on the utility of scenario building or exercises to produce narrative accounts of what might happen. These approaches were typically described as qualitative analysis approaches that could be useful, particularly in data-poor or highly complex problem contexts. Note that occasionally, scenario building was described as an exercise requiring both imaginative skills and data.

In addition to their alternative perspectives about how risk can be analyzed, participants also had differing perspectives about the morality and utility of quantitative risk analysis in particular. The participants seemingly existed along a spectrum with those most enthusiastic about quantitative risk analysis on one end and skeptics on the other. The reasons the skeptics gave for their viewpoints were, for example, that such quantitative risk estimates can be overly certain, simplistic, subjective, or simply wrong. Some were also concerned about the moral implications of quantifying, for example, the value of a life or the impact of suffering. Additionally, some participants were unsure about the utility of the concept of risk for addressing wicked socio-environmental problems, suggesting that a risk-based approach would be too limited to address such large-scale complex issues.

4.1.2 The Rich Elicitation Approach Produces More Thorough Depictions of Mental Models & Was Well Received by Stakeholders

The influence diagrams representing the stakeholders' mental models in **chapter II** were more extensive and more complex following the complete Rich Elicitation Approach (REA) than after direct elicitation alone. Following direct elicitation, the stakeholders' influence diagrams contained a combined total of 349 variables and 496 causal relationships, however after these diagrams were enhanced using indirect elicitation, these numbers rose to 893 variables and 1472 causal relationships (see **chapter II**, table 1 for more details). The influence diagrams included all variables mentioned by the stakeholder, whether they were related to the fish themselves, ecology, employment of fishers, etcetera.

The stakeholders' assessments of the REA process were generally positive (see **chapter II**, table 2). However, they were most convinced of the approach's substantive and educational value[11] and less confident in its normative and instrumental value. In terms of the REA's implementation, most stakeholders quickly understood the process of drawing influence diagrams to represent their mental models. However, most preferred to allow the facilitator to draw the diagram while they dictated their thoughts and directed the facilitator's work. Assigning the effect strengths seemed to be more challenging than drawing the diagrams' structure, although these problems were easily resolved with additional explanation.

4.1.3 15 Themes Describe the Stakeholders' Synthesized View of the Salmon-Climate Change Problem

Fifteen interconnected, synthesized themes were found across the stakeholders' influence diagrams, questionnaire responses, and elicitation session transcripts describing the salmon-climate change problem. Each of these themes is reported in table 3 below, and a synthesized influence diagram depicting the linkages between the themes is available in **chapter III** (figure 9).

4.1.4 Categorized Variables Highlight the Importance of Rivers & the Social System

According to the categorized influence diagram variables, the river was the most frequently discussed environment amongst the stakeholders (**chapter II**I, figure 5). Further, the most frequently discussed phase of the salmon life cycle was the spawning phase (**chapter III**, figure A.3), which occurs within the riverine environment. The categorized influence diagram variables also highlighted the importance of the social system to the salmon-climate change problem, as the second-largest (after salmon-specific variables) and most

[11] Several stakeholders personally acknowledged the educational value of this experience either during their elicitation sessions or in their responses to the questionnaire.

Table 3. The Fifteen Topics Identified in Chapter III			
Topic	**Variable Type**	**Description**	**Number**
Heat stress in the riverine environment	Uncertain	- Rising river temperatures may: stress, increase disease amongst, or kill salmon, and may make them more lethargic and harder to catch. - Stocks dependent on rivers in the southern Baltic may be most at risk. - Stocks in the North maybe benefit.	11
The More Fish the Better	Goal	- Rising salmon populations would be beneficial because they could, for example, increase commercial and recreational catches, improve the well-being of the fish stocks themselves, support predator populations or all of the above.	11
Uncertainty	Uncertain	- The stakeholders expressed uncertainty about, for example: - - How climate change will affect salmon and the salmon system - The dynamics of the problem system - The number of fish caught - The salmon population size	11
The Integral Role of Politics	Action	- Politics play an integral role in the salmon-climate change problem system - Political action could affect climate change itself, influence fisheries management, and alter energy use and production, industrial practices, land use, and agriculture. - Politics affect the problem system at local, national, regional, and global levels.	9
The Importance of Appropriate Flow	Uncertain	- Climate change may affect the hydrological cycle and ultimately river flow. - Increasing prevalence of drought, potentially more problematic in rivers in the Southern Baltic region and may increase stress, mortality, and impede river passage and spawning.	8

		- Increasing flows, particularly in the Northern Baltic region, could increase habitat area and increase the carrying capacity of rivers, remove eggs from river bottoms, affect the efficiency of fishing with flow nets, reduce the ability to fish with lures as the amount floating debris increases, increase the amount of dissolved organic carbon entering the sea, change sea salinity, and affect the size of the river water plume in entering the sea that salmon need to find their way to their home rivers.	
The Economic Security of Fishers and their Communities	Goal	- Particularly important in rural areas in the Northern Baltic region, where employment opportunities in other sectors are limited. - Several stakeholders alluded to the importance of balancing the economic security and wellbeing of fishers with the health of salmon populations as climate change continues.	8
Changes in Fishing Practices	Uncertain	- Climate change may change how well fishers are able to locate and catch these salmon. - For example, salmon may change when they migrate and which routes they take. This may put them out of reach of fishers either spatially, temporally, or both. - Climate change may affect salmon behavior in other ways, for example, warmer river temperatures may make them less inclined to strike bait. - Climate change could change the efficiency of certain types of gear, for example, flow nets by altering river flow. - - Climate change may change fisher behavior. For example, changes in air temperature, cloud cover, and precipitation could influence fishing effort and timing.	8
Changing Food Web Dynamics	Uncertain	- Climate change could alter food web dynamics in both the Baltic Sea and riverine environments. - <u>Sea:</u> Descriptions of changes in the Baltic Sea were more consistent. Changes in salinity, disease and parasite prevalence, temperature, and anoxic zones could affect herring (prey), sprat (prey), and cod (interspecific competitor) populations. In turn, altering salmon growth, spawning age, mortality, and migration routes.	8

		- Sea: Lower cod and/or herring abundance could increase sprat consumption, increasing rates of M74. - River: Air and water temperatures, may affect prey availability, influencing the mortality and growth of young salmon. - River: Changing conditions may be more suitable for the establishment of non-native interspecific competitors.	
The Importance of Improving Fisheries Management and Governance	Action	- There is room for improving the management of Baltic salmon as a whole. - Suggestions for improvement included, for example, improved adaptive management capabilities, improved catch statistics and population estimates, ending mixed stock fishing, improved international cooperation, better regulation of recreational fishing, and incorporating climate change into the political discourse at the national and EU levels.	8
The Importance of Protecting Genetic Diversity	Goal	- Protecting the genetic diversity of Baltic salmon may prove crucial for ensuring salmon populations are resilient and capable of adapting to a changing environment. - Protecting weak salmon populations in the Southern Baltic, on the basis of the diversity they bring to the salmon gene pool may be particularly important. - Ending mixed stock fishing practices could ensure weak populations are not over-exploited. In addition one stakeholder suggested that reared salmon may also negatively affect salmon genetic diversity.	6
Human Impacts on the Riverine Environment	Uncertain	- Anthropogenic disturbances could exacerbate or be exacerbated by the negative effects of climate change. - Hydroelectric dams reduce access to spawning sites, thereby limited spawning success. A rising demand for renewable energy might result in increased reliance on hydropower. - Peat mining, forestry ditches, and clear-cut forestry practices coupled with increased precipitation could cause riverine environments to deteriorate due to increased runoff, nutrient and sediment loading, and flooding. These issues	6

		could lead to stressful low-oxygen conditions and adverse conditions for salmon eggs on the river bottom. - On the other hand, people could work to restore riverine habitats for salmon, by for example, removing barriers to migration or restoring spawning gravel.	
An Accelerating Life Cycle	Uncertain	- Water temperatures rise and prey is abundant, salmon may grow and mature more quickly, accelerating the salmon lifecycle. - Salmon would have "less time to die" between hatching and reproducing. - Juvenile salmon vacate their riverine habitat more quickly, leaving more space and resources for the next generation. - This could result in larger salmon populations.	5
Changing Disease Prevalence	Uncertain	- Mentioned most frequently for the riverine environment, although it was described in the context of the Baltic Sea environment as well. - Most stakeholders indicated that increasing disease prevalence could be driven by increasing temperature-induced stress and/or rising population densities in the riverine environment. - The prevalence of disease could also increase in prey species, negatively impacting salmon. - Stakeholders rarely mentioned any specific disease. However, one was concerned about an increasing prevalence of Ulcerative Dermal Necrosis (UDN), which causes large, open wounds on salmon's bodies.	5
Energy Use and Production Reform	Action	- Energy use and production should be reformed to reduce climate change, and ultimately reduce the effect of climate change on Baltic salmon and their fishery. - This could be accomplished by, for example, adhering to international agreements like the Paris Climate accord, instituting an eco-energy certification system, ending the practice of burning peat, and increasing the production of renewable energy.	4

diverse category of uncertain variables was "social variables" (**chapter III**, figure 4). This category included, for example, national policy, commercial fishing effort, and fishing rights ownership. Further, hydropower, a social variable, was among the variables most frequently described by the stakeholders (**chapter III**, table 1).

4.1.5 Stakeholders Agree About Some Aspects of the Salmon-Climate Change Problem

Chapter III also identified potential areas of conflict and consensus between the stakeholders about the salmon-climate change issue.

Example 1, Potential Consensus: According to the questionnaire results, all 11 stakeholders reported they had thought about the effects of climate change on salmon previously. The majority agreed that climate change will affect Baltic salmon in the foreseeable future and that its effects will be significant.

Example 2, Potential Conflict: Again, according to the questionnaire results, the stakeholders tended to disagree about when the effects of climate change on salmon will become evident and whether they will be positive or negative. Opinions were also mixed about whether or not management could mitigate those effects.

Example 3, Potential Consensus: However, the clear majority of stakeholders felt that if we understood how climate change would affect salmon better, management could make better plans to prepare the fishery for the future.

Example 4, Potential Consensus: During the direct elicitation sessions, several stakeholders recognized the problematic tradeoffs and prioritization of values that climate change could require. A few examples of the stakeholders' conceptualizations are as follows: (1) competition for resources, like water, may intensify between salmon and human society as climate change progresses; (2) climate change could increase competition between priorities. For example, more funding and resources may be given to issues society believes take precedence over salmon management, particularly if salmon appear to be unlikely to adapt to a changing climate; (3) as climate change progresses, the imperative to produce renewable energy, like hydropower, may take precedence over the well-being of salmon.

Example 5, Potential Conflict: Conflict could also arise between different regions or nations regarding the salmon-climate issues, according to the results of **chapter III**. Specifically, the questionnaire questions aimed to gauge the stakeholders' level of satisfaction with Baltic salmon management, indicated that while many were pleased with the management of Northern Baltics stocks, like the Tornionjoki/Torneå stock, they were dissatisfied with the management of weak, southern stocks and Baltic salmon management generally.

Example 6, Potential Conflict: Additionally, although relations between Finland and Sweden were perceived as healthy and productive according to several stakeholders' short-answer questionnaire responses and elicitation sessions, during the elicitation sessions, several stakeholders expressed the need for a joint management plan between the two nations and better-coordinated fishing regulations.

Example 7, Potential Consensus:

According to both the questionnaire results and several of the stakeholders' influence diagrams, the Southern Baltic stocks are most at risk of the adverse effects climate change may bring. They were also considered by many to be an important reservoir of genetic diversity and, therefore, potentially crucial in helping salmon adapt to new climatic conditions.

5 DISCUSSION

5.1 The Significance of the Work

This thesis work contributed to the thesis goals and aims stated in the introduction (see Box. 1) and takes steps toward closing the research gaps described in sections 2.7.1-2.8.1.

*5.1.1 **Chapter I** Provides Insights for The Development of a Concrete Tool to Facilitate Communication Between Participants of ITDR Projects.*

Specifically, **chapter I** tested the ability of a paired approach, including topic modeling and interview analysis, to elucidate and make explicit the different perspectives that exist within diverse problem-solving teams. As a reminder, the rationale behind developing an approach for this purpose was that clearly expressing the different perspectives within a team should help members of a diverse team learn about one another's points of view, the defining characteristic of the expansion phase of cognitive integration (Cronin and Weingart, 2019). Further, making perspective differences explicit could make areas of conflict between perspectives more explicit as well, setting the stage for the discussion and deliberation necessary to reconcile these differences, another critical phase of cognitive integration (Cronin and Weingart, 2019). As cognitive integration improves, so too should communication (Cronin and Weingart, 2019), thereby easing the process of ITDR, which is often challenged by communication difficulties (Hall and O'Rourke, 2014; Harris and Lyon, 2013; Huutoniemi et al., 2010). See section 2.7.1 for more information.

As described in the results section, **chapter I**'s two-pronged approach was successful in identifying several dimensions of the members of the WISE team's perspectives about risk, including:

5. Their diverse conceptualizations of the term.
6. Differences of opinion about how, when, and whether risk should be analyzed quantitatively.
7. Their risk-related interests.

Both the topic modeling and interview analysis strategies uncovered the question of how and whether quantitative risk analysis should be done as a potential area of conflict within the group.

Hence, providing these results at the beginning of an ITDR team's collaborative work and creating space for discussing them, perhaps with the help of a facilitator or translator (Wang et al., 2019), could initiate the process of cognitive integration. This process would likely be more effective if actions to support affective integration, like team bonding activities and group lunches, were taken during the same period (Cronin and Weingart, 2019).

The individual interests the topic model identified could also be used to characterize the team members' strengths, specialties, or values. For example, participant F1, who contributed text primarily to the risk assessment topic, is likely to have expertise in this area and has formed his understanding of risk around this topic. On the other hand, participant H2, who contributed primarily to the decision-making in the sociological context and global risks topics, may be better-versed strategies for societal governance in the face of the large-scale socio-ecological risks facing the world today. The topics each team member contributed to could also indicate their areas of interest or value. For example, H2 is likely to care about decision-making from a sociological perspective and global risks. By observing the composite results, it would also be possible to deduce the strongest and weakest areas of competency or interest within the group overall. A better understanding of the team's competencies and interests could help develop the project's goals, guide the approach to be used, and determine whether additional expertise is needed.

*5.1.2 **Chapter II** Provides a Standardized, Yet Flexible Methodology to Produce Holistic, Accurate Depictions of Mental Models*

Chapter II delivers the Rich Elicitation Approach (REA), a new methodology, and its supporting framework for eliciting mental models, which reflect individual stakeholders' knowledge and perspectives (Johnson-Laird, 2010; Jones et al., 2011). To the best of my knowledge, the REA is the first peer-reviewed methodology for mental model elicitation and documentation focused on ensuring the accuracy and richness of the representations produced and equalizing the power dynamics between researchers and participants, which is a step toward the development of the standardized, concrete, legitimate methodologies some argue are necessary to improve the credibility of ITDR (Lang et al., 2012). Other works related to mental model elicitation certainly exist, but are focused on different aspects of this process like the general types of mental model elicitation, the theory behind the use and implementation (Jones et al., 2011), or include mental model elicitation as a step within a more extensive methodological process, like fuzzy cognitive mapping (Gray et al., 2014, 2013, 2015).

Chapter II's results indicate that the REA works to produce richer, more accurate depictions of stakeholders' mental models. Specifically, the apparent increase in the number of variables and causal relationships included in the stakeholders' influence diagrams following the completion REA process versus after direct elicitation alone indicates that variables and causal relationships discussed during the elicitation sessions are indeed likely to be left out or oversimplified during elicitation sessions. This unintentional simplification could explain why many directly elicited mental models contain relatively few variables and causal relationships, even for complex topics.

It is crucial to ensure the mental models elicited represent stakeholder knowledge as thoroughly as possible, as stakeholder knowledge is a valuable resource for sustainability science and the socio-environmental problems it seeks to address (Jasanoff, 2004; Miller and

Wyborn, 2018). Losing the nuance in this knowledge could result in misunderstanding potentially crucial aspects of the problem system or allow room for incorrect assumptions to be made. Remember, the need for more holistic, rich knowledge to help solve complex problems was one of the primary reasons why many suggest increased participation in science has become necessary (Brown et al., 2010a; Lawrence, 2010; Repko, 2014), why ITDR was developed, and why it was adopted for use in sustainability science (see the theory section of this thesis synthesis). For this reason, producing depictions of mental models for use in ITDR that do not represent a stakeholders' knowledge in full would essentially be defeating their purpose (at least during the first stages of problem-solving).

Ensuring that mental models accurately reflect stakeholder knowledge is not only important for the sake of developing a rich and holistic knowledge base. As described in section 2.7.2, it is also vital for equalizing the power dynamics between researchers and participants. An imbalance of power between researchers and stakeholders and failure to faithfully include stakeholder knowledge threaten the credibility and legitimacy of both the mental model elicitation process and the results. This failure to reflect stakeholders' knowledge faithfully robs them of their voice in ITDR (Mackinson and Wilson, 2014), reproducing the same power dynamics under science's previous contract with society (Lidskog, 2008), which could reduce the credibility of the final project.

To ensure stakeholders' knowledge is represented as accurately as possible, the REA includes three opportunities for stakeholders to comment on, revise, and approve of the depictions of their models (see **chapter II**, figure 1). The method also encourages researchers to engage in critical rationality, i.e., introspective reflection on how the knowledge produced by this process may be affected by their biases, beliefs, heuristics, and values (BBHVs) (Glynn, 2017; Glynn et al., 2017; Russell, 2010) (see **chapter II**, figure 1). Cognizance of these issues could help researchers reduce the influence of these factors on the outcome of the work and ensure they do not unknowingly distort stakeholder knowledge (Glynn, 2017; Glynn et al., 2017). Lastly, the REA attempts to equalize power by encouraging the researcher and participants to decide on the core principles, i.e., the code of conduct or rules of engagement, and the reporting strategy[12] that will be used for the ITDR project together from the beginning of the project (Glynn et al., 2018; Voinov et al., 2016). Completing these steps ensures the ITDR project in which the REA is used will be conducted effectively and that results contribute meaningfully to the co-creation of knowledge in a transparent, accountable, and responsible manner (Voinov et al., 2016).

The stakeholders' generally positive attitude toward the REA process and the ease with which it was implemented were encouraging, suggesting its value in ITDR projects. Further, the stakeholders' responses to the questionnaire indicate the approach's particular value in creating substantive and educational value for ITDR projects. While the more variable responses about the normative and instrumental value of the process are concerning, they led me to include more thorough measures to ensure the legitimacy of the process and its outcomes and to strengthen the relationship between participants and researchers (discussed in the previous paragraph). The steps added to the REA process following stakeholder feedback and personal reflection about the outcomes of its implementation are included in italic font in **chapter II'**s, figure 1.

Given the REA's ability to deliver rich depictions of mental models, its sensitivity to the demands of socially robust knowledge production, the relative ease of implementation, and its ability to produce substantive and education value, I suggest the REA provides sustainability science and ITDR more broadly with a useful tool for producing a comprehensive knowledge base on which to begin collaborative problem-solving efforts. Such an approach will be useful for a variety of ITDR modeling processes that rely on representations of mental models, like fuzzy cognitive mapping (Gray et al., 2014, 2015; Özesmi and Özesmi, 2004) and Bayesian belief network analysis (Haapasaari et al., 2013, 2012b).

5.1.3 Chapter III Reports a Holistic "First Look" at the Problem Climate Change May Pose for the Salmon-System & Identifies Potential Areas of Conflict & Consensus

This thesis also contributes a synthesized frame of the problem climate change could pose for Baltic salmon and

[12] Gray et al. (2018)'s 4P framework and Glynn et al. (2018)'s records of engagement could be used separately or in tandem as templates for appropriate reporting on ITDR projects.

the broader salmon system to advise fisheries management (**chapter III**). The existing literature broadly supported this frame, as several of the synthesized themes (table 3) have been previously recognized as potential climate change-related threats for Atlantic salmon generally (ICES, 2017b; Jonsson and Jonsson, 2009), or even specifically for Baltic salmon (HELCOM, 2011). For example, ICES (2017b) postulated that climate change could affect the prevalence of disease and perhaps accelerate the lifecycle of Atlantic salmon. Additionally, others have described the importance of maintaining the genetic diversity of salmon (ICES, 2019, 2017b; Reusch et al., 2018) and the adverse effects anthropogenic activities can have on their riverine habitats (Elliott et al., 1998; Rivinoja et al., 2001; Romakkaniemi et al., 2003; Young et al., 2011). The literature even supports the stakeholders' concerns that climate change poses the most significant risk for salmon in the Southern Baltic (Lassalle and Rochard, 2009). Further, the themes related to the social aspects of the salmon system, coupled with the sheer number and diversity of social variables included in the stakeholders' influence diagrams (**chapter III**, figure 4) support the assertion that the social system is an integral part of fisheries management (Arias-Schreiber et al., 2019; De Young et al., 2008). Linke and Jentoft (2014) describe the importance of these social aspects for Baltic salmon management, specifically as well.

While the synthesized frame supports previous work, it also provides new information. First, it specifies the causal linkages between these themes, *specifically* in Baltic Sea environment. Second, the frame identifies the potential vulnerability or importance of riverine habitats and the spawning phase of the life cycle, which indicates potential areas for further inquiry and could be used to help prioritize resources for fisheries management. Third, the frame provides an integrated view of stakeholders' knowledge about the abiotic, biotic, and social aspects of the problem system. This information is critical for developing a holistic, credible knowledge base about the problem system[13], which could help

[13]The production of this type of integrated, co-produced knowledge is also an indicator that this ITDR effort has met with success, as ITDR should respond to the societal demand for holistic, credible knowledge for the purpose of problem solving (see sections 2.2 and 2.5.1-2.5.4).

address this wicked socio-environmental problem.

The frame also establishes common ground between the stakeholders, including commonly held beliefs about the causal dynamics of the problem system, mutually acceptable goals for salmon and their fishery, and areas for action, which could prove valuable in further discussions on the topic between stakeholders, considering the contentious nature of the Baltic salmon fishery (Ignatius et al., 2019; Linke and Jentoft, 2016, 2014). For example, many stakeholders believed the Southern Baltic stocks are the stocks most vulnerable to climate change and that they are a vital reserve of genetic diversity, indicating a potential common ground about the value of these stocks and their vulnerability. Considering this information, one can deduce that their management will likely be a topic of particular concern if the discussion about the salmon-climate change problem reaches the EU level. This deduction then allows a negotiator, facilitator, or participants, in general, to prepare to ensure the conversation remains productive and supportive, while this mutual understanding remains the foundation of the discussion.

In addition to exposing potential common ground, the process of producing the synthesized frame and the frame itself also exposed potential areas of conflict between salmon stakeholders or between salmon stakeholders and those with other vested interests. For example, several stakeholders indicated that climate change might necessitate difficult conversations about priorities for the use of riverine habitats. Specifically, suggesting that if climate change reduces water availability, demand for water for municipal and industrial use may supersede the salmon's need for free-flowing riverine habitats. Additionally, several stakeholders focused on the well-understood problems hydropower poses for salmon movement (Scruton et al., 2003; Young et al., 2011), spawning behavior (Haas et al., 2016; Vollset et al., 2016; Young et al., 2011), and mortality (Saltveit et al., 2001; Young et al., 2011). They, like Ashraf et al. (2018), recognized that demand for renewable energy, like hydropower, may rise in response to climate change, which could increase conflicts between fisheries and hydropower interest groups. Further, the issues the stakeholders raised during their elicitation session alluded to the idea that if salmon stocks diminish due to these issues or other climate change-induced problems, the value of fishers' livelihoods must be weighed against the wellbeing of the stocks. Inevitably, assessing these tradeoffs and making decisions about them is likely to insight conflict. Prior knowledge of these potential hot button issues could help a facilitator or stakeholder prepare to deal with them in a prompt, productive, and non-inflammatory manner.

Beyond the substantive knowledge this problem framing study provided, it also provided value, in the form of a learning experience by encouraging the stakeholders to engage with their mental models. Examining one's thoughts in this way can uncover personal knowledge gaps (Kaplan and Kaplan, 1982; Zellner, 2008) and help develop a deeper understanding of the system (Fortuin et al., 2011; Novak and Cañas, 2008; Smajgl and Ward, 2013; Voinov et al., 2016), encouraging the stakeholders (and researchers) to develop their perspectives about how the salmon-system works and how climate change could alter it.

Lastly, the problem framing process conducted and the synthesized problem frame are significant because indicate that the stakeholders find climate change to be a relevant issue for management to address and that understanding it better would help prepare the salmon and their fishery for the future. As such, the synthesized problem frame could provide a starting point for a larger-scale problem-solving effort and sets the precedent that it can and should be done via a transdisciplinary process.

*5.1.4 **Chapters I, II, & III** Each Facilitate Different Aspects of ITDR Communication*

Although the previous three sections of this thesis were dedicated to describing and discussing each thesis chapter's contributions in detail, this section observes the thesis's contributions as a whole on a more abstract level.

Broadly speaking, **chapters I** and **II** contribute to ITDR by enabling participation. Participation, as discussed in section 2.6, is the primary tenet of ITDR, due to its ability to both (1) improve the credibility of science and the legitimacy of decisions made based on its advice and (2) to create the type of holistic, credible knowledge needed to solve wicked problems. Typically, to develop credibility and holistic knowledge, participation in ITDR projects within sustainability science is broad in scope, meaning that such projects aim to include diverse participants, whether they come from inside or outside of academia (Klein, 2015). However, ITDR projects that are broad in scope, which means all transdisciplinary studies and many interdisciplinary studies as well, are prone to communication difficulties due to the conceptual distance, i.e., perspective differences between the participants (Huutoniemi et al., 2010). Put another way, communication within ITDR is problematic because it requires participants to cross epistemic and often, professional boundaries as well (Hall and O'Rourke, 2014). Hence, communication is recognized as one of ITDR's most significant challenges (Hall and O'Rourke, 2014).

Nevertheless, broad participation and, therefore, effective communication between diverse participants is vital to ITDR projects' success, as failure to co-construct knowledge can result in sub-par responses to sustainability challenges (Hall and O'Rourke, 2014). Indeed, not only for Baltic salmon management but for Baltic Sea governance as a whole, increasing the participation of diverse stakeholders and improving the communication that enables participation is a critical for addressing the sustainability challenges therein (Gilek et al., 2016; Gilek and Karlsson, 2016). For this reason, the studies reported in **chapters I and II** provide tools to facilitate stakeholder communication in the context of ITDR. However, the two chapters do this in different ways.

Chapter I tackles a communication challenge participants frequently face, particularly at the beginning of ITDR projects: recognizing and articulating perspective differences among the team members (Hall and O'Rourke, 2014). Hall and O'Rourke (2014) suggest the solution to this problem are tools to assist participants in externalizing their values, assumptions, and knowledge. **Chapter I** presents one such tool, specifically a paired strategy of topic modeling and interview analysis. Few other strategies to address this communication issue exist. However, the "Toolbox" dialogue approach (Eigenbrode et al., 2007; O'Rourke and Crowley, 2013) aims to promote "collective communication competence" (Klein, 2015; Thompson, 2009) by facilitating in-depth dialogue between participants to help them recognize and articulate their perspectives and those of others within the group. The technique is likely to support cognitive integration in much the same way the strategy used in **chapter I** aims to. However, the strategy used in **chapter I** allows participants to express their perspectives individually, hence avoiding the potential influence of normative pressures within the group (Heeren Alexander et al., 2016) or over-emphasizing the views of the most influential or verbose participants (Burgman, 2005; Martin et al., 2012). Perhaps, the strategy presented in **chapter I** could serve as a precursor for the Toolbox dialogue strategy, allowing the participants to engage with and consider their perspectives first before doing so with the full group. Further, the results presented in **chapter I** could be used as a starting point to begin the Toolbox dialogue and ensure that the full group addresses all relevant issues. As the participants of an ITDR project become more cognitively integrated, they should be better able to integrate their heterogeneous knowledge and know-how (Huutoniemi et al., 2010), transcending their limited individual worldviews to develop a more holistic view of the sustainability problem at hand (Klein, 2015).

The REA strategy presented in **chapter II**, on the other hand, addresses two different communication challenges. First, the framework in which the REA is embedded encourages the researcher to engage with participants in a "principles and process" discussion, during which the researcher and participants decide on how the research process will proceed and what the rules of engagement within that process will be. Such discussions equalize power between the researcher and participants (Renn, 2006; Welp et al., 2006), which helps to develop a critical sense of psychological safety (Haapasaari et al., 2012a; Van den Bossche et al., 2006; Wooten and Reed, 2000), which is necessary to allow communication to proceed smoothly throughout the ITDR process (Hall and O'Rourke, 2014).

Second, the REA allows participants to systematically communicate both knowledge and values through targeted questionnaires and mental model elicitation. The mental model elicitation portion of the REA, in particular, facilitated communication of knowledge about a complex issue, in this case, the effects of climate change on the salmon system, from the participating stakeholder to the researcher/facilitator during direct elicitation. By pairing this direct elicitation with indirect elicitation, the researcher clarified the stakeholder's message and then checked with the stakeholder to ensure they had accurately received the message and understood the stakeholder.

The synthesized frame of the Baltic salmon-climate change problem reported in **chapter III** (**chapter III**, figure 7) is the product of communication between stakeholders and researchers. Specifically, the stakeholders communicated their knowledge about the issue facilitated by the REA and questionnaire. Although **chapter III** does not present a method to facilitate communication in ITDR, this synthesized frame can aid in communication as well. Specifically, it could be used to communicate a complex issue in an integrated and summarized way to those external to this ITDR process, such as other scientists or policymakers relevant to the fisheries management process. In this way, the synthesized frame can be used to communicate the results of an ITDR project with members of the wider problem-solving and decision-making effort. Further, the synthesized frame acts as a boundary object for communication within these diverse problem-solving groups. Boundary objects allow team members to understand a concept or situation, their connection to the concept or situation in relation to others, without requiring consensus (Star, 2010; Star and Griesemer, 1989). As such, boundary objects are said to allow coordination and collaborative work toward a common goal between diverse actors without requiring them to conform to the same worldview (Star, 2010; Star and Griesemer, 1989). Other ITDR research projects could adopt a similar approach to create their own integrated and summarized boundary object of the problem in question.

5.2 Limitations of the Study & Future Directions

This thesis represents one small step in the development of ITDR and toward addressing the salmon-climate change problem. There is still plenty of work to be done. Naturally, the gradual development of collaborative problem-solving approaches will require the efforts of multitudes of researchers and practitioners, each learning the increasing importance of engaging with diverse perspectives to provide the holistic, credible knowledge society requires to solve our wicked socio-environmental problems. Here, however, I focus on the limitations of the work described in this thesis and future study areas to improve and expand upon it.

5.2.1 The Next Steps in the Creation of a Strategy to Facilitate Communication

When developing strategies and methodologies for use in ITDR within sustainability science, it is essential to remember that all must strive to produce or enable the production of the credible, holistic knowledge required for socio-environmental problem solving (see sections 2.5.1 – 2.5.4). With this in mind, I begin by discussing the strategy for enhancing communication between the participants of ITDR projects proposed in **chapter I.**

The notion proposed in **chapter I** that identifying, describing, and discussing perspective differences within diverse teams may help facilitate cognitive integration should be tested experimentally. Further, the process devised to do this, namely, via analyzing individual interviews and structural topic models, could be compared with other strategies to elicit perspectives, like mental model elicitation or targeted team discussions alone, to determine the best facilitation method. Because cognitive integration can occur within diverse teams without facilitation over time, under the right conditions (Cronin and Weingart, 2019; Haapasaari et al., 2012a), a particularly useful facilitation methodology would produce evidence of cognitive integration more rapidly than a control group and would help teams struggling to make steps toward cognitive integration to recover.

I believe rapidity is crucial because I assume elucidating participant perspectives quickly at the beginning of a project would help ensure cognitive integration proceeds as quickly as possible, thus promoting better communication sooner[14]. Better communication earlier in an ITDR project could equate to more efficient and effective knowledge production, particularly in the context of tight project deadlines or urgent socio-environmental problem circumstances. Failure to begin the process of cognitive integration early could also lead to miscommunications, followed by a retreat into like-minded silos, thus undermining the ITDR imperative to integrate diverse perspectives (Huutoniemi et al., 2010).

Rapidity would also be beneficial because it could allow more perspectives to be analyzed in less time. Participation in ITDR is often limited by the practical difficulties of involving a large number of

[14] Naturally, as this is an assumption currently, this, too, should be tested empirically.

participants (Linke and Jentoft, 2016), like a lack of time or resources to accommodate them. This conundrum can lead to the exclusion of legitimate stakeholders or precipitate debate about stakeholder legitimacy as potential participants jockey for a limited number of seats (Linke and Jentoft, 2016). This issue has been documented in the context of EU level fisheries management. For example, Linke and Jentoft (2016) report a case where two antagonistic Lithuanian fishery associations became engaged in a conflict over the legitimacy of one another's claims to the single available seat within the Baltic Sea Advisory Council (BSAC) to represent Lithuanian fishers. As such, a rapid tool to analyze perspectives could have paved the way for cognitive integration among larger groups of participants, thus relieving one barrier to working with all legitimate resource stakeholders.

A driving factor behind my choice to use topic modeling in the study reported in **chapter I** was precisely its ability to analyze text data rapidly, which I had suspected could allow more perspectives to be analyzed in less time. However, the results reported in **chapter I** indicate that *when paired*, topic modeling and interview analysis can elicit a nuanced view of the different perspectives about a key topic within an ITDR group. This strategy is most effective when the two methods are paired because the topic modeling portion of the study captured different aspects of the stakeholders' perspectives than the interview analysis portion did. Specifically, the topic modeling portion captured the participants' interests or competencies, whereas the interview analysis portion captured their perspectives about the meaning of risk and opinions about risk analysis in depth. Although both methods captured the differences of opinion about when and whether to conduct quantitative risk analysis, it was much more apparent in the interview analysis results.

Unfortunately, although it is effective, interviewing and the subsequent analysis is a lengthy process, particularly when resources (the time of interviewers and analysts) are limited. As such, the level of nuance that the paired strategy provides comes at the price of speed. As such, if a rapid approach is required, this method should be developed further. Perhaps the interview analysis portion could be replaced with something equally as thorough, yet less time-consuming. Alternatively, more additional help with the interview and analysis process could be secured to help move the process along more quickly.

An additional potential issue for the topic modeling portion of the strategy described in **chapter I** is that it requires text data as an input. Using journal articles that the participants believed reflected their perspective of risk was appropriate and relatively easy to obtain from the interdisciplinary scientific team studied. However, obtaining journal articles from non-scientific actors may prove more difficult. As such, an alternative text resource describing perspectives about a pertinent topic may be necessary, depending on the participants of an ITDR effort. Perhaps written questionnaire responses, interview transcripts, tweets, popularize online articles, or etcetera could be used instead.

5.2.2 Improving Mental Model Elicitation Methodologies

Hopefully, future users of the REA can learn from the experiences with its implementation reported in **chapters II and III** to ensure their results are even more rigorous. I recognize that the biases, beliefs, heuristics, and values (BBHVs) of both the participants and modelers affect every participatory modeling process and their results (Glynn et al., 2017; Hämäläinen, 2015). However, these should be limited as much as possible to avoid damaging the credibility of the work (Glynn et al., 2017). For this reason, I included the imperative to consider these issues within the REA framework (**chapter II**, figure 1).

Nevertheless, during the implementation of the REA described in **chapter II**, the facilitator noticed a few potential points where bias may have been introduced into the elicitation process. For example, she noticed that describing her background in fisheries science to the stakeholders affected the way they described their mental models because they made assumptions about the common understanding of fisheries they shared. Additionally, some of the teaching materials used to assist the stakeholders in building their influence diagrams may have biased the variables they included in their influence diagrams. Considering this experience, future users of the REA should familiarize themselves with the BBHV literature and evaluate how BBHVs could affect their study ahead of time, and design their research protocol accordingly. For example, facilitators should provide teaching materials that are neutral and completely unrelated to the study subject. However, even when one is cognizant of one's influence on an ITDR project and goes to considerable effort to limit it, not easy to control entirely. As such, it is essential to transparently report how the researcher's BBHVs may have affected the results of the study, as I have done here and in **chapter II**.

However, the most concerning issue with implementing the REA was the low response rate received when the stakeholders were sent the "enhanced" versions of their influence diagrams following indirect elicitation. Only one out of 11 stakeholders completed the task of reviewing their diagram, adding any missing components, and approving the final product. These enhanced versions were sent to the stakeholders with the hope that they would thoroughly check the changes the analyst had made to ensure she had represented their beliefs accurately and had not injected her own beliefs or biases into their influence diagrams. Although the elicitation session transcripts were carefully coded to leave a trail of justification for the modifications made, it is still possible that the analyst may have interpreted something a stakeholder said wrongly. Put another way, asking the stakeholders to check the analyst's work was an attempt to safeguard the authenticity of the stakeholders' knowledge and the credibility of the study's results. The decision to communicate with the stakeholders remotely via email may have been partially to blame for this poor result (Kuhnert et al., 2010; Nevalainen et al., 2018), in conjunction with the long time delay between communications, and perhaps my failure to make the importance and purpose of this phase of the elicitation process and the study itself apparent to the stakeholders (Bracken et al., 2015).

To avoid low post-indirect elicitation response rates in the future, I suggest that the stakeholders should be engaged in planning the study and defining a protocol for engagement (Voinov et al., 2016) before mental model elicitation. During this planning phase, the facilitator should clearly explain the importance of the study, the steps required to conduct the full elicitation process, and the importance of each step. Then, the facilitators and stakeholders could decide on their expectations for one another elicitation process's outcome, an appropriate timetable, and mode of communication. Doing this may help increase the stakeholders' investment in the study and sense of ownership over it, keeping them engaged in the study throughout the REA and potentially improving the REA process's normative and instrumental value as well. Additionally, **chapter II** suggests implementing a second questionnaire following the completed REA to give stakeholders another opportunity to voice their opinions about the process and what should be changed for subsequent implementations. My co-authors and I added these recommendations to the REA protocol based on our experience implementing it (italics in **chapter II**, figure 1).

When implemented with this advice in mind, the REA is well suited for providing holistic, thorough depictions of mental models. However, although the REA rectifies *unintentional* model simplification, it does not address *intentional* simplification. The majority of studies that rely on depictions of mental models representing complex systems include depictions that contain relatively few variables. This appears to be true even for those studies, which use indirect elicitation, which should allow the facilitators the time and freedom to represent stakeholders' thoughts in detail. If we assume these studies are consulting stakeholders who know the system in question well (Kinchin et al., 2000; Nersessian, 2002), such simplified models should not be the standard unless intentional simplification and, therefore, information loss, is widespread among studies using mental model elicitation.

This purposeful simplification could result from analytical, time, resource, or technological constraints (Kuparinen et al., 2012). However, they could also be driven by the researcher's belief that simpler models are better models. If this is the case, a paradigm shift is necessary because, when using ITDR to address wicked socio-environmental problems, the more thorough and complete the understanding of a problem is, the better. After all, a more complete knowledge base allows more solutions to be discovered and considered (Özesmi and Özesmi, 2004). As such, representations of mental models should begin as comprehensive as possible and then be condensed and simplified later as necessary to accommodate, for example, the limitations of computing power.

One final consideration for the development of the REA is the need for a follow up study in which we discuss the method with stakeholders and take their opinions and ideas for its improvement into account. As stated in the results section of this thesis synthesis (section 4.1.2), not all of the stakeholders involved in the **chapter II/III** study were convinced of the REA's normative or instrumental value. To improve this, we added additional steps (italics **chapter II**, figure 1), like involving stakeholders more in the planning of the ITDR project and agreeing upon rules of conduct within it, which could equalize power dynamics between researchers and participants and lend more credibility to the results of the process. However, it is important to follow up with the stakeholders to ensure that those additions were enough to improve the normative and instrumental value of the process in their eyes.

5.2.3 Moving Ahead with Baltic Salmon Management in the Face of Climate Change.

Lastly, addressing the effects of climate change on Baltic salmon and their fishery should not end with this thesis. A multistep and likely iterative transdisciplinary process would be required to understand and address this problem comprehensively. Unfortunately, completing this process would have required a longer timeframe and more effort and commitment from a wider array of actors than was feasible to accomplish during my Ph.D. work. Nevertheless, I hope the problem framing study conducted in **chapter III** can help justify investigating this matter more closely, build a crucial knowledge base about how the salmon system works, and emphasize both the utility and the importance of using a transdisciplinary approach for Baltic salmon management.

On a small scale, the logical next step following the problem framing study presented in **chapter III** would be to host a workshop to share the results of the problem-framing study with the stakeholders who participated as a group. During such a workshop, the stakeholders could comment on the synthesized frame and any modifications they deemed necessary could be made, which would be a natural extension of the efforts that have already been made to ensure the stakeholders' knowledge is presented accurately and thoroughly. Further, it is an invitation for the stakeholders to take ownership of the project and its results as partners in the research process, a crucial aspect of ITDR (Durham et al., 2014). Such a meeting could also encourage co-learning and cognitive integration between the participants.

Although this would provide a natural conclusion for *this* problem framing, problem framing, and ITDR in general, are typically iterative processes (Hirsch Hadorn et al., 2008b). Therefore, the problem framing process may need to be repeated before a mutually acceptable frame is found to form the basis of a management effort to address the effects of climate change on salmon. This will be particularly true if the climate change issue is taken up by fisheries management at, for example, the national or EU level. If this were to happen, a second problem framing would indeed be necessary because both robust problem framing in general (Hirsch Hadorn et al., 2008b) and effective fisheries management (De Young et al., 2008), particularly for species as controversial as Baltic salmon (Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014) must include all relevant stakeholder groups. Unfortunately, the problem framing described in **chapter III** did not meet this goal, due to the researchers' limited access to all of the stakeholder groups. Commercial fishers, for example, were not represented in the study. This is particularly problematic because this is a powerful and invested group in Baltic salmon management (Haapasaari et al., 2007; Linke and Jentoft, 2016). As such, a broader effort to engage more relevant stakeholder groups must be made for subsequent problem framing iterations.

To accommodate a larger number of stakeholders in a subsequent round of problem framing, it would be wise to collect stakeholder's mental models as fuzzy cognitive maps[15] rather than the influence diagrams described in **chapters II and III**. While fuzzy cognitive maps are quite similar to the influence diagrams used for this thesis, rather than documenting qualitative effect strengths (i.e., high, medium, low), they instead typically document the strength and type of correlation between variables quantitatively as real numbers between -1 and 1 (Gray et al., 2015; Özesmi and Özesmi, 2004). This transition is recommended because individual fuzzy cognitive maps are easily aggregated (Aminpour et al., 2020; Gray et al., 2014; Özesmi and Özesmi, 2004), and large, complex representations of mental models, like those produced with the REA, can be condensed into themes when recorded as FCMs (Olazabal et al., 2018). These advantages would likely make FCM a more efficient method for

[15] Fuzzy cognitive maps also rely on mental model elicitation. Therefore, the REA could still be applied.

problem framing, particularly with more stakeholders.

Follow up work should also be done to determine the relative importance of the different environments (river, sea, etcetera) and salmon life stages (eggs, spawners) the stakeholders included in their influence diagrams. The results **chapter III** provides, like, for example, that the stakeholders described the riverine system the most, could be interpreted to mean that this environment may be the most vulnerable or essential in the context of climate change. However, on the other hand, it could reflect the stakeholders' more extensive and detailed knowledge of this portion of the system, because richer mental models, or segments of mental models, typically reflect higher levels of knowledge and understanding (Nersessian, 2002). Answering these questions about whether or not the prevalence of specific environments and life stages indicate their vulnerability are crucial to answer because this information could be used to target management efforts and prioritize resources.

Lastly, the outputs of ICES' stocks assessment models form the basis of their advice to the EU (Kuikka et al., 2014) and consequently play a leading role in producing informed fisheries management decisions. Therefore, because climate change will likely affect Baltic salmon, according to the results of **chapter III** and other studies (ICES, 2017b; Jonsson and Jonsson, 2009; Lassalle and Rochard, 2009), I encourage ICES to integrate the effect of climate change into their stock assessment model for Baltic salmon (Michielsens et al., 2008) as soon as possible to ensure their stock projections remain accurate and realistic.

The problem framing results reported in **chapter III** could provide a useful starting point for this process by prioritizing concepts to be incorporated into the model. Further, the individual stakeholders' influence diagrams could offer alternative hypotheses about the causal dynamics between salmon and climate change. To make the results of **chapter III** more directly applicable to ICES' model, a follow-up study could be done, during which stakeholders would build directed acyclic diagrams (DAGs) to relate the variables and themes developed during problem framing to existing concepts within the ICES model by a process similar to the one described in Haapasaari et al. (2013). This process would be in many ways similar to the influence diagram building process described in **chapters II and III**, however, rather than qualitatively describing effect strengths, causal relationships would be quantified as joint probability distributions, identifying either a positive or negative correlation between two variables (Jensen and Nielsen, 2007). Then, these parameterized DAGs could be integrated into the ICES model via Bayesian model averaging (Mäntyniemi et al., 2013). A similar approach should also be possible if FCMs were collected for a subsequent, larger-scale problem framing effort.

*5.2.4 Using the Insights from **Chapters I, II, & III** Together*

As described in the proceeding section, the insights from the problem framing study reported in **chapter III** provide a starting point to address the problem climate change could pose for the Baltic salmon system. If this issue were to gain traction at a broader management or governance scale, particularly at the EU level, the insights gained from the research reported in **chapters I and II** could be applied there as well, although they are related to the development of ITDR more generally.

As discussed in section 2.8.1 in particular, the EU's science-based fishery governance system, the CFP, suffers from the credibility and holistic knowledge deficits discussed in section 2.5.1-2.5.4. The governance of Baltic salmon, in particular, has presented a clear example of this debacle. It has a history of controversy (Ignatius et al., 2019; Ignatius and Haapasaari, 2018), plagued by conflicting stakeholder interests (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014), which has led stakeholders to feel that their values, beliefs, and role in the salmon management process have been marginalized (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014). The current system has also failed to recognize the complex socio-environmental context surrounding these fish (Linke and Jentoft, 2014). Together, these issues have led to a stalemate in Baltic salmon governance, evidenced by the failure to adopt a new multi-annual management plan, to succeed the Salmon Action Plan, which ended in 2010. Further, this situation may worsen if climate change affects the Baltic salmon fishery or if action is taken preemptively to prepare for the reality of climate change. In this challenging context, increased meaningful participation in the form of ITDR and robust strategies to facilitate communication therein could offer a solution for addressing the salmon-climate change issue and other salmon management concerns as well.

Inclusive rounds of participatory problem framing could be facilitated by the REA process, which may help stakeholders communicate their knowledge and beliefs about this fisheries management issues more clearly and in the context of more equal power dynamics. As in **chapter III**, these subsequent problem framings could be used to develop a more complete integrated and summarized frame of fisheries management issues and used as a boundary object to facilitate and encourage further discussion. Further, understanding the importance of cognitive integration and implementing a strategy for elucidating perspectives about key topics similar to the approach described in **chapter I** would be useful for improving communication and reducing conflict at several stages of the salmon management process. For example, if we consider Baltic salmon management at the EU level alone, the process described in **chapter I** to elicit stakeholder perspectives could be used to facilitate communication (1) within ICES; (2) between ICES and the European Commission; (3) within the Baltic Sea Advisory Council (BSAC), an assemblage of stakeholders including, for example, between environmental non-government organizations, recreational fishers, and commercial fishers, which advise the European Commission; and (4) between the BSAC and the European Commission.

6 CONCLUDING REMARKS

The wicked socio-ecological problems Earth faces today, including the management of Baltic salmon under conditions of climate change, make ITDR more critical now than ever because these approaches have the potential to create the credible, holistic knowledge needed to address such challenges. However, ITDR is still relatively new to the mainstream academic world, and must, therefore, be developed, expanded, and refined to ensure they deliver the socially accountable, scientifically robust solutions society and the environment require. This thesis is a single step in the evolution of these approaches, making a small contribution to the growing body of ITDR literature, particularly regarding communication facilitation within ITDR. Specifically, I hope this thesis will contribute to this collective effort by:

1. Providing insights for developing a concrete tool for facilitating cognitive integration and communication between the members of diverse ITDR teams.

2. Ensuring mental models are depicted holistically and accurately.

3. Beginning what I am optimistic will become a genuinely collaborative fisheries management effort to address the challenge climate change poses for Baltic salmon.

With these contributions, we come a bit closer to harnessing the power of our perspectives for the benefit of people and the planet.

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CHAPTER I

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BRIDGING PERSPECTIVES: RISK COMMUNICATION WITHIN INTERDISCIPLINARY TEAMS

Manuscript

BRIDGING PERSPECTIVES: RISK COMMUNICATION WITHIN INTERDISCIPLINARY TEAMS

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ABSTRACT

Perspectives, built on personal knowledge and experience, influence the way we see the world and interpret information. Successful collaborations between those with different perspectives are powerful, often generating innovative ideas. However, perspective diversity can also make communication difficult, which may delay progress and reduce the quality of results. Using structural topic modeling and interview analysis, we demonstrate diverse perspectives in the context of an operational interdisciplinary team working with complex socio-environmental problems. Specifically, we focus on their perspectives about "risk," a core concept within their team and central theme in management and decision-making problems. Their perspectives included different conceptualizations of risk and various risk-related interests. However, quantitative risk analysis was the greatest source of perspective diversity within the team. We argue that transparently investigating and addressing perspective differences, as we have done here, allows interdisciplinary teams to begin bridging the gaps between them, improving their internal communication while preserving their unique viewpoints. This way, teams can use their perspective diversity to its greatest potential to collaboratively address today's most pressing socio-environmental problems.

KEYWORDS: Risk Management, Cognitive Integration, Wicked Problems, Interdisciplinary Communication, Linguistic Uncertainty

1 INTRODUCTION

Communication lies at the heart of every risk assessment process (Fischhoff, 1995; Heath & O'Hair, 2010; ISO, 2018; Lundgren & McMakin, 2013; Slovic, 1993; Steelman & McCaffrey, 2013; Wachinger et al., 2013). This is evidenced by the disparity between the impacts of risk communication successes and failures. Successes lead to triumphs. For example, the implementation of new technologies or the protection of critical assets, like the ozone layer (Oberthür, 2001). Failures, on the other hand, may result in tragedy. Consider the Challenger disaster in 1986 (Winsor, 1988), the eruption of the belief that vaccines cause autism in children (Burgess et al., 2006), or the botched advice about infant sleeping positions that led to thousands of deaths in Europe, the United States, and Australia (Gilbert et al., 2005).

When successful, risk communication facilitates the exchange of knowledge between stakeholders, ensuring awareness and a thorough understanding of a given risk, while 1) combining relevant expertise for risk management, 2) considering alternative points of view, 3) assisting in decision-making, and 4) empowering those affected by the risk (ISO, 2018). To ensure we achieve these objectives, risk communication research has developed insights and advice to aid us, emphasizing communication between groups, for example, between the scientific community and other stakeholders (i.e. decision-makers, corporations, the public, etc.) (Geden, 2015; Pidgeon & Fischhoff, 2011; Simis et al., 2016; Spiegelhalter David J. & Riesch Hauke, 2011) Despite this comprehensive body of work, investigations into risk communication issues *within* groups are rare. Here we examine this knowledge gap.

The rapidly developing wicked socio-environmental crises, like climate change, resource consumption, and disease (Barnosky et al., 2014, 2016; Pecl et al., 2017; Watts et al., 2018), we currently face make this an urgent issue. These crises are themselves amalgamations of complex risks (Head, 2008; Rittel & Webber, 1973). Ensuring successful communication is an essential element in solving and coping with them (Weber & Khademian, 2008). By definition, wicked problems are those, where 1) issues are complex, resulting from multiple simultaneous disruptions

(Barnosky et al., 2014, 2016; Liu et al., 2003); 2) decision options are tightly coupled, and 3) must be made rapidly despite high levels of uncertainty (Cosgrave, 1996; Sinn, 2008; Steffen, 2011) . We argue that improving communication and subsequent decision-making within this challenging context must begin with effective, coherent communication within teams about risk.

Nowadays, these teams are frequently interdisciplinary, as risk management in the context of wicked problems, requires a truly multifaceted approach (Fischhoff, 1995; Holsman et al., 2017; Trucco et al., 2008). These problems and their potential solutions are social-ecological-technological by nature, requiring a diverse cast of characters with different knowledge bases, to understand and solve them. By design, diverse, interdisciplinary teams like these, embody an array of skills, expertise, experience, and therefore, heterogeneous perspectives (Catney & Lerner, 2009; Haapasaari et al., 2012), including risk perspectives. Risk perspective is one's personal conceptualization of risk, which affects the way information is interpreted (Veland & Aven, 2013). Differences in interpretation may lead to miscommunication and misunderstandings, reducing communication success (Winsor, 1988). No matter the key concept in question, risk or otherwise, it is essential to acknowledge and understand the differences in perspectives, i.e. perceptual gaps (Cronin & Weingart, 2019), surrounding it. By doing so, teams can improve their internal communication and their odds of producing innovative ideas while avoiding unproductive conflict or retreat into like-minded silos. To these ends, we address the following questions: 1) Do different risk perspectives exist within interdisciplinary teams? And 2) what are those perspectives? Then, we discuss how these perspectives might be leveraged for the benefit of scientific work while minimizing communication breakdown.

2 METHODS

We investigated these questions in the context of a case study, using (PROJECT NAME)[i], our own research consortium, as the study group. Broadly speaking, this group is comprised of social scientists, natural scientists, futurists, and humanities scholars (humanists). Together, we aim to develop tools to improve societal resilience to wicked social-environmental disruptions in the (NATION) context. The names of the team members who participated in this study and the transcripts of their interviews have been kept confidential. As such, we refer to each participant by a pseudonym reflecting his or her discipline and a randomly assigned number (SI Appendix, Table S1).

We identified and characterized the participants' risk perspectives via a two-pronged approach (parts A and B):

2.1 Part A

First, 19 participants, including the members of this authorship team, provided between one and five texts (SI Appendix, Table S1) they felt had influenced their understanding of risk. We requested these texts because we thought they might reveal the basis on which each participant formed their risk perspectives and differences and commonalities between them. In total, this corpus (i.e. observed set of documents) included 53 English language texts, including journal articles, books, book chapters, reports, a blog text, and a PowerPoint presentation (SI Appendix, Table S1). Then, we used structural topic modeling (STM) (Roberts et al., 2016, 2018) to help discern the main themes within the corpus.

Mixed membership topic models are algorithms for detecting themes within large bodies of text (Blei, 2012; Roberts et al., 2016). In brief, the user specifies the number of topics (*k*) the algorithm should find, and it, using the statistical likelihood of word co-occurrence, computes two primary metrics (Roberts et al., 2018). First, it calculates probability distributions indicating the likelihood that each word in the corpus belongs to a given word distribution (Blei, 2012). These word distributions are called topics because words with a high probability of occurrence within a topic typically concern the same theme or area. For example, if a topic model was run on all the articles from all issues of a pet magazine from the last 10 years, one topic may include words like "meow," "purr," "mouse," "yarn," and "litter," which an analyst could interpret as a topic about cats. Second, the algorithm also calculates the prevalence of each topic within a document (Blei, 2012). Mixed membership models allow individual documents to contain more than one topic (Blei, 2012; Roberts et al., 2016). For example, the topic model could indicate that a single article contains the topic about cats, but also another referring to dogs, and another to gerbils. For this study, we used structural topic modeling, which conducts the same process as described above, but also allows the inclusion of document-level metadata (Roberts et al., 2016, 2018). For example, the name of the participant who submitted the document. Including this metadata allows the user to make comparisons between metadata categories, for example, comparisons between the topics discussed in the documents submitted by the study participants. We used R's "stm" package for performing the structural topic modelling (Roberts et al., 2016, 2018) and network packages igraph (Csardi & Nepusz, 2006) and ggraph (Pedersen, 2018) for presentation.

To prepare the contributed documents for topic modeling, we converted each text into .txt file format. For those documents not easily converted directly into .txt form, we scanned the documents using automatic optical character recognition software from Adobe and corrected any mistakes made by the software by hand. Afterward, we used the stm package's textProcessor function to preprocess the corpus in R. Preprocessing ensured that all words were converted to lowercase, and all stop words, punctuation, and numbers were removed. Stop words are very common words like "and," "but," and "so." We also chose to remove a custom list of stop words from the corpus, including words like "table" and "figure," which we agreed dealt with the structure of scientific presentation and did not add value to our analysis. Our full custom stop word list is available in SI Appendix section 1.1.

We chose not to stem or lemmatize the words, as these treatments have been found to worsen topic model quality (for English language corpora) (Schofield & Mimno, 2016). Words were required to be greater than three letters long to remain in the corpus (wordLengths function). Within stm's prepDocuments function we also used lower.thresh and upper.thresh to specify that words must be included in between two and 52 texts to remain in the corpus. The model was run with spectral initialization, recommended by Roberts et al. (2018) for the standard 500 iterations. A graph of model convergence is included in this SI Appendix (SI Appendix, Fig. S2). The model seed was set at a randomly chosen large prime number.

As mentioned above, in topic modeling, the number of topics, *k,* is chosen by the researcher. There are statistical methods for choosing the optimal number of topics, but the semantic validity or interpretability of the model is important as well

(Grimmer & Stewart, 2013). To determine *k,* we first used stm's searchK function to compare the held-out likelihood, residuals, semantic coherence, and lower bounds for between two and 50 topics (SI Appendix, Fig. S3) (Roberts et al., 2018). Using this information, we narrowed our selection of *k* values to between two and 25 topics. Then we compared the exclusivity of words to a topic and semantic coherence for models with *k* values of between two and 25 (SI Appendix, Fig. S4). Semantic coherence is a good proxy for human judgment of topic quality (Mimno et al., 2011), with higher semantic coherence being equal to higher topic quality. High exclusivity of words to a given topic ensures topics are unique. As such, choosing an appropriate *k*-value is a trade-off between semantic coherence and exclusivity, making *k* values closest to the upper right-hand corner of SI Appendix, Fig.4 the most appropriate choices. Next, we considered word clouds, common terms, and exclusive terms for each topic, for a few *k* values determined as suitable based on SI Appendix, Fig.4. As a team, we decided *k* = 8 (eight topics) produced the most sensible and explainable results.

Note that while topic models create topics from a given corpus, analysts must determine what those topics mean. Therefore, at least one member of this authorship team read each text and produced a summary of it. We shared these summaries amongst the group to familiarize ourselves with the corpus to ensure the best possible interpretation of the topics produced by the STM. After running the topic model with *k* = 8, we analyzed each topic again by assessing word clouds, common (SI Appendix, Fig. 2) and exclusive words (SI Appendix, Table 3) within each topic, examining the top 3 texts containing the greatest proportions of each topic (Table 1), and consulting the summaries of those texts. The code used to produce the STM and graphics is available at: (WEB ADDRESS) .

2.2 Part B

In addition to the topic modeling work, between February and May 2018 we conducted semi-structured, individual interviews with 16 team members, including all subproject leaders, except one, who is one of the authors of this manuscript (NAME). We also interviewed one natural scientist from a related project[ii] to provide a stronger representation of the views of natural scientists about risk, as the majority of (PROJECT)'s members representing the natural sciences are coauthors of this paper and therefore, did not participate in this portion of the study. Each interview lasted approximately two hours and was comprised of several key questions (SI Appendix, Section 1.2) meant to direct the conversation and ensure the areas of interest we had identified were discussed. However, the interviews were flexible, allowing the interviewer(s) and participants to elaborate on their thoughts or pursue relevant ideas (Gill et al., 2008). This semi-structured approach was adopted to ensure we gathered the most relevant material for our analysis, including issues we had not considered while developing the interview questions and protocol (Gill et al., 2008). A pair of interviewers conducted the majority of interviews, although on some occasions only one interviewer could be present. Audio was recorded for each interview.

For this study, we focus on our analysis of the participants' responses to two primary interview questions (SI Appendix, S1.2). The answers to the first question, "What is risk? What does it mean to you?" helped elucidate the participants' fundamental understanding of risk as a concept. Different perspectives about what this concept represents have the potential to create unique perspectives for problem solving within the group on the one hand, but could also spark confusion and frustration among them on the other. Therefore, we aimed to make these underlying dichotomies explicit to the team, allowing them to address any issues they may cause.

The second question is comprised of a suite of questions about risk analysis (ISO, 2018): 1) How can risks you identified be estimated (by you or others)? 2) Which risks do you believe you (or others) could estimate? 3) How would you (or others) proceed with analyzing the risks? and 4) Would you (or others) quantify risks? If so, then how? We chose to analyze the risk analysis questions and report them here because the greatest differences in risk perspective revolved around these questions during the interviews. We analyzed them together as a unit because the ideas they sought to elicit were overlapping and our participants' answers to one question tended to bleed into the others, often resulting in broad contemplation of risk analysis rather than distinct, concise answers to each question. We asked these questions after participants drew influence diagrams representing their mental models (Jones et al., 2011) about the risks related to a winter storm emergency scenario (SI Appendix, S1.2). This short scenario was developed after consulting the Finnish “National Risk Assessment 2015” (Vainio et al., 2016) and was chosen because such events would have been relatable to all our study’s participants. We included the scenario and influence diagramming activity in the interviews to make discussing the questions above more intuitive and to provide a concrete and comparable problem to address.

Then, following a theory-directed content analysis approach (Hsieh & Shannon, 2005), the two primary questions described above were coded into themes that emerged during the interviews. Initially, we coded every statement made by the interviewees about the selected questions into the following themes: (1) Risk definition, (2) Methods for Risk Estimation, (3) Risk can(not) be estimated/quantified, (4) Risks that are (not) estimable & justifications, (5) How risk should be analyzed, (6) The participant would (not) quantify risk and why, and (7) Other considerations. Statements that did not pertain to any of these categories were removed from the study. Although these categories are very similar to the initial questions, we performed this step because the interviewees’ responses to the risk analysis questions tended to bleed into one another, interviewees often returned to previous questions, and due to linguistic ambiguity regarding the word “estimate (SI Appendix, Section).” Then, within these broader themes, each statement was labeled according to its basic sentiments and categorized. Each statement could be considered to contain multiple sentiments and be placed in multiple categories.

3 RESULTS

3.1 Diverse Perspectives about the Meaning of Risk

Our interview analysis revealed that for our participants, the term “risk” is a flexible concept, whose meaning was dependent on who was asked, the perspective they took, and the context of the discussion. This was implicitly clear from the diversity of definitions offered and was made explicit by several of the participants themselves. Some participants acknowledged their context-dependent use of different definitions. For example, after first supplying the interviewers with one definition of risk, participant SS7 explained that this definition was not part of his own "analytical mindset (SS7)" and that he does not typically think about risk in this way. On the other hand, other participants switched between definitions freely, without recognition, throughout their interviews.

Generally, the definitions the participants offered were 1) probability-based, impact/ hazard-based, or a combination of the two and 2) either qualitative or quantitative (Fig. 1a).

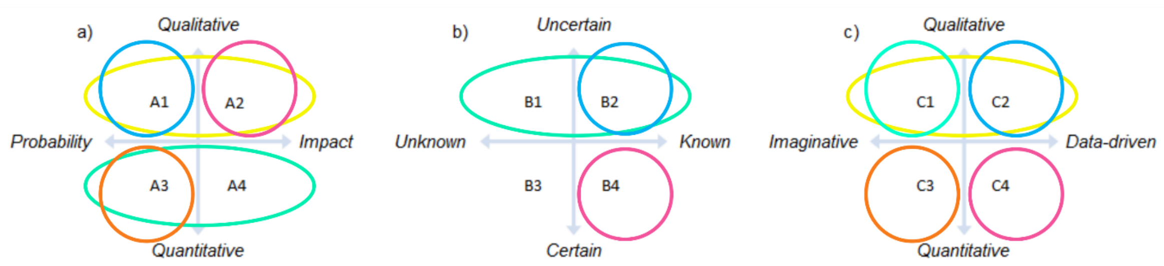

Figure 1. Each 4-field describes a different aspect of risk perspective. Each quadrant represents the intersection of two characteristics of a participant's risk perspective. a) Participants' conceptualization of risk as related to probability or impact and as qualitative or quantitative; b) participants conceptualization of risk as a more certain or uncertain concept about known or unknown phenomena; c) Participants' conceptualization of approaches that should be used to analyze risk, which were primarily imaginative or data-driven and qualitative or quantitative. Colored circles represent different perspectives found within the group.

One class of definitions offered by the participants simply acknowledged the relationship between risk and probability and described this relationship in either qualitative or quantitative terms (Fig. 1a; quadrants A1 and A3, blue and orange, respectively). More commonly, however, participants conceptualized risk as the relationship between probability and an impact or outcome. On the quantitative end of this spectrum was the perspective: risk is equal to probability multiplied by impact (i.e. R = P x I) (Fig. 1a, quadrants A3 and A4, green). Other definitions were qualitative in nature. These were not explicit about multiplying P x I, but retained the sentiment that risk is the interaction between them (Fig. 1a, quadrants A1 and A2, yellow). Risk was also often conceptualized as a typically negative consequence or hazard (Fig. 1a, quadrant A2). For example, some regarded risk as “some degree of harm to something (SS4)” or a negative external force, like an “economic crisis (SS5).” Another more philosophical conceptualization of risk, beyond the scope of Fig. 1, considered risk to be a conceptual tool. For example, risk is a technique for “foreseeing or knowing the unknown (F3)” or a style of reasoning with which “the contingent future is brought to our present” by “shrinking the distance from future present to actual present (SS2).”

Uncertainty and surprise also appeared to be important components of the way the participants conceptualized risk (Fig. 1b). During their interviews, several mentioned uncertainty. However, their understandings of the relationship between risk and uncertainty varied and were, in some cases, in direct opposition. For example, one participant described risk and uncertainty as opposed on a scale, where “hard, quantitative risk, calculable risk” sits at one end and “at the other end are uncertainties and unknowns (SS3).” Hence, this perspective seems to describe risk as a state where one knows what event may occur and can confidently calculate its probability of occurrence (Fig.1b; quadrant B4, pink).

Alternatively, many participants considered uncertainty to be an intrinsic component of risk. These perspectives fell into two groups. Those that fell into the first implied that risk pertains to a known event, which occurs with some inherently uncertain probability (fig. 1b; quadrant B2, blue). On the other hand, those in the second group implied that risks, “can be unforeseen and uncontrollable (SS4).” In this case, risk is a state where the probability that an event may occur is inherently uncertain *and* the events that may occur may be unknown; i.e. black swans (Taleb, 2007) (fig. 1b; quadrants B1-B2, green).

3.2 Diverse Perspectives about Risk Analysis

In addition to reporting the differences between participants’ conceptualizations of risk, we also analyzed their responses to the interview questions regarding risk analysis (ISO, 2018), where opinions were diverse and often polarized. The different perspectives regarding risk analysis within the (PROJECT) group focused on which risks can be estimated, how estimation can or should be done, the reliability of risk estimates, and the moral implications of making them.

3.2.1 Estimable Risks

According to most participants, at least some risks could be estimated (in the context of the winter storm scenario (SI Appendix, S1.2)). The specific risks within the scenario that participants typically indicated were estimable were those they believed society had some form of prior knowledge about, like winter storm events, power outages, or traffic accidents. However, even those who were most enthusiastic about risk estimation acknowledged that some risks are difficult or even impossible to estimate. The participants' responses suggested three interrelated reasons why a risk may not be estimable: 1) lack of information, 2) complexity, and 3) a high level of uncertainty.

We identified lack of information as a barrier to risk estimation because participants frequently suggested that estimable risks are those for which there is plenty of prior knowledge and data, while risks lacking such a knowledge base are more difficult to estimate.

Complexity was seen as the second barrier to estimation because estimating complex risks requires "such a wealth of information to perform" that "the task becomes infeasible (SS6)." Skepticism about estimating complex risks was also exemplified by the comment "I think you could always try to quantify and estimate these risks, but as we can see, there are a lot of interdependencies, so it'll make whatever estimate it is very complex (SS1)." This statement suggests that it may be difficult or impossible to estimate risks involving many interdependencies. Participants did suggest the complexity barrier could be lowered, however, by breaking a large problem or system into smaller more manageable fragments.

Uncertainty was also described as a barrier to risk estimation because the participants tended to less certain about risks they knew less about or believed were more complex. This was exemplified by NS2's contemplation of his mental model of the winter storm scenario. He was concerned that critical goods and services would not be delivered if a winter storm were to occur. Further, he believed calculating the risk of this outcome would be difficult, given the uncertainty he felt due to the lack of empirical data about the delivery of goods and services under such winter storm conditions.

Several participants believed that lack of information, complexity, and uncertainty characterized risks related to the social, cultural, and political aspects of society, in particular, thereby making them the least estimable types of risks.

3.2.2 Methods for Estimating Risk

Of those risks that *were* considered estimable, however, two primary methods for doing so emerged: estimation via 1) prior information (data-driven approach) (Fig. 1c, quadrants C2 and C4, blue and pink) or 2) via scenarios (imaginative approach) (Fig. 1c, quadrants C1 and C3, green and orange). Participants suggested that prior knowledge allows us to make predictions based on what we know has happened in the past and that such information can be incorporated into models or used as “common sense” experiential knowledge to judge risk. The participants acknowledged four sources of applicable prior information: 1) historical or statistical data, 2) expert knowledge, 3) personal knowledge, and 4) systems knowledge. Here, systems knowledge refers to an understanding of how different actors, policies, and circumstances affect and interact with one another in a system. Many of these data-driven approaches were either implicitly or explicitly quantitative in nature (Fig. 1c, quadrant C4, pink), however, a few were described in qualitative terms (Fig. 1c, quadrant C4, blue).

On the other hand, participants conceptualized scenario building as an imaginative exercise to produce narrative accounts of what *could* happen (Fig. 1c, quadrant C1, green). These could be used as tools to understand, for example, “to how people would react (SS2)” if a particular event were to occur. Some participants indicated that scenarios are strategically important for estimating risk, or as implied by their responses, for managing it. One participant suggested narrative accounts of risk like this, are useful for describing global risks on a scale where mathematical estimates become difficult to produce, necessitating narrative description (Fig. 1c., quadrant C1). In such cases, where prior information is likely sparse and complexity and uncertainty are high, some participants seemed to suggest scenario building would prove more useful than producing numerical estimates of risk from quantitative data. In some cases, scenario building was described as an exercise in combining imagination and prior knowledge (Fig. 1c, quadrants C1 and C2, yellow), exemplified by the notion that "sociological imagination (H3)" allows one to use their knowledge about societies, how they function, and how they are affected by crisis to build scenarios and enact them. Therefore, presumably, scenarios enable their builders to envision alternate realities and strategies to reach desirable outcomes under different conditions of risk.

3.2.3 The Reliability and Morality of Risk Estimation

Although many participants suggested that at least some risks could be estimated and provided methodologies for doing so, their opinions about the value and purpose of this practice diverged. These opinions ranged from strong conviction that risks should be estimated to cautious optimism about doing so, to skepticism. Typically, participants were concerned about the reliability of such estimates, which some thought may be overly simplistic, certain, subjective, or just plain wrong. Numerical estimates specifically seemed to be the source of the greatest consternation. Some participants perceived that uncertainty is often unaccounted for in such estimations and others believed that the choice of the models used to produce numerical estimates of risk was too subjective. Further, others objected to the moral implications of quantifying some impacts, for example, life or suffering. Others raised concerns about the value of the concept of risk itself, suggesting that it may be an overly narrow-minded approach for dealing with large-scale, wicked socio-environmental issues.

3.3 Topic Models Display Diverse Risk Perspectives

Table 1 includes the eight topics we identified (Topic Name) from the corpus of documents submitted by the study participants, a brief description of our interpretation of their meanings (Topic Focus), and the titles of the three texts containing the highest proportions of each topic (Top Texts). Fig. 2 depicts each participant's contribution by topic (also see SI Appendix, Table S2). The topics found within each participant's submitted texts did not appear to be related to his or her discipline (Fig. 2 and SI Appendix, Table S2).

STM TOPICS

TOPIC NAME	TOPIC FOCUS	TOP TEXTS
RISK ASSESSMENT (RISK ASSESS.)	- Risk assessment, skewed toward the quantitative risk analysis phase.	1. “An Emerging New Risk Analysis Science: Foundations and Implications.” 2. “Advanced Impact Analysis: the ADVIAN® method - an enhanced approach for the analysis of impact strengths with the consideration of indirect relations.” 3. “Identifying Uncertainty in Environmental Risk Assessments: The Development of a Novel Typology and Its Implications for Risk Characterization.”
DECISION-MAKING IN THE SOCIOLOGICAL CONTEXT (DECISION-MAKING)	- The risk-related decisions society makes and the grounds on which they are made. - Societal methods for responding to risk.	1. *Risk: A Sociological Theory*. 2. “Systems Theory and Risk, in: Social Theories of Risk and Uncertainty: An Introduction.” 3. “When the Risk of Harm Harms”
QUANTITATIVE RISK ANALYSIS (RISK ANA.)	- Quantitative methods for risk analysis and prediction. - Alternatives to and warnings against the use of quantitative risk analysis	1. “Good judgments do not require complex cognition.” 2. “A belief network approach to optimization and parameter estimation: application to resource and environmental management.” 3. “Surrogate Science: The Idol of a Universal Method for Scientific Inference.”
GLOBAL RISKS	- Large-scale environmental risks and their impacts on human needs. - The international political and social ramifications of these risks.	1. “The Arab Spring and Climate Change, A Climate and Security Correlations Series” 2. “Epicenters of Climate and Security: The New Geostrategic Landscape of the Anthropocene.” 3. “The Global Risks Report 2018”
INFRASTRUCTURE RISKS (INFRA. RISKS)	- Risks to infrastructure systems, most notably power infrastructure.	1. “Valuing dedicated storage in electricity grids.” 2. “National Security and the Threat of Climate Change.” 3. “Application of a Risk-Based Decision Making Framework for Critical Infrastructure Exposed to Extreme Weather Events.”
LOCAL ENVIRONMENTAL RISKS (LOCAL RISKS)	- The impacts of certain hazards, particularly contaminants and climate change, on the aquatic environment, wildlife, and local communities.	1. “Climatic Effects on Atlantic Salmon and Brown Trout.” 2. “Seismic survey noise disrupted fish use of a temperate reef.” 3. “Gender, race, and perceived risk: The “white male” effect.”
SOCIAL RISKS	- The effects negative events, i.e. realized risks, have	1. Flammable - Environmental Suffering in an Argentine Shantytown. 2. “Aggregation, Complaints, and Risk”

	or could have on society.	3. X-Events: The Collapse of Everything.
RISK GOVERNANCE (RISK GOV.)	- The risks associated with the collective use and management of common-pool resources.	1. Governing the Commons: The Evolution of Institutions for Collective Action. 2. "Climatic Effects on Atlantic Salmon and Brown Trout" 3. "Has land use pushed terrestrial biodiversity beyond the planetary boundary?"

Table 1. This table displays the eight topics produced by the topic model, the focus of each topic as assessed by the authorship team, and three texts contributing the greatest number of words to each topic. See SI, Figure S1 and Table S3 for the top ten most prevalent and exclusive terms for each topic.

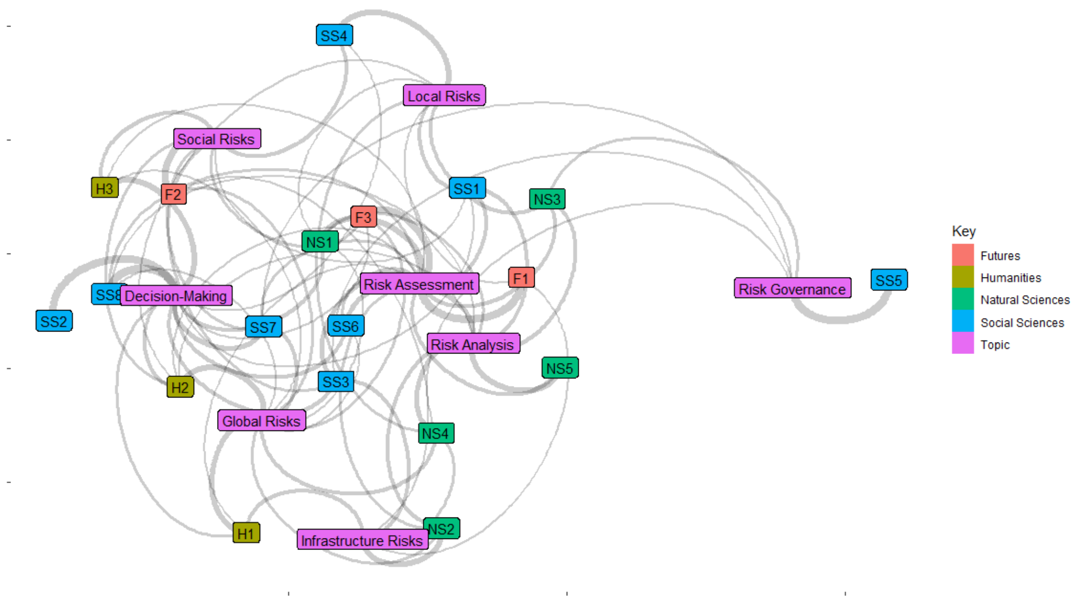

Figure 2. The network depicts each participant's contributions to the topics identified by the topic model. Topics are represented in purple and participants are color-coded by discipline. Edge width represents the percent contribution of text from a participant to a topic; thicker lines denote a higher percentage of text contributed. Participants are identified by pseudonyms (SI, Table S1).

4 DISCUSSION

4.1 Perspective Differences

Our results demonstrate that different risk perspectives existed within the team we studied. Here we summarize the dimensions of those perspectives. First, team members often interpreted risk as a concept differently. They described risk 1) either qualitatively or quantitatively, 2) described it as a function of probability, a hazard, the relationship between the two, or as a philosophical tool for understanding the world, and 3) depicted different relationships between it and uncertainty and surprise (Fig. 1).

In addition to parsing out the team members' different conceptualizations of what risk is, we also performed "risk perspective triage" by analyzing the interview questions that revealed the greatest amount of perspective diversity within the group. For this team, risk analysis, particularly in quantitative sense, was the most likely source of confusion, miscommunication, and subsequent frustration regarding risk within the team, due to the highly diverse and often opposing perspectives about it we observed. For example, during the interviews, participants provided conflicting opinions about how risks should be estimated, the reliability of risk estimates, and the value and morality of making them. The tension surrounding this topic was also reflected in the topic modeling results. Both the first (risk assessment) and third (risk analysis) most prevalent topics emphasized the importance of risk analysis within this team, as both contained a high prevalence of words related to analysis methods (SI Appendix, Fig. 1 and Table S3), like "analysis," "scenarios," "cross-impact matrix," "probability," "methods," "model," and "heuristic." We believe there is also evidence of conflicting opinions about whether or not quantitative risk analysis is the best method for addressing potential hazards. For example, one of the three texts containing the highest proportions of the risk analysis topic (Table 1), "Good judgments do not require complex cognition" (SI Appendix, Table S1), argues for the utility and validity of heuristics in decision-making over more complex quantitative methods. Such examples indicate perspective differences regarding appropriate methods for addressing potential hazards between the contributor of this text, SS1, and the contributors of the other two texts containing the highest proportions of the topic, NS5 and NS4. Their contributed texts focused on the utility of Bayesian inference, a quantitative analysis method, and quantified impacts of long-term climatic trends on extreme weather events, which indicates approval or at least acceptance of quantitative methods for risk estimation (SI Appendix, Table S1).

In addition to the participants' diverse perspectives about the meaning of risk and its analysis, it was also clear that they had a diverse array of risk-related interests. These interests can be characterized by two broad categories: 1) the risk management and governance process (process-interests) and 2) specific risks or hazards (hazard-interests).

Process-interests were exemplified by the risk assessment, decision-making, risk analysis, and risk governance topics produced by the STM. Process-interests were also apparent during the interviews, as some participants showed particular enthusiasm for, for example, risk analysis, or focused on how certain risks can be mitigated and prepared for. These were often most obvious during the interviews when we asked participants to consider and draw their mental models of the risks pertaining to a severe winter storm event.

Hazard-interests were even more obvious and were often announced at the beginning of an interview when participants made statements like "my work focuses on the risks posed by global climate change" or "I am concerned about food security in complex systems." Hazard-interests were also reflected by the global socio-environmental risks, infrastructure risks, local socio-environmental risks, and social risks topics produced by the STM.

Even before conducting interviews or topic modeling, the titles of the texts the participants submitted hinted at specific process or hazard-interests. Consider these titles, for example: "An emerging new risk analysis science: foundation and implications" (a process-interest) and "Sources of human insecurity in the face of hydro-climatic change" (a hazard-interest). Although we did not initially intend to identify specific risk-related interests, we believe they are an important facet of each participant's risk perspective. A diverse array of interests within the team will help ensure that the wicked socio-ecological problems they grapple with together are addressed from more angles than they would be if interests were homogenous within the group.

4.2 The Value of Multiple Risk Perspectives

We consider perspective differences, like those we observed, to be positive attributes, as they may boost the team's creative thinking, innovativeness, and problem-solving capacity (Alves et al., 2007). In the context of risk specifically, a wider range of perspectives increases the potential to identify risks, related triggers, chains of consequences, and flawed assumptions (Stirling, 2010). Additionally, Stirling (2010) asserts that a narrow focus on risk, or rather, a narrow interpretation of it, is an inadequate approach for dealing with incomplete knowledge, a sentiment echoed by some of our study's participants. Therefore, it may be prudent to leave a narrow understanding of risk behind, in search of a more comprehensive one (Stirling, 2010). Instead of negotiating to a single consensual interpretation of risk across a spread of contending contexts, analyses, and judgments, as is often done under the traditional model of science-based decision-making, it would be more accurate and useful to accept divergent interpretations and focus on documenting the rationale behind them (Stirling, 2010). Compared to a single, definitive representation of incomplete scientific knowledge, a plural, conditional approach (Heath & O'Hair, 2010) would make scientific advice more rigorous, robust, and democratically accountable - and thereby, less vulnerable to political manipulation (Stirling, 2010). As such, the perspective diversity we encountered within the studied team should be appreciated and encouraged.

4.3 Improving Risk Communication within Diverse Teams

Although perspective diversity is an asset, it can also make communication difficult, leading to misunderstandings and frustration. Such issues can hamper a team's capacity to build a shared understanding among them, which is crucial because shared understanding allows teams to develop the trust, transparency, and collaboration required to successfully integrate knowledge (Catney & Lerner, 2009; Haapasaari et al., 2012). Therefore, productive interdisciplinary teamwork requires a balancing act. The gaps between team members' perspectives must be closed enough to allow fruitful communication between them and therefore the development of shared understanding (Cronin & Weingart, 2019), while maintaining their heterogeneous viewpoints at the same time (Stirling, 2010).

Teams can achieve this balance via cognitive integration (Cronin et al., 2011; Cronin & Weingart, 2019), which brings perspectives closer together, by enhancing a group's ability to imagine circumstances from one another's perspectives. Put another way, cognitive integration improves an individual's ability to translate between perspectives and therefore, better understand another's intended meaning (Cronin & Weingart, 2019). This is achieved via three interconnected processes, namely, Enrichment (where one party teaches the other about their perspective), Expansion (where combining perspectives brings forth new knowledge), and Reconciliation (where conflicting perspectives are fitted together or find new space to coexist) (Cronin & Weingart, 2019).

For cognitive integration to succeed, however, developing an appropriate environment is crucial (Carr et al., 2018). Specifically, affective integration, building a social environment based on mutual fondness, trust, and respect, encourages teams to persevere and continuously close the gaps between their perspectives, while maintaining conflicts within the realm of constructive debate (Cronin et al., 2011; Cronin & Weingart, 2019).

We suggest that cognitive integration allows teams to develop boundary objects or concepts to further ease communication amongst themselves. Boundary concepts, defined by their interpretative flexibility, enable shared work across perspectives without necessarily establishing consensus (Star, 2010; Star & Griesemer, 1989). Teams that have undergone cognitive integration may better understand that different perspectives about a key concept exist within the team, understand what they are, and what the concept means in a given context. Hence, following cognitive integration a key concept, like risk, which was once confusing due to its multiple latent meanings, can become a functional boundary concept. Further, functional boundary concepts, positioned at the nexus between perspectives, provide a wealth of opportunities for learning (Akkerman & Bakker, 2011), which may enhance the team's problem-solving capacity.

Although the key concepts and specific perspectives may be different within other teams and organizations, we suspect the perspective diversity we found is not unique. As such, we propose that analytical studies like ours, or even smaller-scale investigations, could support cognitive integration and the development of boundary concepts within other teams by transparently revealing perspective differences and providing the basis for targeted conversation about them. Using these results to aid in learning about the similarities and differences in perspectives, the logic behind them (Expansion), and to help address any conflict between perspectives begins the process of cognitive integration (Cronin & Weingart, 2019). Hence, allowing key concepts to become functional boundary concepts within the team. Further, combining our approach with other techniques for improving shared understanding, like the ASPIRe model for developing shared goals (Cvitanovic et al., 2020), could further improve interdisciplinary teamwork .

5 CONCLUSIONS

We have identified and described the different perspectives regarding risk, a key concept, within our studied team. We argue that this case study should be viewed as a demonstration of a wider phenomenon, perspective diversity, which likely affects other heterogeneous teams and organizations dealing with complex concepts understood by team members in multiple ways. Where various perspectives about key concepts exist, the gaps between them must be bridged to allow fluent communication. To do this, at the beginning of a project, a team's key concept(s) should be identified, the different perspective about them articulated, and the reasons for those perspectives disclosed. Concurrent with this process cognitive integration can begin, enabling the development of a shared understanding amongst the group. To create the appropriate conditions for cognitive integration, a social environment fostering fondness, trust, and mutual respect is required. Over time, cognitive integration could allow key concepts to become useful boundary concepts, which may ultimately improve communication, contributing to more productive teamwork. Developing a shared understanding and better communication within the team could also help them create clearer and more cohesive messages about their work for other stakeholders, supporting prior research aimed at improving communication between stakeholder groups. We encourage further investigation and documentation of the different perspectives surrounding key concepts in other teams and organization. Further, we also suggest additional research should be done to determine whether or not collecting and sharing these results with the team promotes cognitive integration and whether cognitive integration ultimately improve communication amongst team members. With this knowledge interdisciplinary teams and organizations will be better able to fulfill the expectations of interdisciplinary work and combine their collective wisdom to create the high quality, novel solutions necessary to manage wicked problems.

6 ACKNOWLEDGMENTS

REMOVED FOR BLIND PEER REVIEW

7 AUTHOR CONTRIBUTIONS

REMOVED FOR BLIND PEER REVIEW

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[i] More information at (WEB ADDRESS)
[ii] More information at (WEB ADDRESS)

9 SUPPLEMENTARY MATERIAL

9.1 Custom Stop Word List

Custom Stop Word List: "can", "also", "may", "well", "one", "two", "three", "four", "five", "first", "second", "third", "fourth", "fifth", "e", "Will", "will", "way", "rather", "like", "thus", "therefore", "figure", "table", "example", "since", "fig", "however", "within", "many", "Many", "use", "used", "let's", "'re", "'ve", "'ll", "'re", "'ve", "'ll", "risk", "risks", "Risk", "Risks", "even", "just"

9.2 Interview Questions

1. *Background Information*
   a. What is your:
      i. Field of study
      ii. Job title
      iii. Short description of work
      iv. Educational background
      v. Education related to risks
      vi. Statistical background.
   b. Have you conducted any previous risk assessment studies? What was the aim?
   c. Have you written any publications related to risk? What were they about?
   d. How would you define risk? What does risk mean to you? How it is usually defined in your field?

2. *Discuss 3 Articles Provided by the Participant*
   a. Please explain why you have chosen your three articles.
   b. How have these articles shaped the way you think about risk?
   c. How have they shaped the methodologies you use to assess risk?
   d. What are the strengths/weaknesses of these articles in terms of risk assessment?
   e. How do these articles relate to interdisciplinary risk analysis?
   f. How do you believe one could apply the methodologies or ideas portrayed by these articles to the (NAME) project?
   g. What kind of additional skills might be needed for risk assessment in (NAME) project scenarios?

3. *Risk Scenario*
   a. A strong winter storm hits a large population center and surrounding areas in southern (COUNTRY). Prior to the storm, temperatures were above 0°C and the ground was not frozen. During the storm, the wind gusts violently at ≥20 m/s and 30 cm of heavy wet snow falls. Following the storm, temperatures rapidly drop to ~-15°C and remain there for the next several weeks. As a result of the high wind speeds, previously unfrozen ground, and heavy wet snow, enormous swaths of forest have fallen, resulting in downed power lines. The wet snow followed by a hard freeze has made driving conditions treacherous.
   b. This storm is intended to represent a worst-case scenario. Please consider the situation following the storm.
   c. From what point of view are you considering the risks?

4. *Risk Analysis Questions*
   a. How can risks you identified be estimated (by you or others)?
   b. Which risks do you believe you could estimate?
   c. How would you proceed with analyzing the risks?
   d. Would you quantify risks? If so, then how?

5. *Risk Evaluation Questions*
    a. How should society decide whether the risks you identified in your mind map are acceptable or not? At what point do we need to take action to manage the risks?

6. *Uncertainty and Probability*
    a. How would you define uncertainties?
    b. How would you define probabilities?
    c. Does risk include probabilities? Why or why not?

7. *Risk Communication*
    a. How would you communicate the risks related to the scenario or how should risk communication be arranged?
    b. To those who are responsible for management actions (policymakers)?
    c. To the public?
    d. Which parts of the overall risks are difficult to communicate?

9.3 Disciplinary Perspective Differences within (PROJECT NAME)

Although we found several differences in risk perspective between the participants, these differences did not fall along obvious disciplinary lines (Fig. 2, SI, Table S2). Both the interview and STM results indicated that individual perspectives varied drastically within disciplinary groups. This result suggests that risk perspectives may be diverse in any scientific team, interdisciplinary or otherwise. However, we do not believe the sample size in this study and the methodological approach used here allow us to make conclusive statements about whether or not risk perspectives between individuals within the same discipline are more similar than they are between individuals from different disciplines.

By their very nature IS teams should include members with different experiential and academic histories, worldviews, and assumptions. In essence, the purpose of bringing IS teams together is to ensure the perspectives between their members are more divergent than perspectives between members of disciplinary teams. Therefore, we assume that differences in perspective should be greater within interdisciplinary teams. However, testing whether or not interdisciplinary teams do indeed include more diverse perspectives than disciplinary ones could be the subject of another study.

9.4 Methodological Considerations

We would like to acknowledge a few areas for methodological improvement. First, upon examining the topic modeling results, we noticed that one topic, risk governance, was comprised almost entirely of words from Elinor Ostrom's "Governing the Commons." This occurred because it was the longest text included in the corpus and contained unique and cohesive content. Participants submitting full books as opposed to shorter articles may have allowed them to disproportionately influence some of the other topics, in a similar fashion

Participants also chose to submit different numbers of texts, for example, F2, SS2, SS5, and SS7 each chose to submit only one text, whereas F3 and NS4 each contributed five. Participants submitting more texts could induce the same effect as those submitting longer ones, i.e. by contributing a greater proportion of the total number words in the corpus, however, we did not see evidence of this issue within our results. Nevertheless, we may have avoided these problems altogether had we enforced the types of texts (i.e. only journal articles) and the number of texts that participants were allowed to submit more strictly. However, had we done this, the texts may not have been adequate representations of the foundations of the participants' risk perspectives.

Note also that topic models form topics based on the frequency with which words co-occur. As such, sometimes the same words used in different contexts produce topics that do not represent a cohesive theme. We noticed this in the local environmental risks topic. NS3 and SS4's contributions formed a well-defined and understandable topic. However, the contributions from SS1 did not fit the topic. Portions of one of SS1's contributed text "Gender, race, and perceived risk: The "white male" effect" (SI, Table S1) were pulled into the topic because they used demographic words like age, male, female, sex, etc. which were also common in NS3 and SS4's fish-related articles. For this reason, we highlight the importance of thoroughly understanding the content of the corpus in topic modeling studies. As such, we recommend reading all the corpus material, as we did, when it is small enough to do so.

Last, we would like to acknowledge linguistic concerning the word "estimation" in our interview questions. We used this term to refer to *either* qualitative or quantitative estimation in keeping with the ISO's definition of risk analysis, which indicates the use of both quantitative and qualitative methodologies (ISO, 2018). However, when analyzing the participants' responses, it was clear that many considered estimation to be a strictly quantitative term, or used the terms estimation and quantification interchangeably. Therefore, in our analysis, we have chosen to make the distinction between these terms clear when necessary.

9.5 Data and Software Availability

Although interview transcripts and audio recordings will not be shared to protect the privacy of our study's participants, the code we used for topic modeling is available at: (WEB ADDRESS). Additionally, a list of the texts submitted by the participants and used for topic modeling is available in the Supplementary Information.

9.6 Supplementary Figures

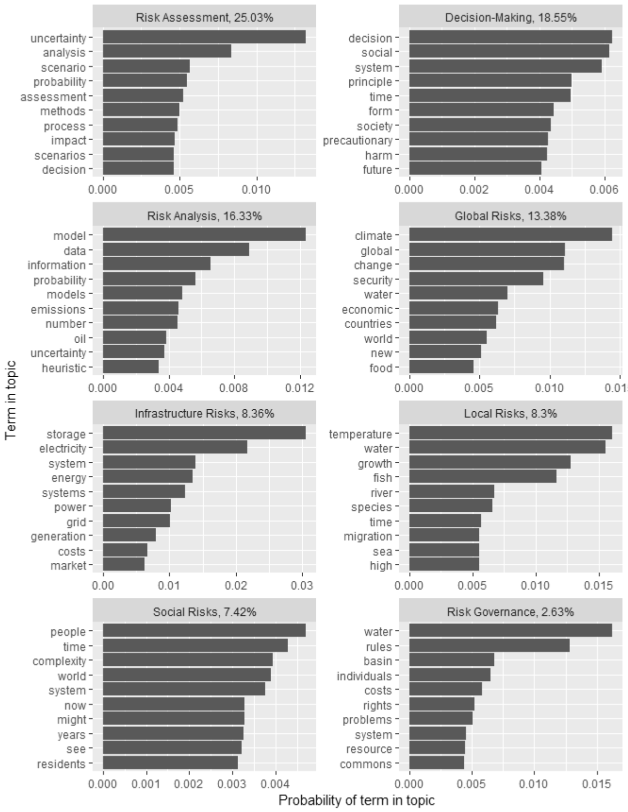

Figure S1. The ten most common terms per topic. Topics are organized by the proportion of the corpus they include. Note: the probability scale varies by topic, as the terminology included in some topics is more focused than in others.

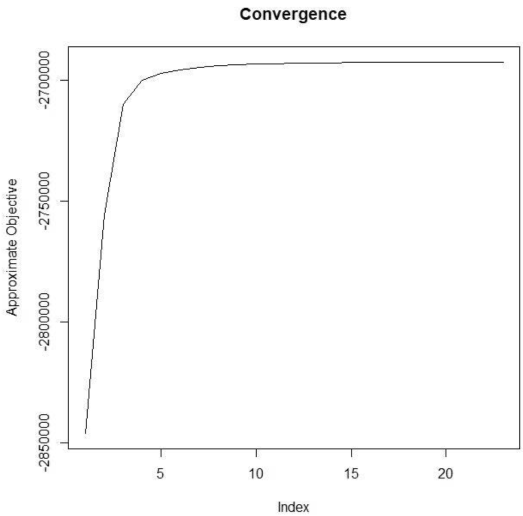

Figure S2. Topic Model Convergence. Figure Depicts model convergence when the model is set to run with 500 iterations.

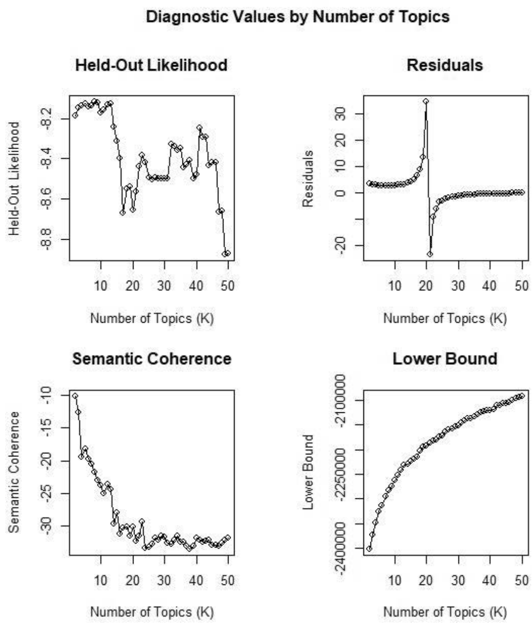

Figure S3. The output of stm’s search function run for *k* values between two and 50.

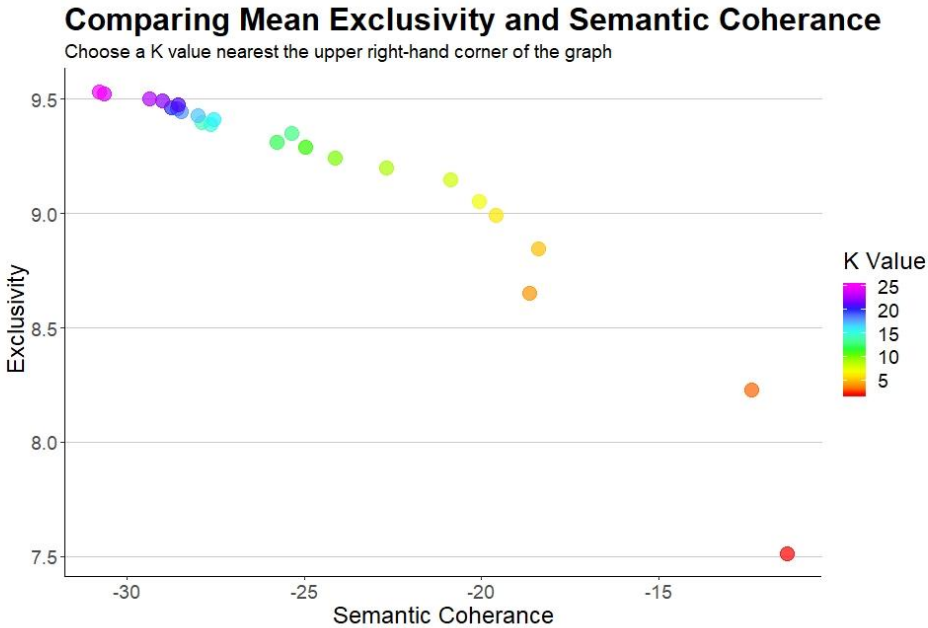

Figure S4. Exclusivity Vs. Semantic Coherence. Plot comparing the semantic coherence and exclusivity of topics for *k* values between two and 25.

9.6 Supplementary Tables

Table S1. Participant Pseudonyms, Contributed Text, & Text Type

PARTICIPANT PSEUDONYM	TEXT CITATION	TEXT TYPE
FUTURES 1 (F1)	T. J. Gordon, H. Hayward, Initial experiments with the Cross Impact Matrix Method of forecasting, *Futures* **1**, 100–116 (1968).	Journal Article
	V. Linss, A. Fried, Advanced Impact Analysis: the ADVIAN® method - an enhanced approach for the analysis of impact strengths with the consideration of indirect relations. *Papers and Preprints of the Department of Innovation Research and Sustainable Resource Management (BWL IX), Chemnitz University of Technology* **1**, 1-12 (2009).	Report
	W. Weimer-Jehle, Cross-impact balances: A system-theoretical approach to cross-impact analysis. *Technol. Forecast. Soc. Change* **73**, 334–361 (2006).	Journal Article
FUTURES 2 (F2)	J. Casti, X-Events: The Collapse of Everything (Harper Collins Publishers, 2012).	Book
FUTURES 3 (F3)	R. Amara, The futures field - Searching for definitions and boundaries. *Futurist* **15**, 25–29 (1981).	Journal Article
	T. Aven, An emerging new risk analysis science: Foundations and implications. *Risk Anal.* **38**, 876-888 (2018).	Journal Article
	L. Ilmola, E. Rovenskaya, Three experiments: The exploration of unknown unknowns in foresight. *Technol. Forecast. Soc. Change* **106**, 85–100 (2016).	Journal Article
	Ph. W. F. van Notten, A. M. Sleegers, M. B. A. van Asselt, The future shocks: On discontinuity and scenario development. *Technol. Forecast. Soc. Change* **72**, 175–194 (2005).	Journal Article

	M. Wilenius, J. Casti, Seizing the X-events. The sixth K-wave and the shocks that may upend it. *Technol. Forecast. Soc. Change* **94**, 335–349 (2015).	Journal Article
HUMANITIES 1 (H1)	C. Carey, J. Clarke, Application of a risk-based decision making framework for critical infrastructure exposed to extreme weather events. (2017).	PowerPoint Presentation
	E. Hakala, Climate security: Strategy or necessity for Finland? *The Finnish Institute of International Affairs* (2016).	Briefing Paper
	World Economic Forum, The Global Risks Report 2018, 13th Edition (2018).	Report
HUMANITIES 2 (H2)	Y. Haila, C. Dyke, "What to say about nature's "speech"" in How Nature Speaks: The Dynamics of the Human Ecological Condition, New Ecologies for the Twenty-First Century, (Duke University Press, 2006), pp 1–48.	Book Chapter
	C. E. Werrell, F. Femia, A.-M. Slaughter, The Arab Spring and Climate Change (2013).	Report
	C. Zografos, M. C. Goulden, G. Kallis, Sources of human insecurity in the face of hydro-climatic change. *Glob. Environ. Change* **29**, 327–336 (2014).	Journal Article
HUMANITIES 3 (H3)	S. M. Gardiner, A core precautionary principle. *J. Polit. Philos.* **14**, 33–60 (2006).	Journal Article
	J. Horton, Aggregation, complaints, and risk. *Philos. Public Aff.* **45**, 54–81 (2017).	Journal Article
	A. Placani, When the risk of harm harms. *Law Philos.* **36**, 77–100 (2017).	Journal Article
HUMANITIES 4 (H4)	NA	NA
NATURAL SCIENCES 1 (NS1)	M. Burgman, "Values, history and perception" in Risks and Decisions for Conservation and Environmental Management (Cambridge University Press, 2005), pp. 1–25.	Book Chapter
	M. Burgman, "Kinds of uncertainty" in Risks and Decisions for Conservation and Environmental Management (Cambridge University Press, 2005), pp. 26–41.	Book Chapter
	M. Burgman, "Conventions and the risk management cycle" in Risks and Decisions for Conservation and Environmental Management (Cambridge University Press, 2005), pp. 42-61.	Book Chapter
	T. Dietz, What is a good decision? Criteria for environmental decision making. *Human Ecology Review* **10**, 33–39 (2003).	Journal Article
	D. J. C. Skinner, S. A. Rocks, S. J. T. Pollard, G. H. Drew, Identifying uncertainty in environmental risk assessments: The development of a novel typology and its implications for risk characterization. *Hum. Ecol. Risk Assess.* **20**, 607–640 (2014).	Journal Article
NATURAL SCIENCES 2 (NS2)	European Academies Scientific Advisory Council. Valuing dedicated storage in electricity grids (2017).	Report
	J. Rogelj J, et al., Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **534**, 631–639 (2016).	Journal Article
	J. Xie, A. Stefanov, C.-C-. Liu, Physical and cyber security in a smart grid environment. *Wiley Interdisciplinary Reviews: Energy and Environment* **5**, 519–542 (2016).	Journal Article
NATURAL SCIENCES 3 (NS3)	R. Gregory, et al., "Structuring environmental management choices" in Structured Decision Making: A Practical Guide to Environmental Management Choices (Blackwell Publishing Ltd, 2012), pp. 1–20.	Book Chapter
	B. Jonsson, N. Jonsson, "Climatic effects on Atlantic salmon and brown trout" in Ecology of Atlantic Salmon and Brown Trout: Habitat as a Template for Life Histories, Fish & Fisheries Series, B. Jonsson, N. Jonsson N, Eds. (Springer, 2011), pp. 473–515.	Book Chapter
	A. Lehikoinen, et al., A Bayesian network for assessing the collision induced risk of an oil accident in the Gulf of Finland. *Environ. Sci. Technol.* **49**, 5301–5309 (2015).	Journal Article
NATURAL SCIENCES 4 (NS4)	The CNA Corporation, National Security and the Threat of Climate Change (2007).	Report
	T. Newbold, et al., Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* **353**, 288–291 (2016).	Journal Article
	A. E. Raftery, A. Zimmer, D. M. W. Frierson, R. Startz, P. Liu, Less than 2 °C warming by 2100 unlikely. *Nat. Clim. Chang.* **7**, 637–641 (2017).	Journal Article
	S. Rahmstorf, D. Coumou, Increase of extreme events in a warming world. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 17905–17909 (2011).	Journal Article
	C. E. Werrell, F. Femia, Epicenters of Climate and Security: The New Geostrategic Landscape of the Anthropocene (The Center for Climate and Security) (2017).	Report
NATURAL SCIENCES 5 (NS5)	J. S. Clark, Why environmental scientists are becoming Bayesians. *Ecol. Lett.* **8**, 2–14 (2005).	Journal Article
	D. J. Spiegelhalter, H. Riesch, Don't know, can't know: embracing deeper uncertainties when analysing risks. Philos. Trans. A Math Phys. Eng. Sci. **369**, 4730–4750 (2011).	Journal Article
	O. Varis, A belief network approach to optimization and parameter estimation: application to resource and environmental management. *Artifi. Intell.* **101**, 135–163 (1998).	Journal Article

NATURAL SCIENCES 6 (NS6)	NA	NA
SOCIAL SCIENCES 1 (SS1)	M. L. Finucane, P. Slovic, C. K. Mertz, J. Flynn, T. A. Satterfield, Gender, race, and perceived risk: The “white male” effect. *Health Risk Soc.* **2**, 159–172 (2000).	Journal Article
	J. N. Marewski, W. Gaissmaier, G. Gigerenzer, Good judgments do not require complex cognition. *Cogn. Process.* **11**, 103–121 (2009).	Journal Article
	P. Slovic, Perception of Risk. *Science* **236**, 280–285 (1987).	Journal Article
SOCIAL SCIENCES 2 (SS2)	K. P. Japp, I. Kusche, “Systems theory and risk” in Social Theories of Risk and Uncertainty: An Introduction (Blackwell Publishing Ltd, 2009), pp. 76–105.	Book Chapter
SOCIAL SCIENCES 3 (SS3)	E. Roe, P. R. Schulman PR, A reliability & risk framework for the assessment and management of system risks in critical infrastructures with central control rooms. *Saf. Sci.* **110**, 80–88 (2018).	Journal Article
	A. Stirling, Risk, precaution and science: towards a more constructive policy debate: Talking point on the precautionary principle. *EMBO rep.* **8**, 309–315 (2007).	Journal Article
SOCIAL SCIENCES 4 (SS4)	J. Auyero, D. A. Swistun, Flammable - Environmental Suffering in an Argentine Shantytown (Oxford University Press, 2009).	Book
	A. B. Paxton, et al., Seismic survey noise disrupted fish use of a temperate reef. *Mar. Policy* **78**, 68–73 (2017).	Journal Article
	S. Sawyer, Crude Contamination: Law, Science, and Indeterminacy in Ecuador and Beyond. (2015)	Report
SOCIAL SCIENCES 5 (SS5)	E. Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action (Cambridge University Press, 1990).	Book
SOCIAL SCIENCES 6 (SS6)	G. Gigerenzer, J. N. Marewski, Surrogate science: The idol of a universal method for scientific inference. *J. Manage.* **41**, 421–440 (2015).	Journal Article
	A. Stirling, “Precaution in the governance of technology” in The Oxford Handbook of Law, Regulation and Technology (Oxford University Press, 2017), pp. 645–669.	Book Chapter
SOCIAL SCIENCES 7 (SS7)	E. Shove, Beyond the ABC: Climate change policy and theories of social change. *Environment and Planning A: Economy and Space* **42**, 1273–1285 (2010).	Journal Article
	L. Holappa, Keynes’s Revolution: From Barter to Monetary Economics. Mustarinda. Available at: https://mustarinda.fi/magazine/keynes/keyness-revolution-from-barter-to-monetary-economics [Accessed July 5, 2019].	Blog Post
SOCIAL SCIENCES 8 (SS8)	F. Ewald, “Insurance and risk” in The Foucault Effect: Studies in Governmentality, G. Burchell, C. Gordon, P. Miller, Eds. (The University of Chicago Press, 1991).	Book Chapter
	N. Luhmann, Risk: A Sociological Theory (Walter de Gruyter & Co., 1993).	Book
	P. O’Malley, “Risk, uncertainty, and government” in Risk, Uncertainty and Government (Cavendish Publishing, 2004), pp. 1–28.	Book Chapter

Table S2. Topic Proportions by Participant

participant	RISK ASSESS.	DECISION-MAKING	RISK ANA.	GLOBAL RISKS	INFRA. RISKS	LOCAL RISKS	SOCIAL RISKS	RISK GOV.
F1	0.97	0.00	0.00	0.00	0.02	0.01	0.00	0.00
F2	0.00	0.00	0.00	0.14	0.02	0.00	0.83	0.00
F3	0.75	0.02	0.00	0.13	0.00	0.00	0.09	0.00
H1	0.03	0.05	0.00	0.62	0.30	0.00	0.00	0.00
H2	0.02	0.22	0.02	0.63	0.00	0.01	0.09	0.00
H3	0.02	0.64	0.00	0.01	0.00	0.00	0.33	0.00
NS1	0.64	0.24	0.07	0.01	0.00	0.03	0.00	0.00
NS2	0.05	0.00	0.23	0.09	0.63	0.00	0.00	0.00
NS3	0.29	0.00	0.33	0.00	0.00	0.34	0.00	0.04
NS4	0.00	0.00	0.47	0.26	0.20	0.06	0.00	0.02
NS5	0.29	0.00	0.71	0.00	0.00	0.00	0.00	0.00
SS1	0.27	0.03	0.33	0.00	0.00	0.33	0.02	0.00
SS2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
SS3	0.45	0.25	0.00	0.00	0.22	0.00	0.06	0.02
SS4	0.00	0.03	0.00	0.00	0.00	0.61	0.34	0.00
SS5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
SS6	0.16	0.33	0.49	0.01	0.00	0.00	0.00	0.00
SS7	0.06	0.51	0.00	0.35	0.00	0.00	0.04	0.03

Tables S2. The proportion of each participant (contributor) text contributed to a given topic. Rows add to one. For example, 97% of F1’s text contributed to the “Risk Assessment” topic.

Table S3. Top 7 Terms for Three Measure of Exclusivity: Frex, Lift, & Score

TOPIC NAME	FREX	LIFT	SCORE
RISK ASSESSMENT	cross-impact, matrix, uncertainties, assessments, futures, assessment, methods	collation, cross-impact, delphi, judgmental, micmac, godet, diagonal	micmac, cross-impact, scenarios, matrix, scenario, ifs, swan
DECISION-MAKING IN THE SOCIOLOGICAL CONTEXT	precautionary, insurance, precaution, distinction, harm, distinctions, principle	accuse, determinate, distinguishable, doubtless, effected, ern, eventualities	risking, precaution, insurance, precautionary, distinctions, attribution, protest
QUANTITATIVE RISK ANALYSIS	bayesian, inference, heuristic, bayes, gigerenzer, parameter, heuristics	raftery, moscow, posterior, bayes, gigerenzer, priors, shaded	moscow, bayes, posterior, gigerenzer, heuristic, node, null
GLOBAL RISKS	africa, arab, arctic, nations, global, military, geopolitical	alleviate, clash, clashes, diplomacy, erode, humanitarian, interstate	climate, arctic, securitization, security, global, migration, syria
INFRASTRUCTURE RISKS	electricity, storage, grid, dedicated, grids, battery, batteries	compressor, metering, surge, upgrades, back-, dispatch, grids	surge, electricity, storage, grid, batteries, dedicated, generators
LOCAL ENVIRONMENTAL RISKS	spawning, seismic, males, abundance, rivers, elliott, mortality	seismic, invertebrates, abundances, spawning, females, elliott, reef	seismic, spawning, migration, temperature, females, males, ellio
SOCIAL RISKS	neighborhood, complaint, residents, shell, compound, neighbors, post	ante, forget, nice, paralyzed, replies, windows, doesn't	ante, neighborhood, complaint, residents, shell, contamination, relocation
RISK GOVERNANCE	basin, commons, irrigation, basins, farmers, rules, institutional	richness, appropriation, raymond, basin, basins, nets, villages	commons, basin, richness, arc, water, groundwater, villages

Table 3. FREX, Lift, and SCORE each compute term exclusivity differently. Exclusive terms are those that are "exclusive" to the topic, or in other words, are not likely to be found in other topics. For more information about these three measures of exclusivity see Roberts et al. (2018) (12).

CHAPTER II

Kelsey LaMere, Samu Mäntyniemi, Jarno Vanhatalo, Päivi Haapasaari (2020).

MAKING THE MOST OF METAL MODELS: ADVANCING THE METHODOLOGY FOR MENTAL MODEL ELICITATION AND DOCUMENTATION WITH EXPERT STAKEHOLDERS

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Making the most of mental models: Advancing the methodology for mental model elicitation and documentation with expert stakeholders

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ABSTRACT

Eliciting stakeholders' mental models is an important participatory modeling (PM) tool for building systems knowledge, a frequent challenge in natural resource management. Therefore, mental models constitute a valuable source of information, making it imperative to document them in detail, while preserving the integrity of stakeholders' beliefs. We propose a methodology, the Rich Elicitation Approach (REA), which combines direct and indirect elicitation techniques to meet these goals. We describe the approach in the context of the effects of climate change on Baltic salmon. The REA produced holistic depictions of mental models, with more variables and causal relationships per diagram than direct elicitation alone, thus providing a solid knowledge base on which to begin PM studies. The REA was well received by stakeholders and fulfilled the substantive, normative, instrumental, and educational functions of PM. However, motivating stakeholders to confirm the accuracy of their models during the verification stage of the REA was challenging.

1. Introduction

Mental model, or cognitive map, elicitation is an essential tool within the increasingly popular field of participatory modeling (PM) (Voinov et al., 2016; Voinov and Bousquet, 2010), owing to its utility in formalizing knowledge and facilitating problem-solving (Özesmi and Özesmi, 2004). This technique extracts a person's "internal representation of an external reality (Jones et al., 2011)," or put another way, their conceptualization of a system's causal dynamics (Moray, 1998), built on personal experience, knowledge, and values (Johnson-Laird, 1983; Jones et al., 2011) to cognitively aid in reasoning (Johnson-Laird, 2010; Nersessian, 2002). Here we develop a methodology, the Rich Elicitation Approach (REA), to improve the elicitation and documentation of stakeholders' mental models. Advancing these processes is crucial to ensure they adequately contribute to the functions of PM (Fiorino, 1990; Jones et al., 2009), which are:

1) *The normative function*, which suggests, incorporating stakeholder knowledge into a model increases its legitimacy in the decision-making context.
2) *The substantive function*, which is the capacity to synthesize available knowledge from a variety of sources to enhance problem-solving.
3) *The instrumental function*, which describes the process of relationship-building between stakeholder groups,[1] may reduce conflict and ease the implementation of decisions made using model outputs.

PM also serves a fourth function.

4) *The educational function*, which describes the act of engaging with the PM process as an educational experience for stakeholders (Voinov et al., 2018; Voinov and Bousquet, 2010).

The REA primarily develops the substantive function of mental model elicitation and documentation, while preserving the educational

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[1] In this study, we specifically consider the role of the instrumental function in relationship building between PM practitioners and other stakeholder groups.

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experience elicitation provides (Voinov et al., 2018; Voinov and Bousquet, 2010). However, we briefly address our participants' perceptions of the process's normative and instrumental value as well.

Substantive gain is an important output of many PM techniques, including mental model elicitation, which collect, inventory, and build knowledge relevant to a given issue, particularly in complex and data-poor contexts (Özesmi and Özesmi, 2004). Under such circumstances, stakeholder knowledge is often the best available source of information (Krueger et al., 2012; Kuhnert et al., 2010; Sutherland, 2006), hence its prior application to a variety of natural resource issues, including, fisheries stock assessment (Chrysafi et al., 2017; Haapasaari et al., 2013, 2012; Mäntyniemi et al., 2013) and Arctic oil spills (Nevalainen et al., 2018). Mental model elicitation specifically, provides substantive gain because individual stakeholders' mental models offer alternative hypotheses about a system's causal dynamics (Krueger et al., 2012) and when aggregated, allow for the co-production of systems knowledge (Olazabal et al., 2018). Stakeholder input is particularly relevant for solving high-stakes natural resource-related problems when time is limited and action cannot be delayed while more formal scientific knowledge is generated (Kangas and Leskinen, 2005; Knol et al., 2010). Moreover, mental model elicitation serves an educational function, allowing stakeholders to engage with their cognitive structures, exposing personal knowledge gaps (Kaplan and Kaplan, 1982; Zellner, 2008) and aiding the development of an integrated understanding of complex socio-ecological systems (Fortuin et al., 2011; Novak and Cañas, 2008; Smajgl and Ward, 2013). Hence, the use of mental models is commonplace in a variety of PM methods, including the development of Bayesian belief networks (Haapasaari et al., 2012; Meynecke et al., 2017; Smith et al., 2018), fuzzy cognitive maps (Olazabal et al., 2018; Özesmi and Özesmi, 2004; Solana-Gutiérrez et al., 2017), conceptual content cognitive maps (Kearney and Kaplan, 1997) and Actors, Resources, Dynamics, and Interactions models (Etienne et al., 2011; Mathevet et al., 2011). Guidelines for discerning whether mental modeling (cognitive mapping) is an appropriate methodological choice for a given study are given by Voinov et al. (2018).

Presently, stakeholders' mental models are obtained via either direct or indirect elicitation (Jones et al., 2011). During direct elicitation, participants, individually or in groups, actively create and define the structure of their models themselves, typically assisted by a facilitator and visualization tools depicting system variables and the connections between them (Dray et al., 2006; Haapasaari et al., 2012; Özesmi and Özesmi, 2004). This deliberate articulation and visualization of knowledge constitute a learning experience for participants (Marcot et al., 2001; Uusitalo, 2007). The hallmark of direct elicitation, however, is an immediate means of verifying participants' representations of their mental models (Jones et al., 2011), reducing reliance on the skill and interpretation of an analyst (Abel et al., 1998). This immediate feedback is likely why direct elicitation is more common than indirect elicitation in natural resource-related PM. Alternatively, during indirect elicitation, an analyst determines the structure of the participant's mental model based on textual information, like interview transcripts or written questionnaire responses (Carley and Palmquist, 1992; Masinde et al., 2018; Verkerk et al., 2017). However, an important and largely unexplored question is, do these techniques accurately transfer knowledge from brain to paper?

This question became important when we noticed that the mental models we documented with stakeholders during direct elicitation were simplified in comparison with their verbal descriptions, equating to a loss of potentially critical information. We suspect this was the unintentional result of time constraints and stakeholder fatigue (Burgman, 2005) coupled with the difficulty in articulating and visualizing variables and complex model structures, both on the part of the stakeholder and the PM facilitator. Hence, direct elicitation did not represent stakeholders' mental models as accurately as we would have hoped. We believed taking an indirect elicitation approach instead may have reduced simplification and subsequent information loss, as this technique allows an analyst time to carefully consider and define model variables and structure. However, this technique is also susceptible to inaccuracies, since an indirectly elicited representation of a stakeholder's mental model reflects only the analyst's interpretation of it, which may be influenced by their own biases, beliefs, and values. Besides, we were not keen to give up the educational benefits direct elicitation provides. Therefore, we propose *combining* direct and indirect elicitation methods to retain the strengths of each, while compensating for their shortcomings.

Radonic (2018) adopted a related approach in his cultural anthropological study, using audio recordings of stakeholder interviews to ensure they had succeeded in drawing the concepts vocalized during direct elicitation (Radonic, 2018). We take Radonic's approach one step further, employing indirect elicitation as a verification method for directly elicited models *and* as a measure to ensure they are represented in the same level of detail as described verbally while maintaining the stakeholder's control over their accuracy. We demonstrate that the REA reduces information loss compared to direct elicitation alone, resulting in "rich models," which are holistic depictions of stakeholder knowledge created per their understanding of the world around them.

In addition to improving the process of mental model elicitation, we also believe it is imperative to improve the documentation of PM methodologies, which is often poor or bypassed altogether in the literature (Voinov et al., 2016). Some resources provide general guidelines relevant to the PM process (e.g., Durham et al., 2014), but peer-reviewed articles describing the lessons learned from completed PM studies are few (Gray et al., 2018; Nevalainen et al., 2018) and the methodological mistakes others could learn from are rarely published (Krueger et al., 2012). Since PM methods are included in virtually all environmental modeling efforts today (Gray et al., 2018; Voinov and Bousquet, 2010), it is important to describe the techniques used to produce and analyze the results of these processes. To these ends, Gray et al. (2018) assert that despite increasing interest, PM has not been able to establish itself as a cohesive field of study owing to poor reporting and a lack of reproducibility. As a solution, they suggest the "4P framework" for reporting PM studies, which encourages documentation of (1) the purpose for choosing the PM approach (why); (2) the process used to involve participants (how); (3) the partnerships formed as a result of the PM process (who); and (4) the products resulting from the PM study (what). We are dedicated to the improvement of PM methodologies, reproducibility, and wish to promote the effective and transparent use of stakeholder knowledge in natural resource management, and as such, report our study using the 4P framework.

Therefore, the purpose of this article is to present the methodology (the REA) we used to enhance mental model richness, without sacrificing the integrity of stakeholders' ideas or their learning experience, through the combination of direct and indirect elicitation techniques. Further, we hope this article will contribute to the development of guidelines for best practices in PM, thus deepening the rigor and expanding the utility of these techniques in the scientific process.

2. The why: The effects of climate change on the salmon system

We tested the REA in the context of a problem-framing study, a process for exploring the dimensions of the problem from multiple perspectives and re-defining it to allow for the development of clearer, more mutually beneficial, and creative solutions (Bardwell, 1991). The goal of our problem-framing study was to determine the effects climate change may have on Atlantic salmon (*Salmo salar* L.) in the Baltic Sea, hereafter referred to as "Baltic salmon" and to begin to adapt salmon management accordingly. We explored this problem with expert stakeholders individually, asking them targeted questions and documenting the mental models underlying their answers. This text specifically addresses the elicitation of these expert stakeholders' mental models, not their analysis or aggregation. These steps were conducted later to produce a synthesis of these individual results, which is intended to be the first step in a multi-step modeling process to incorporate climate change effects into the pre-existing Baltic salmon stock assessment model (Michielsens et al., 2008). The results of this model form the basis of the International Council for the Exploration of the Seas' (ICES) fishery management advice to the European Union (Kuikka et al., 2014). Here we provide the context, which prompted us to begin our study.

Baltic salmon management has been a priority since the formation of the internationally adopted "Salmon Action Plan" in 1997, implemented in response to severe population declines, attributed largely to decades of overfishing (Romakkaniemi et al., 2003) and reduced access to spawning rivers (Romakkaniemi et al., 2003). In recent years, however, salmon populations have rebounded and fish have been observed returning in increasing numbers to many of their traditional spawning grounds (HELCOM, 2011; ICES, 2018; LUKE, 2016). Nevertheless, Baltic salmon are still considered vulnerable (HELCOM, 2013). Therefore, continued management efforts to support the long-lasting sustainability and recovery of salmon stocks in the Baltic Sea are imperative, including prompt action to address existent and emerging threats.

While many factors, like overfishing (Romakkaniemi et al., 2003), reduced access to spawning rivers (Romakkaniemi et al., 2003), changing food web dynamics, and nutrient deficiencies (Ejsmond et al., 2019; ICES, 2018) are already understood to affect salmon, climate change presents a new challenge for these fish, since this phenomenon is expected to bring substantial change to the Baltic Sea environment (Graham, 2004; HELCOM, 2013; Reusch et al., 2018). Though articles discussing the effects of these changes on Baltic salmon are limited, a tentative link between these fish and climate change has been established (Huusko and Hyvarinen, 2012; Jokikokko et al., 2016; Jutila et al., 2005; Kallio-Nyberg et al., 2004; Russell et al., 2012). Nevertheless, the causal mechanisms by which climate change is likely to impact Baltic salmon are under-researched at present.

Therefore, we believe it is critical to develop a better understanding of the ways in which climate change may affect or may already be affecting Baltic salmon and their fishery, to better direct further research, explore management goals and strategies, and to begin the process of incorporating these effects into ICES' existing stock assessment model as expediently as possible. Although climate change is by no means the only factor influencing Baltic salmon populations, incorporating its effects into ICES' model is a step towards ensuring stock estimates are realistic and that they thereby assist in producing reasonable management recommendations. The results of this problem-framing can also help kick-start a conversation about the impacts of climate change on salmon, how management goals and strategies may need to be reassessed considering these changes, and the importance of including this issue in a new long-term management plan for Baltic salmon stocks. Additionally, since the research linking climate change and Baltic salmon is limited, it is worthwhile to develop a holistic understanding of the intertwined social and ecological systems linking climate change, salmon, and their fishery, as changes in salmon populations are likely to cascade, impacting other species, the environment, and human society. This task is time-sensitive and research about the topic is lacking. Therefore, we identified PM, specifically mental modeling, as an appropriate strategy to develop a knowledge base about the effects of climate change on the "salmon system."

3. Who & how: Eliciting & documenting mental models via the Rich Elicitation Approach

To build our knowledge base about the salmon-climate change problem, we elicited stakeholders' mental models and documented them as influence diagrams using the REA approach, illustrated in Fig. 1. Here, we describe our experience conducting this process, although we expect that the REA will be adapted to suit the specific contexts where it may be applied in the future (Voinov et al., 2016). Those interested in implementing the REA should consult both this section of the text *and* the discussion section for guidance.

3.1. Preparation

3.1.1. Stakeholder selection

We included only expert stakeholders, hereafter referred to as "stakeholders," in our study, since domain-specific knowledge enhances mental model richness (Nersessian, 2002). The distinction between experts, stakeholders, and expert stakeholders is presently fuzzy within the PM literature (Krueger et al., 2012). However, we consider expert stakeholders to be individuals encompassing both the concept of expert, defined by extent and depth of their experience (Fazey et al., 2006), and stakeholder, broadly considered to be those who influence or are influenced by the research in question (Durham et al., 2014). We considered stakeholders working with salmon and salmon issues, either professionally or as part of a registered leisure organization, like angling clubs, to be sufficiently experienced to be considered experts. Although we determined expert stakeholders to be the correct group to engage for this PM process, we recognize that salmon are a common-pool resource, managed for the benefit of society and the environment. As such, engaging non-expert stakeholders should also be considered at appropriate points in the salmon management process.

We identified stakeholders to participate in our study via snowball sampling (Browne, 2005). First, we reached out to our contacts whom we considered to be Baltic salmon experts based on their contributory and interactional expertise (McBride and Burgman, 2012). Then, we asked them to pass on our request for participation to others who might be interested and fit our criteria.

The 11 stakeholders who chose to participate described their salmon expertise in a variety of contexts and came from a diversity of organizations, including a transnational management agency, a government ministry, a university, three county management agencies, and five non-government organizations (see Table A1). Only stakeholders working in Finland and Sweden were asked to take part, as the majority of Baltic salmon production occurs in these two countries (ICES, 2018). To protect our participants' privacy, they were randomly assigned a letter pseudonym from A-K, e.g. "stakeholder K."

3.1.2. Facilitator learning

Before the direct mental model elicitation sessions, hereafter referred to as "elicitation sessions," mock sessions were conducted to help the facilitator develop the skills needed to elicit and document mental models. Afterward, we revised the elicitation session protocol and questionnaire per the mock participants' comments and critiques.

3.2. Direct mental model elicitation sessions & administering the questionnaire

Elicitation sessions were semi-structured and one-on-one between a facilitator and stakeholder, lasting approximately 2 h each. We chose to conduct elicitation sessions individually because we were interested in aggregating the thoughts of individuals, rather than producing a single collective response. The rationale behind this decision was to avoid the influence of perceived normative pressures (Heeren Alexander et al., 2016) on the stakeholders' depictions of their mental models, or over-representing the views of the most influential stakeholders (Burgman, 2005; Martin et al., 2012). Stakeholders were asked to describe their own beliefs rather than attempting to represent those of their organizations and audio was recorded throughout the duration of each session.

3.2.1. Stakeholder learning

At the beginning of their elicitation session, the stakeholder was asked to describe their career background and interests related to salmon. Next, the facilitator prepared the stakeholder for the task of representing their mental model as an influence diagram (Haapasaari et al., 2012), by explaining how to interpret and visualize them in this format, using simple examples (Fig. 2).

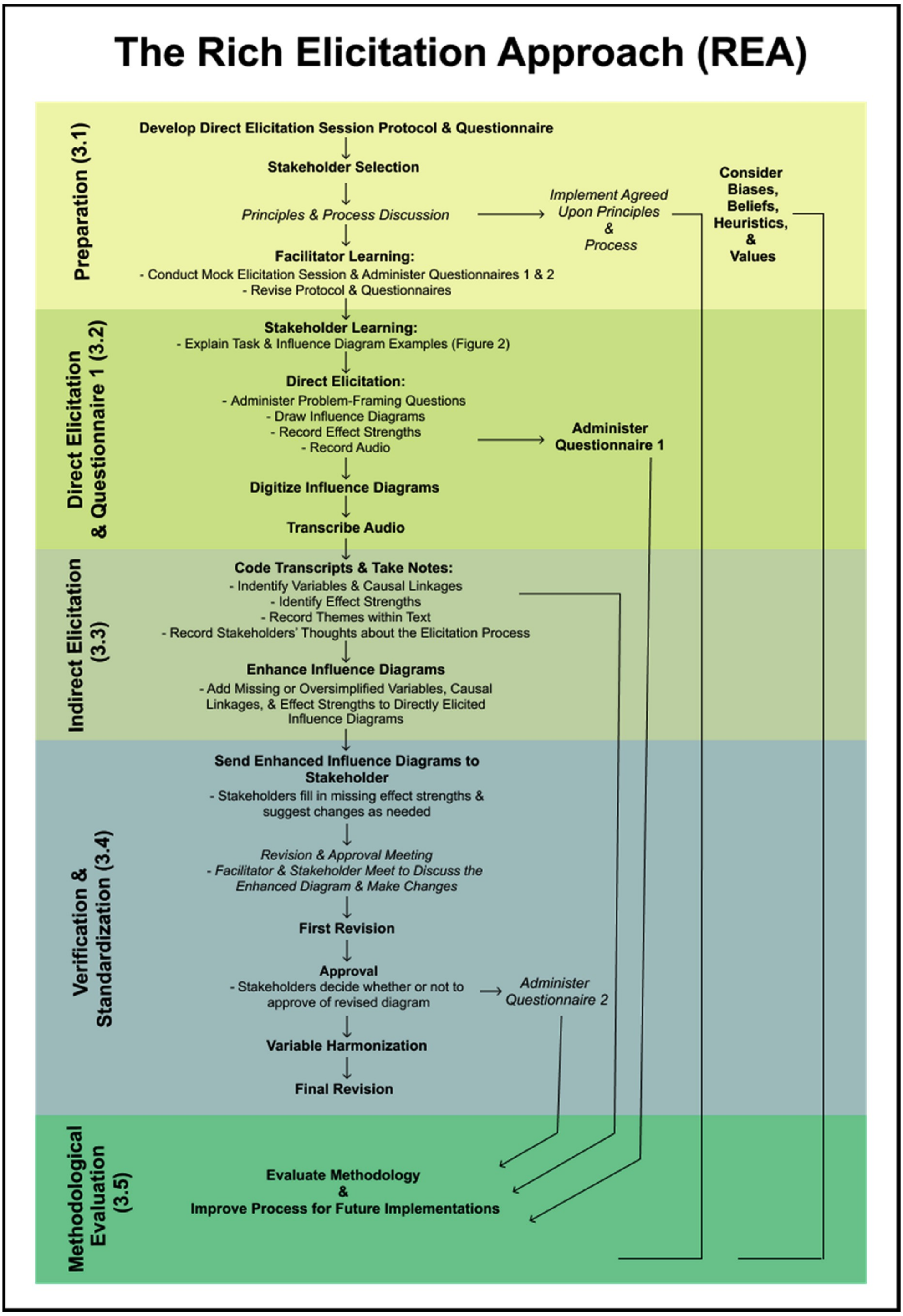

Fig. 1. Schematic diagram representing the Rich Elicitation Approach (REA) from beginning to end. The bolded text represents the steps we carried out during our implementation of the REA and italicized text represents steps we recommend adding for future use (see discussion).

Influence diagrams include three variable types: uncertain variables, actions, and personal valuation of the outcomes (goals) (Haapasaari et al., 2012). These variables are then connected with arrows representing the causal relationships between them and the direction of the effect (Haapasaari et al., 2012). Influence diagrams include personal uncertainty about these relationships, expressed as degrees of belief, which are elicited either qualitatively (Haapasaari et al., 2012; Varis and Fraboulet-Jussila, 2002; Varis and Lahtela, 2002) or quantitatively as joint probability distributions (e.g. Mäntyniemi et al., 2013). By eliciting quantitative degrees of belief, influence diagrams are easily transformed into risk assessment models (Haapasaari et al., 2012), however, for problem-framing, we chose a qualitative approach, representing uncertainty by the thickness of the arrows drawn between variables (with thicker arrows representing more certain relationships). Whether quantitative or qualitative, model building, as influence diagrams or otherwise, is a useful tool to encourage participants to think deeply and clearly articulate their thoughts (Lynam et al., 2007; Marcot et al., 2001; Uusitalo, 2007).

3.2.2. Direct elicitation

During the elicitation session, the facilitator asked the stakeholder to consider three primary problem-framing questions, adapted from those used by Haapasaari et al. (2012):

1) What variables and causal relationships do you think should be considered when determining the impacts of climate change on Baltic salmon and their associated fishery?
2) What goals do you have for salmon and their fishery in the future considering climate change?
3) What management strategies or actions can be undertaken to achieve those goals?

The purpose of the first question was to elicit the stakeholders' mental models of both the direct and indirect cause and effect relationships between salmon, the environment, society, and climate change. The second explored these mental models further, eliciting the future outcomes the stakeholders hoped to see for salmon, highlighting the perceived value of this species, it's utility, and the importance of addressing the issue of climate change. We asked the final question to identify human actions that stakeholders believed affect or could affect the achievement of these goals. These questions were reiterated as needed over the course of the elicitation session. Other questions asked by the facilitator were meant to provide clarification, keep the session on task, or prompt discussion while influencing the stakeholder as

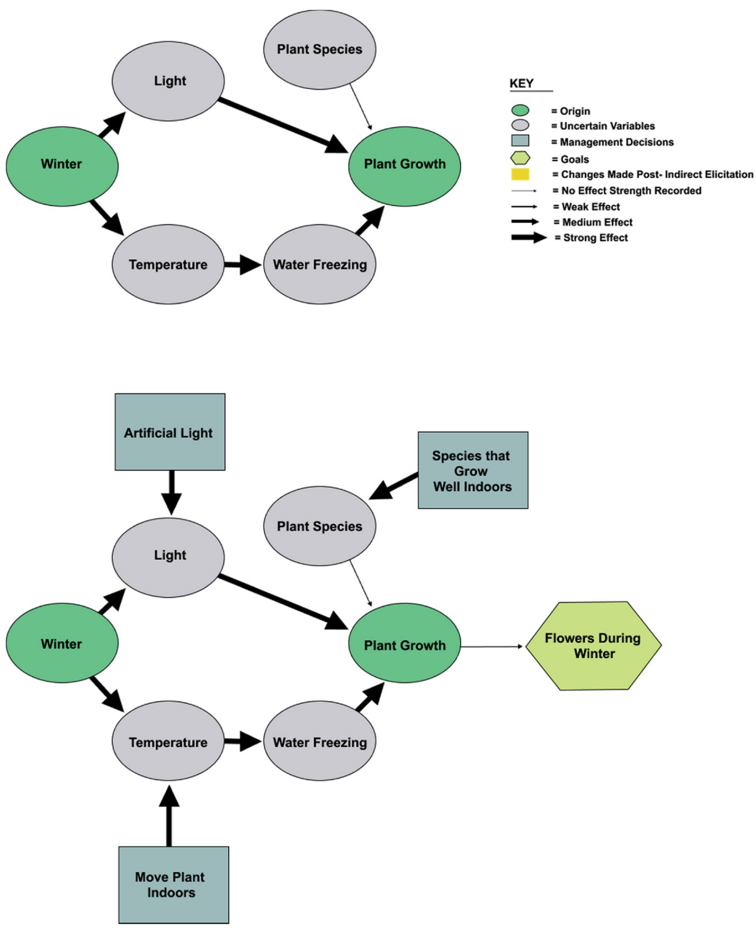

Fig. 2. The influence diagram examples used as learning aids at the beginning of each elicitation session. These diagrams are intended to represent the effects the winter season (in the Baltic Sea area) has on plant growth. The first diagram includes uncertain variables only. The second includes action and goal variables as well.

minimally as possible.

As a starting point for their influence diagrams, we gave the stakeholders one variable, climate change. We also provided them with a core biological model (Fig. A1) originally developed to depict the annual stock dynamics of Central Baltic herring by Haapasaari et al. (2012). Its inclusion in their diagrams was optional. The rationale behind providing this model was to give the stakeholders some sense of the types of connections that could be drawn between different aspects of the salmon life history and the fishery system, and to provide a starting point for idea generation. At the time, we believed the herring model was general enough to be repurposed for this use and vague enough to avoid the anchoring effect (Oppenheimer et al., 2008; Tversky and Kahneman, 1974).

The influence diagrams were hand-drawn on large sheets of paper and stakeholders chose to either draw the diagrams themselves or allow the facilitator to draw. When the facilitator was responsible for drawing, she encouraged the stakeholders to explicitly describe the relationships between variables, frequently reminded them to interject if the influence diagram was not drawn according to their beliefs, and regularly confirmed the model's accuracy.

After defining the system variables and the structure of their influence diagrams, stakeholders were asked to express the certainty or "strength" of the relationships between variables as either (1) weak, (2) medium, or (3) strong. Recording these "effect strengths" was the last step in the elicitation process, to avoid disrupting the stakeholders' flow of thoughts as they constructed their models.

3.2.3. Administering the questionnaire

Following each elicitation session, we sent the stakeholder a link to an online questionnaire created on the SurveyPlanet© (https://surveyplanet.com/) website. The questionnaire included questions intended to (1) contextualize thestakeholders' perceptions of the salmon-climate change problem, (2) determine the utility of problem-framing and the elicitation process, and (3) assist in improving future elicitations. The questions were asked in multiple-choice, scoring, and short answer formats. Most multiple-choice and scoring questions were followed by space for the stakeholders to elaborate if desired. Unexpectedly, SurveyPlanet recorded multiple values when a stakeholder chose to change their answer. In these cases, it was impossible to distinguish their final choice and therefore, we report the average of the two answers. Stakeholders could skip questions they did not wish to answer. All responses were anonymous, except for one stakeholder who completed the questionnaire in paper form and therefore, that stakeholder's responses were not anonymous to us.

3.2.4. Digitizing influence diagrams

Once the elicitation sessions were completed, the facilitator digitized each hand-drawn influence diagram using GeNIe 2.0 Academic software (BayesFusion, LLC).

3.3. Indirect elicitation

3.3.1. Transcription, note taking, & coding

To begin the indirect elicitation phase of our study, the audio recording from each elicitation session was transcribed. Then, the analyst read and coded each transcription, categorizing passages as variables within the salmon system, causal linkages between them, effect strengths, or remarks about the elicitation session itself. Additionally, the analyst recorded two sets of notes on each transcription, hereafter referred to as "elicitation notes (A) and (B)." (A) documents the stakeholders' comments during the elicitation session about the activity itself, major themes described during the session, and novel ideas about either the elicitation process or the effects of climate change on salmon. (B) documents the stakeholders' predictions about how climate change will affect Baltic salmon and their associated fishery, which are not necessarily reflected by their influence diagrams. These notes were used for two purposes: (1) to analyze and improve the elicitation process and (2) to supplement problem-framing analysis later.

3.3.2. Enhancing influence diagrams

Following coding, each directly elicited influence diagram was "enhanced" by restoring all the variables and causal relationships that had been described verbally by the stakeholders during the elicitation session, but which were later identified by the analyst as missing or oversimplified upon inspection of the coded transcripts and elicitation notes (A).

3.4. Verification & Standardization

3.4.1. Sending enhanced diagrams for stakeholder approval & first revision

Once the enhanced versions of the influence diagrams were completed, they were sent back to the stakeholders via email for their approval and to ensure the analyst had represented their beliefs accurately. The stakeholders were given a deadline to contact the analyst to express their approval or disapproval of the diagrams and describe any changes they wished to make. They were explicitly instructed that no response would be interpreted as their approval. Additionally, stakeholders were asked to provide effect strengths for any new causal linkages included in their influence diagram or original linkages that had not been assigned a strength during the elicitation session. After the allotted time had passed, any corrections the stakeholders indicated were addressed by the analyst and the influence diagrams were revised.

3.4.2. Variable harmonization & final revision

Next, variables included in the influence diagrams were harmonized at the analyst's discretion, as was done in Martinez et al. (2018) and Olazabal et al. (2018), as stakeholders often articulated the same concepts in slightly different terms. For example, "how warm the river is" and "the temperature of the river" were both changed to "temperature: river." After harmonization, the influence diagrams were revised a final time to reflect these changes.

3.5. Methodological evaluation

An evaluation of our methodology's performance was conducted in two parts. First, we analyzed the REA's ability to produce richer depictions of stakeholders' mental models. We compared the number of variables and causal relationships included in the influence diagrams produced via direct elicitation alone with their final versions, completed after indirect elicitation, verification, and standardization. In addition to interest in producing richer, more accurate mental models, we also believe that by taking note of stakeholders' experiences and suggestions, we can improve the process of mental model elicitation, leading to better results in the future. Therefore, for the second stage of our methodological evaluation, we consulted select questionnaire questions and elicitation notes (A) to assess how well the stakeholders felt the approach addressed the four functions of PM. Additionally, we used the stakeholders' comments and recommendations extracted from the coded transcriptions and the facilitator's observations to identify areas for methodological improvement and suggest solutions. The results of the methodological evaluation of the REA will be the focus of the remainder of this article.

4. The what: study results

4.1. Comparison of influence diagrams post-direct elicitation versus post-REA

The REA produced richer representations of stakeholders' mental models than direct elicitation alone. Following the REA, the stakeholders' diagrams contained more variables and causal relationships. See Table 1 for a numerical comparison of the influence diagrams post-direct elicitation versus post-REA and Fig. 3 for a visual comparison.

4.2. Evaluation of the elicitation process

Table 2 summarizes the stakeholders' responses to the questionnaire questions concerning their perceptions of the mental model elicitation process and its ability to fulfill the four functions of PM. Although their responses varied, they generally found the process useful for fulfilling these functions. They were most convinced that mental model elicitation offers substantive and educational gains, with the clear majority recording the highest or second-highest score in favor of these capabilities. The stakeholders were less certain, however, about mental model elicitation's normative and instrumental value. Their opinions spanned from negative to positive for most questions in these categories (see Table 2). However, the stakeholders would, in general, feel more satisfied with management decisions if their influence diagrams were considered during the decision-making process (normative), exemplified by majority reporting scores of ≥4. When asked whether mental model elicitation could be useful in reaching consensus about how to manage the fishery (instrumental), the majority of stakeholders reported scores of ≥4. The second instrumental function question received the highest number of negative responses; when asked if they would feel more invested in the scientific process by attending problem-framing events with researchers (instrumental), three stakeholders responded with a score of ≤2, two with non-committal 3s, and six with scores of ≥4.

The general positive attitude toward mental model elicitation was reflected in the elicitation notes (A) as well, with several stakeholders remarking that they found the process interesting. Two stakeholders asked to take pictures of their influence diagrams to show colleagues and one later enquired about facilitating a group mental model elicitation for problem-framing about another topic. One stakeholder mentioned that the elicitation process helped him think deeply about his ideas, specifically in response to the facilitator's question about why biodiversity is important, intended to encourage him to clarify his thoughts for the influence diagram.

During the elicitation sessions, the majority of stakeholders quickly understood the process of creating influence diagrams. Only three expressed some uncertainty or difficulty beginning the task. This challenge was largely overcome, however, since the majority of stakeholders preferred to allow the facilitator to draw. Three suggested both they and the facilitator should contribute. While the facilitator was drawing the diagram, some stakeholders were highly engaged in ensuring their thoughts were represented accurately, providing detailed instructions about how the diagram should be drawn. Others were more interested in verbalizing their thoughts than documenting them on paper.

The core biological model (see appendix) seemed to be of little interest to the stakeholders. Three stakeholders mentioned they felt it might be useful and wished to keep it on hand as reference material. However, only one stakeholder incorporated a portion of the model into his influence diagram.

Understanding how to document the strengths of the effects between variables proved to be a more conceptually challenging task than understanding how to draw influence diagrams. Two stakeholders wondered whether the effect strengths should be considered in isolation, concentrating on only the strength of the effect between one variable and another, or whether an entire causal pathway with several connected variables should be given the same effect strength. In such cases, the stakeholders were advised to concentrate on individual linkages between two variables. There was also some concern over the relative proportions of the three types of effect strengths. One stakeholder wondered whether there should be 33% of each strength category included in the diagram. Some also questioned whether it was appropriate to include a greater proportion of one strength than the others. Based on the stakeholders' comments, it is also apparent that the effect strengths represented their level of certainty about the relationship between two variables, as intended, *but also* perhaps their perceived importance of the relationship. When questioned about his reasoning behind his assignment of effect strengths, one stakeholder stated the weak effect strengths represented relationships he was uncertain of. Another mentioned, however, that a strong effect represented established knowledge and also signified that the relationship was important. Two stakeholders chose not to include effect strengths in their diagrams at all. While one did not give a reason for this, the other was too fatigued after creating the influence diagram to continue with the effect strengths as well.

Many stakeholders felt uncomfortable with the uncertainty inherent in the complex interactions between climate change, salmon, and society. Some also found the scope of the problem difficult to grapple with. These issues were reflected in one stakeholder's comment that "there are factors (related to the effects of climate change on the salmon system) that we cannot even begin to speculate about" and another stated that "there are so many dependencies and feedbacks that I find it difficult to write down." Phrases like "I guess" and "I don't know" were very common throughout the elicitation sessions. This uncertainty promptedthe facilitator reassure the stakeholders and remind them that they were not expected to produce a correct diagram, but rather one reflecting their own best judgments.

Several stakeholders acknowledged the complexity of the influence diagrams as the elicitation sessions progressed, most commonly by indicating that they felt the diagrams were "messy." Two stated their unease with the complexity of the maps more explicitly. One jokingly commented, "there might be too much information (in the diagram)" and another indicated that portions of his diagram had become confusing due to the number of causal linkages.

The facilitator also remarked that the stakeholders may have altered their description of their mental models in response to her background credentials. For example, some stakeholders meticulously described the

Table 1
The number of variables and causal relationships included in each stakeholder's influence diagram before and after enhancement via indirect elicitation.

Stakeholder Alias	Variables Pre-Transcription	Variables Post-Transcription	Causal Relationships Pre-Transcription	Causal Relationships Post-Transcription
A	21	101	24	138
B	11	69	14	98
C	33	85	43	173
D	49	63	90	143
E	22	48	24	69
F	28	39	40	60
G	26	110	41	235
H	49	127	75	195
I	30	83	37	118
J	26	80	36	117
K	47	107	72	151
Total:	**349**	**893**	**496**	**1472**

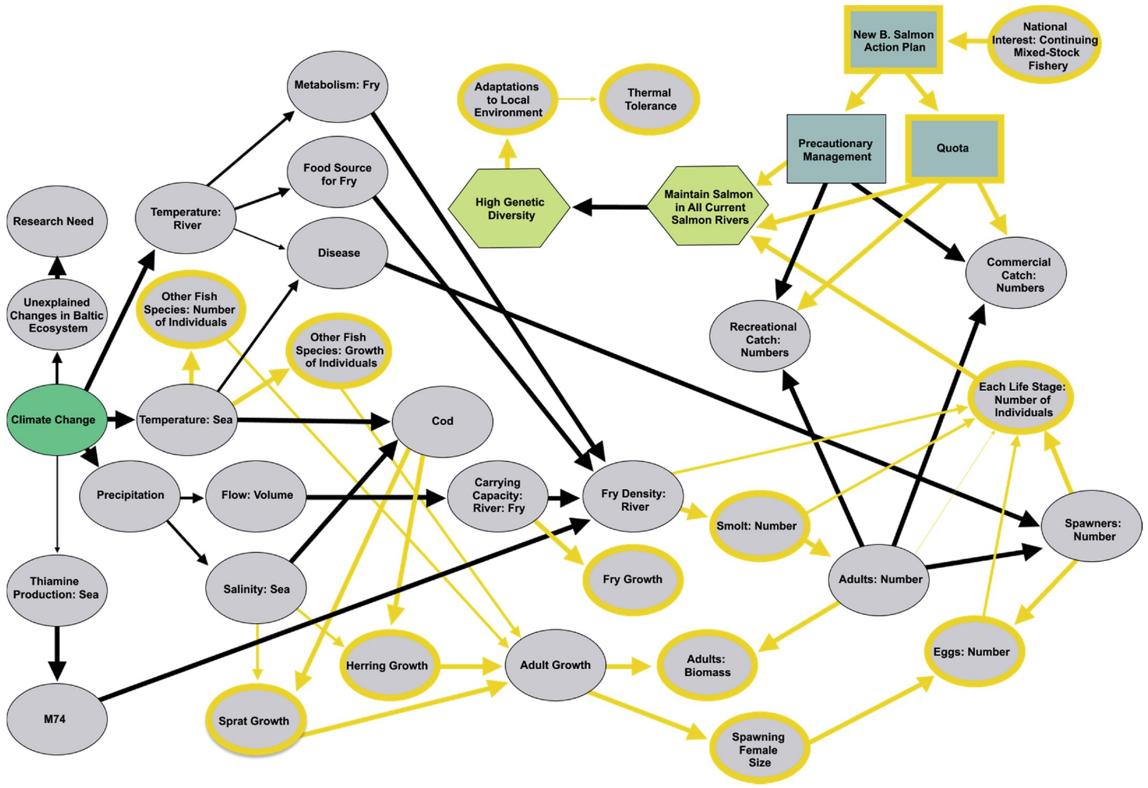

Fig. 3. An example of one stakeholder's influence diagram after direct elicitation alone, versus after the complete REA process. The variables and effect strengths highlighted in yellow indicate where changes were made during indirect elicitation. See Fig. 2 for the key. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

salmon lifecycle when they assumed the facilitator to be a non-expert, but became less explicit about perceived areas of common knowledge after asking about her educational background and work experience in fisheries science.

After the enhanced versions influence diagrams were sent back to the stakeholders (Fig. 1), only two responded. One stakeholder remarked that the new diagram looked "complicated" and he trusted our judgment to represent his thoughts accurately. A second completed the task in its entirety, returned the diagram with most of the effect strengths filled in and confirmed his approval of the enhanced diagram. The remaining nine stakeholders chose not to respond to our inquiry, thereby tacitly giving their approval. One stakeholder contacted us about completing the task after the allotted time but never submitted any requested changes.

5. Discussion

5.1. Rich representations of stakeholders' mental models

Demonstrated by the clear increase in the number of variables and causal linkages included in the stakeholders' influence diagrams after implementing the REA, coupled with our process to ensure all their articulated thoughts were documented clearly, leads us to conclude that the REA was successful in producing richer models. We believe this increase in detail equates to more accurate depictions of stakeholders' thoughts, allowing us to take fuller advantage of the valuable knowledge they possess. In short, the REA improves the transfer accuracy of mental models from brain to paper, making a more complete depiction of stakeholders' knowledge accessible. As such, we suggest rich models are useful in the development of a holistic knowledge base from which to begin comprehensive PM studies on complex knowledge-limited socio-ecological systems.

Although the REA provides methodological advancements intended to reduce *unintentional* model simplification, we argue a paradigm shift is also necessary to reduce premature *intentional* simplification. Typically, studies using *either* direct or indirect elicitation methods contain relatively few variables and causal relationships, indicating that needless simplification and subsequent information loss may be widespread in mental model elicitation of both types.

Purposeful simplification may be driven by adherence to a "simpler is better" mindset, analytical and technological constraints, or a lack of resources needed to conduct in-depth and time-consuming studies (Kuparinen et al., 2012). The merit of the simpler is better mindset is often attributed to the principle known as Occam's razor. However, the principle states, "entities should not be multiplied without necessity" (Schaffer, 2015). As such, the definition of necessity dictates when and where Occam's razor should be applied. Here, the objective is to gather a holistic picture of potentially important social and environmental factors according to a set of stakeholders. The diversity and depth of thought they provide useful for informing the models and the problem-framing results we use to better understand and develop solutions to complex and poorly understood socio-environmental issues. In this sense, the acquisition of holistic mental models is necessary to develop the broad and comprehensive knowledgebase this task requires.

Table 2
Stakeholder responses to relevant questionnaire questions. The questions are grouped into four categories: substantive function, normative function, instrumental function, and educational function, based on the four functions of PM. Stakeholders provided a ranking between 1 and 5 for each question according to a scale where 1 = *No, definitely not* and 5 = *Yes, definitely*. *NR* = *No response.* X represents one stakeholder's response. The term "mind mapping" is analogous to "mental model elicitation."

	Score:	NR	1	1.5	2	2.5	3	3.5	4	4.5	5
Substantive Function	*Could mind mapping be useful in solving fisheries related problems?*				X		X	X	XXXXX		XXX
	Do you believe the results of mind mapping exercises with salmon fishery stakeholders would be valuable to decision-makers when determining how to manage the fishery?		X		X				XXXXX		XXXX
Normative Function	*Should the results of stakeholder mind mapping activities be used to help determine future goals for the salmon fishery?*	XX	X				XXX		XX		XXX
	Would you feel more satisfied with management decisions if the results of stakeholder mind mapping activities were considered during the decision-making process?				X		XXX		XXXX		XXX
	Would sharing the results of stakeholder mind mapping activities with decision-makers help ensure stakeholder values are represented in the decision-making process?				XX		XXXX		XX		XXX
Instrumental Function	*Would mind mapping be useful in reaching consensus about how to manage the fishery?*				XX		XXX		XXX		XXX
	Would attending stakeholder mind mapping events with researchers who give recommendation for salmon fishery management make you feel more invested in the scientific process?		X		XX		XX		XX	X	XXX
Educational Function	*Was this experience helpful in organizing your thoughts and opinions about salmon and climate change?*				X		X	X	XXXX		XXXX

From this perspective, everything a stakeholder says *is* necessary and should not be discarded on grounds of artificial preference for simpler explanation or practicality. Therefore, we urge PM practitioners to alter their perception that simpler is always better and to do their best to meet the practical demands of studying complex systems. After all, "To keep every cog and wheel is the first precaution of intelligent tinkering" – Aldo Leopold (1972).

5.1.1. Rich mental models & their applications in environmental modelling & problem framing

Environmental modeling processes begin with perceptual models, which are systematic and qualitative representations of reality, analogous to the mental models discussed here (Beven, 2009). These perceptual models are later simplified and abstracted to accommodate the terms of mathematics and coding (Beven, 2009). Since necessary simplification is built into the modeling process, which should be deliberate and iterative by default (Jakeman et al., 2006), a rich perceptual model should not hinder later stages of the model development process. Additionally, it is more practical to reduce a rich model than to return to stakeholders later to develop a wider knowledge base if new ideas, hypotheses, and potential solutions are required. We posit that if care is taken to ensure mental models are elicited from truly expert stakeholders dedicated to the success of the PM project, richer models may provide a more realistic understanding of complex natural resource problems. Improving realism is frequently considered a goal of environmental modeling (Aben et al., 2016; Kuparinen et al., 2012), since improved realism equates to a more accurate representation of the world and therefore, improved model performance. Kuparinen et al. (2012), illustrate the necessity of model realism in the context of fisheries stock assessment models, notorious for their lack of biological realism and tendency to neglect relevant information. As a result, these models have frequently failed to provide adequate population dynamics information, contributing to stock collapse.

Problem-framing, which may be used to develop perceptual models at the outset of environmental modeling processes (Haapasaari et al., 2013, 2012), is intended to develop a holistic understanding of a problem to best direct problem-solving (Bardwell, 1991) in the research, policy, management, and risk assessment arenas. As Özesmi and Özesmi (2004) suggest, the more comprehensive the understanding of a problem is, the more interventions that can be identified and explored. Since mental model elicitation is often included in problem-framing, it is imperative to elicit rich mental models to ensure a more detailed understanding of the issue at hand, reducing the chance that important aspects are overlooked.

In addition to the sources of simplification described, simple mental models may also indicate poorly informed stakeholders, since learning domain-specific information is linked with increased model richness and reasoning capabilities (Kinchin et al., 2000; Nersessian, 2002). However, this is a question of stakeholder selection and beyond the scope of this article.

5.2. Fulfilling the functions of PM

Based on the feedback the stakeholders provided, they were interested in the elicitations sessions and building their influence diagrams, found the topic relevant, and felt that the incorporation of their influence diagrams (i.e. knowledge) into the fishery management process could substantively aid in problem-solving and decision-making. Although their perceptions of elicitation and more generally, problem-framings' normative and instrumental value were more mixed, their generally positive responses do suggest these methods hold value in these domains.

The stakeholders' overall positive response to the questionnaire's learning-related question and their comments about how building influence diagrams made them think deeply about their beliefs suggest direct elicitation was a valuable learning experience. This finding is consistent with existing literature documenting the value of mental models in scientific and environmental education (Fortuin et al., 2011; Kinchin et al., 2000). We believe this provides a clear rationale for the direct elicitation phase of the REA, further excluding the option of performing indirect elicitation alone.

5.3. Methodological considerations

5.3.1. Improving stakeholder response rate to enhanced influence diagrams

Despite the REA's successes, post hoc analysis of its implementation indicated potential areas for improvement. One of the most concerning issues was the low response rate we received when we requested that stakeholders review, revise, approve, and include missing effect strengths in the enhanced versions of their influence diagrams (verification stage in Fig. 1). By providing stakeholders with this opportunity for revision, we intended to reduce misinterpretations of their thoughts made by the analyst following indirect elicitation (Abel et al., 1998). We suspect the low response rate resulted in part from our choice to communicate remotely, via email, which often leads to poorer response rates than face-to-face communication (Kuhnert et al., 2010; Nevalainen et al., 2018). The complexity of the enhanced influence diagrams may have also made the task of assessing them and providing missing information seem daunting and time-consuming. A general lack of commitment to the project may have also been at play if the stakeholders felt burdened by the collaboration process or uncertain about its real-world value and impact (Bracken et al., 2015). The long gap in time between the elicitations sessions and the delivery of the enhanced models to the stakeholders may have also been to blame for their disengagement in the final stages of the REA.

To rectify this issue, we suggest discussing expectations for the elicitation processes thoroughly with prospective participants before beginning the study. We also recommend clearly explaining the importance of the stakeholders' role in the study, its implications for the natural resource they and PM practitioners are mutually invested in, and adhering to a pre-determined schedule for interactions with the stakeholders (Fig. 1). This way they will clearly understand what the study will require of them before committing and be fully aware of the real-world impacts of their involvement. Additionally, we propose a second face-to-face meeting between the stakeholder and facilitator after indirect elicitation to assist with the process of correcting and completing the enhanced diagrams to reduce confusion and frustration with the task Fig. 1).

5.3.2. Coping with complexity, uncertainty, & "messiness"

Another important consideration for future use of the REA is coping with the messiness and uncertainty inherent in describing the cause and effect structure of complex socio-ecological systems. The influence diagrams' messiness, which troubled some stakeholders, could be reduced by creating them digitally during direct elicitation. However, this tactic may reduce the ease and accessibility that drawing by hand provides. Additionally, it is logical that the complexity of a well-informed expert stakeholder's mental model would reflect the complexity of the socio-ecological system in question. As such, when the goal of elicitation is to preserve the details of stakeholders' complex mental models, as it is in the REA, some degree of messiness is unavoidable.

The discomfort with messiness, however, may have been less to do with the actual organization of the figures and more to do with complexity itself. The complexity of the salmon system adn the effects climate change has on it seemed to be the source of the uncertainty, which caused nearly all the stakeholders to express concern about the validity of their ideas. When stakeholders question their ability to provide accurate information, they should be encouraged to speak freely and contribute their ideas to the best of their ability despite their uncertainty. Since expert knowledge is likely the best source of information when access to more traditional forms of data is unavailable, their opinions are valuable (Kuhnert et al., 2010; Sutherland, 2006).

During his elicitation session, one stakeholder suggested that asking participants only about issues directly related to their fields of expertise may go a step beyond encouragement to help them feel more competent and confident in expressing their ideas. Firstly, he suggested that since climate change is highly complex and predicting its effects on the abiotic environment is generally not directly within the knowledge domain of salmon experts, it may help to provide a specific climate change scenario and subsequent abiotic effects at the outset of the elicitation process. This would allow stakeholders to focus on what they know well: how the abiotic environment affects fish, the biological community salmon are embedded within, and the downstream impacts on the socio-economic system. Taking this idea a step further, he suggested the creation of an aggregated model of the salmon-climate change system developed by combining the knowledge of a variety of experts, each specializing in one portion of the system. Although this may be the best possible way to produce the most thorough depiction of the system, as Burgman (2005) writes, "(modeling is a) balancing act between keeping experts within their domain of knowledge and putting aside sufficient time for the elicitation process." In short, such an effort may require more time and effort than is feasible for practical reasons, like budget restrictions or the timeline of the political decision-making process.

5.3.3. Representing mental models as influence diagrams

In addition to the issues mentioned above, several small improvements should be made to the REA's direct elicitation phase (Fig. 1) based on our experience. Firstly, the mild confusion expressed by some stakeholders about how to draw influence diagrams could be corrected by spending more time teaching them to express their thoughts in this format. Perhaps the facilitator could coach stakeholders to develop this skill through practice with a simpler and more straightforward subject. Facilitators should consider this tactic when stakeholders directly express confusion or ask the facilitator to draw their map without explaining why they prefer this arrangement. The high percentage of stakeholders who preferred to allow the facilitator to draw could be linked with discomfort in visualizing mental models as influence diagrams. Stakeholders must develop enough competence with this process to interject if they feel their views have been misrepresented.

Since there was some confusion surrounding the concept of effects strengths and how to assign them, we suggest describing this more thoroughly during the stakeholder-learning portion of the elicitation sessions (Fig. 1). Additionally, many stakeholders did not assign effect strengths to their models or did not complete the task, presumably since the demanding modeling process exhausted them (Burgman, 2005). This issue could be corrected by incorporating more breaks into the elicitations sessions, breaking it into multiple sessions, or recording effects strengths throughout the diagramming process, rather than leaving the task until the end. Assigning effects strengths at the end of the elicitation sessions may be preferable, however, because stakeholders may fatigue before completing their model's structure, which is likely more detrimental than missing effect strengths.

5.3.4. Coping with biases, beliefs, heuristics, & values

Other considerations for future users of the REA are the biases, beliefs, heuristics, and values (BBHVs) of both participants *and* modelers, which are inherent in every PM process and shape their outcomes (Glynn et al., 2017; Hämäläinen, 2015). Left unchecked, BBHVs can diminish the rigor and credibility of the scientific process (Glynn et al., 2017). Therefore, PM practitioners must recognize the influence BBHVs exert on their studies and their origins, which are not only the study's participants but also themselves (Glynn et al., 2017; Hämäläinen, 2015). To these ends, PM practitioners should introspectively evaluate how their own preferences, values, and motivations may affect a project from its inception to the publication of its results, in addition to how the participants' do. Further, a PM practitioner's BBHVs may affect the participants' behavior (Slotte and Hämäläinen, 2015). Therefore, all conscience PM practitioners must acknowledge the problems BBHVs pose and strive to reduce their influence where appropriate (Hämäläinen, 2015).

To aid in this pursuit, all PM practitioners should familiarize themselves with the BBHV literature when planning a PM study. Seminal works regarding BBHVs include Kahneman (2011); Kahneman and Tversky (2012), 1979; Tversky and Kahneman (1981), 1974. Glynn (2014), 2017; Glynn et al. (2017); Hämäläinen (2015); Voinov et al. (2016) describe BBHVs in the context of natural resource-related PM. While a robust understanding of this field will assist PM practitioners in anticipating and therefore, mitigating the effects of BBHVs, their consideration should not end with the preparation phase of the REA but should continue throughout the project (Fig. 1).

While conducting elicitations using the REA approach, we addressed the potential effects of BBHVs during all its steps, from Preparation to Verification & Standardization (Fig. 1). During Preparation, we carefully considered the wording of the three problem-framing questions (see section 3.2) and the questionnaire, and later discussed and revised them per the suggestions made by our test participant. We did this to reduce framing biases (Tversky and Kahneman, 1981), which may have caused us to unintentionally lead stakeholders to respond in a manner supporting our own beliefs about the effects of climate change on salmon. We were also careful not to include leading information in our communications with the stakeholders before the study, discussing only the necessary logistics information, our justification for contacting them, and minimally stating the topic we planned to discuss.

Nevertheless, our study's focus on the effects of climate change may have itself introduced a framing bias, implying that climate change does indeed impact these fish. To control for this potential bias, however, we included questions 6–11 in the questionnaire (see appendix), which were intended to gauge whether the stakeholder believed climate change will affect salmon, by how much, and during what time frame. In general, the stakeholders tended to believe that it would affect these fish, although some indicated that climate change was not the most pressing threat facing Baltic salmon.

As described in section 3.2, we conducted direct elicitations sessions one-on-one with each stakeholder to avoid the influences of social norms (Heeren Alexander et al., 2016) and group dynamics (Glynn et al., 2017). These issues may have otherwise altered the stakeholders' depictions of their mental models, via, for example, groupthink (Janis, 1982; McCauley, 1989), or lead to issues like the overrepresentation of the most influential stakeholder's ideas (Burgman, 2005; Martin et al., 2012). Although conducting elicitations individually may limit problem-solving potential or diminish the benefits a group setting offers, like strengthening relationships between stakeholders, we believe our strategy was justifiable given our aims. Our problem-framing study and hence, the REA, were intended to build as holistic a view of a complex system as possible. As such, we were uncomfortable with the limits group interactions may have imposed. Nevertheless, the REA, as with all PM methodologies, should be adaptable depending on the circumstances and aim of individual PM processes (Voinov et al., 2016). Therefore, we acknowledge that the REA could be conducted in a group setting if desired, following the same procedure we have described here.

During Direct Elicitation, the facilitator's BBHVs may also affect stakeholders' influence diagrams. When drawing, a facilitator may depict a skewed interpretation of the stakeholder's statements, which instead reflect their own BBHVs. To reduce this effect in our study, the facilitator ensured the stakeholder could see what she was drawing, consistently asked for confirmation of her interpretation's accuracy, and encouraged interjection at the first sign of departure from the stakeholder's ideas (see section 3.2.2). However, if a stakeholder is uncertain or uncomfortable with the process of drawing causal diagrams, their ability and confidence to interject may be jeopardized. For this reason, the facilitator was as thorough as possible when explaining causal diagrams, how to read them, and how to produce them during the Stakeholder Learning portion of Direct Elicitation. For future implementations of the REA, we would add that if a stakeholder seems unsure about how to proceed or asks the facilitator to draw, the facilitator should ask the stakeholder to briefly draw a sample causal diagram and explain its contents before moving on. Additionally, when confirming the accuracy of the diagram with a stakeholder, the facilitator should verbally describe what each portion of the diagram depicts, indicating her position within the diagram as she describes it.

The facilitator's behavior or speech may also subtly influence the visualization of a participant's mental model. To reduce this influence in our study, the facilitator made an effort to remain encouraging of the participant's progress drawing or describing their mental model, while remaining neutral about its contents. Instead, she made comments intended to request clarification, further explanation, confirm the model's accuracy.

Before conducting our elicitations, we were keenly aware of the problem inherent in indirect elicitation: without the stakeholder's immediate guidance, a PM practitioner may inject their own BBHVs as they attempt to reproduce the stakeholder's mental model from textual information (see introduction). For this reason, we conducted direct elicitation first. It was imperative to ensure, in real-time, that each stakeholder's influence diagram was drawn according to their internal mental model. During Indirect Elicitation, careful coding and note-taking before enhancing the diagrams served to limit the analyst's interpretation and provide a trail of justification for each change made. Lastly, we incorporated the Verification Stage, during which that stakeholder must approve of the changes made by the PM practitioner. During this phase, the stakeholder also has the chance to make changes to the model or revoke permission for its use, providing one further check on the PM practitioner's interpretation. However, we discussed the difficulties we encountered during this stage in section 5.3.1.

Despite these safeguards, we suspect some of our actions during direct elicitation may have unintentionally biased the stakeholders' influence diagrams. Although we initially thought the core biological model for herring (see Fig. A1) was general enough not to trigger anchoring bias (Oppenheimer et al., 2008; Tversky and Kahneman, 1974) when used as an example during the Stakeholder Learning (Fig. 1), we cannot rule out the possibility that it did. Additionally, based on the stakeholders' disinterest in it, we believe it was unnecessary as a tool for idea generation. Explaining the core biological model also took valuable time, which could have been better spent practicing the process of building influence diagrams or on the elicitation process itself. Due to its lack of utility and its potential to induce anchoring bias, we recommend only exposing participants to example diagrams entirely unrelated to the subject at hand during the Stakeholder Learning.

We are also concerned that the stakeholders' knowledge about the facilitator's professional background may have influenced the study. Stakeholders often asked about the facilitator's career background and educational history while building rapport at the beginning of their elicitations sessions. Later, some seemed to tailor their descriptions of their mental models accordingly. After learning of the facilitator's experience with fisheries science, stakeholders tended to leave out the causal relationships within their mental model they assumed were common knowledge between them. For example, the stages of the salmon life cycle. To adapt to this situation in real-time, during our study, the facilitator frequently requested that the stakeholder be explicit about the causal relationships within their mental model, explain as if to a non-expert, and clarify portions of their model where they appeared to assume something about the facilitator's prior knowledge. We recommend that other PM facilitators follow this practice as well. Further, the facilitator should not discuss their background with stakeholders, although any interested stakeholder could undoubtedly find this information online before meeting the facilitator.

Despite the potential for a PM practitioner's BBHVs to affect the visualization of stakeholders' mental models, the REA coupled with our advice for its implementation and perhaps, facilitation training (Voinov et al., 2016), can address many of these issues. Further, we reiterate that by coupling direct and indirect elicitation, the REA reduces the potential introduction of an analyst's BBHVs, while maintaining the thoroughness indirect elicitation provides. Additionally, questionnaires implemented after both direct and indirect elicitation (Fig. 1) should include questions to gauge the participants' understanding of and satisfaction with these processes. This information should be used to improve future facilitation of the REA and to develop the methodology over time. As such, the REA provides a cohesive methodology, which acknowledges and reduces the effects of BBHVs. We believe this is a step forward for mental model elicitation in PM. Nevertheless, PM practitioners cannot control for their influence completely and therefore, in addition to learning from past facilitations and endeavoring to reduce their influence in each subsequent facilitation, PM practitioners should thoughtfully and honestly report how BBHVs may have influenced their study.

5.3.5. Formalizing core principles & process

In addition to the methodological recommendations we have provided here, we also recommend that all PM processes including the REA, be governed by a set of thoughtfully developed core principles, agreed upon by all the actors involved (Voinov et al., 2016). Although by necessity these principles will differ between PM processes, owing to the vastly different circumstances under which they are conducted, their aim should be to establish norms, or "rules of engagement" for each PM process and to ensure it is conducted in an effective manner and that results contribute meaningfully to knowledge co-production and decision-making (Voinov et al., 2016). These principles should be based on ensuring transparency, accountability, and follow-through between PM practitioners, participants, and the end-users of the PM process's products. Additionally, they should act as a code of conduct between these groups, ensuring fairness, civility, and fostering trust between them, while reducing the influence of BBHVs (Glynn et al., 2017; Voinov et al., 2016). An example of such core principles is available in Voinov et al., (2016). To ensure the PM process adheres to these principles, a process for appropriately documenting and reporting the PM process is essential. Although no standard process has yet been identified, Gray et al. (2018)'s 4P framework, the records of engagement suggested by (Glynn et al., 2018), or both could help fulfill this need.

Although we discussed the general aims of our study with the stakeholders, how their contributions would be used and made a commitment to inform them about how the study results were ultimately employed, we believe a more formalized process for discussing and agreeing on the study process and its core principles would have been warranted (Fig. 1, Principles & Process Discussion). A more thorough discussion about what to expect from the PM process, about the aims of the study, and more contact with the stakeholders throughout may have improved their commitment to it, potentially encouraging more engagement during the model verification stage of the REA. In the future, discussing the REA process itself with stakeholders may prepare them better for elicitation and emphasize the importance of their continued involvement in the study after direct elicitation. Additionally, agreement on the core principles of the project may have given the stakeholders a stronger voice in shaping the study and its outcomes into more relevant and mutually beneficial, real-world advice for salmon management in the face of climate change. A greater degree of connection, transparency, and shared control over the project may improve the fulfillment of the instrumental and normative PM functions as well.

It is also worth noting that PM is typically a sub-process within a larger scientific and decision-making efforts to govern socio-ecological systems. While we have discussed the importance of defining core principles and processes in the context of PM specifically, these ideas also apply to the overarching processes they are embedded within. See Glynn et al. (2018) and Glynn et al. (2017) for discussion of these ideas in the broader scientific and decision-making context.

5.4. Analyzing rich mental models & problem-framing

Although the purpose of this article is to describe the REA, not discuss the results of our problem-framing study, we find it pertinent to exemplify how one can use rich depictions of mental models. As stated previously, the purpose of collecting rich influence diagrams was to frame the problem of the impacts of climate change on Baltic salmon. This study's results are intended to guide the incorporation of climate change effects into ICES' existing Baltic salmon stock assessment model by indicating areas of special concern that the model should take into account and prepare for future management challenges. We suggest the number of times the stakeholders included a particular variable, category of variables, life stage, or habitat in their causal diagrams can serve as a proxy for their importance within the salmon-climate change system. Therefore, more frequently identified variables should be prioritized for inclusion in the model.

We recognize there are disadvantages to prioritization based on frequency alone, as this technique is not well suited for capturing important causal pathways or "themes." For example, we may be able to detect that river temperature, age at smoltification, and the number of salmon occur frequently in stakeholders' influence diagrams. However, by considering their frequency alone, we may miss the concept they represent together. A stakeholder may have used these variables to indicate that changes in river temperature alter the time it takes for young salmon to leave the river, altering the age at maturity, resulting in changes in population size. Stakeholders may describe the same process in vastly different terms and different levels of specificity, further complicating the task of identifying themes. Therefore, we suggest it is imperative to couple this analysis strategy with analysis of elicitation notes (A) and (B) (Fig. 1), which describe the stakeholder's thoughts, predictions, and common themes.

Alternatively, visualization techniques, like fuzzy cognitive mapping (FCM) (Olazabal et al., 2018; Özesmi and Özesmi, 2004; Solana-Gutiérrez et al., 2017), may help to more smoothly aggregate stakeholders' depictions of their mental models, making identification of frequently described causal pathways (themes) easier. FCMs can also be deconstructed to explore causal relationships pertaining to particular variables of interest (Olazabal et al., 2018). Creating FMCs also requires mental model elicitation and therefore, the REA approach could be applied to this methodology as well. Additionally, we recognize the number of times a variable is mentioned may also be indicative of the limits of stakeholders' knowledge, with well-understood variables and causal pathways occurring more frequently, than potentially poorly understood, but highly instrumental ones. Nevertheless, the inclusion of frequently cited variables in ICES' stock assessment model should reflect the best available knowledge, providing a starting point for further work, and promoting the model's legitimacy in the eyes of the stakeholders and hopefully, in their peers.'

If desired, after the decisions about which aspects of the salmon-climate change system to include in the stock assessment model have been made, a second PM process, similar to "task 1" described in Haapasaari et al. (2013), can begin. As in their study, we propose that stakeholders build directed acyclic graphs (DAG), explaining how the variables identified during the elicitation sessions connect with the current stock assessment model and with climate change. Unlike the qualitative influence diagrams we produced for problem-framing, the strengths of the effects between variables in DAGs should be quantified, expressed as joint probability distributions (Jensen and Nielsen, 2007). Whether a causal link is positive or negative should also be noted. In their study (Mäntyniemi et al., 2013)[2], instructed stakeholders to choose variables to include in their DAGs from a previously collected list provided by herring experts. In our case, these variables would come from the influence diagrams developed during the elicitation sessions described here. Once completed, the DAGs can be pooled via Bayesian model averaging (Mäntyniemi et al., 2013) and subsequently incorporated into the stock assessment model. Fully quantified influence diagrams also enable Value of Information (VoI) analysis (Mäntyniemi et al., 2009), which measures the maximum amount a decision-maker should be willing to pay to obtain more precise information before making a decision. As such, VoI can help determine what data to collect to assist decision-making.

In addition to the utility they provide in incorporating new information into environmental models, rich depictions of mental models provide context and justification for doing so. Their development also serves as a brainstorming tool, identifying the goals stakeholders have for a particular natural resource, strategies to reach those goals, areas where knowledge is lacking, and providing new, testable hypotheses about how a system works. Beyond the results of the study themselves, the process of conducting mental model elicitation promotes stakeholder learning and causal thinking (Fortuin et al., 2011; Kinchin et al., 2000; Marcot et al., 2001; Uusitalo, 2007) and begins to build stakeholder support for management recommendations (Fiorino, 1990; Jones et al., 2009).

5.5. Future directions

We suggest future users of the REA implement the suggestions for methodological improvement discussed in section 5.3 and that targeted questionnaires administered following Direct Elicitation *and* the completion of the full REA process could develop the methodology further (Fig. 1, Final Questionnaire). Additionally, we encourage further advancements to ensure mental model elicitation fulfills all functions of PM effectively.

Beyond the practical advice and suggestions we provide here, we also believe PM practitioners should strive to reduce the loss of valuable stakeholder knowledge even further. The most pressing barrier preventing the acquisition of holistic stakeholder knowledge in PM is limited participation, since typical studies include 30 or fewer participants (Voinov and Bousquet, 2010). Eliciting the beliefs of such a small segment of the stakeholder population constitutes its own form of knowledge simplification and potentially reduces PM's substantive, normative, instrumental, and educational value. These low numbers may be the result of limited time, financial, and analytical resources, or arise from the difficulty in securing stakeholder participation (Nevalainen et al., 2018). These obstacles may be circumvented by making the PM process easier, more enjoyable, or by connecting it more clearly with real-world impact. Improving communication styles and channels between stakeholders and researchers may also help. Traditionally, stakeholder participation has been increased by conducting group PM activities, like group problem-framings, but eliciting stakeholder knowledge in groups presents drawbacks as well (see sections 3.2 and 5.3.4). Still, group participation may only marginally increase the number of stakeholders involved in PM processes. Less traditionally, text analysis techniques, like topic modelling (Blei, 2012) from the computational social sciences literature, could provide analytical tools for extracting important insights from text (interview or elicitation session transcripts, questionnaires, tweets, blogs, etc.) provided by a number of stakeholders orders of magnitude greater than more traditional means allow. However, employing these techniques could mean less face-to-face time between researchers and stakeholders, limited verifiability of their ideas, and less opportunity for learning. Additionally, the time-consuming steps, like coding and note-taking, involved in traditional PM studies force the analyst to engage deeply with the data, improving their depth of knowledge and ability to draw conclusions from the data. As such, alternative means for incorporating more stakeholders into the PM process should be developed.

6. Conclusions

In conclusion, the Rich Elicitation Approach (REA) presented here is a strategy for eliciting rich mental models from expert stakeholders. The approach's novelty comes from the deliberate combination of direct and indirect elicitation strategies to ensure stakeholders' mental models are represented as holistically as possible while preserving the integrity of their knowledge and the learning process inherent in direct elicitation. We believe this approach can and should be adapted and applied to any PM process involving the elicitation of mental models.

Though the rich mental models the REA produces are time-consuming to create and complex, making their analysis more challenging, we believe they are necessary for forming a strong knowledge base on which to begin any PM project in the face of data limitation and incomplete scientific knowledge. Greater detail allows researchers to take advantage of the full depth of stakeholder knowledge, reducing the propensity to overlook potentially instrumental causal pathways, promoting the production of new testable hypotheses, improving realism, and generating more thorough solutions and management strategies. Developing a comprehensive knowledgebase may also improve the resilience of PM projects, by providing a reservoir of new ideas when researchers find themselves going "back to the drawing board." Despite the challenges, the best available expert knowledge should be used to its fullest potential to solve natural resource-related challenges. We also encourage researchers and PM practitioners to transparently and thoughtfully share their experiences to allow for the development of best practices and to bring PM into the light as a legitimate and valuable field of its own.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2019.104589.

[2] Further analysis of this study is available in (Haapasaari et al., 2013).

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Appendix A

Making the Most of Mental Models: Advancing the Methodology for Mental Model Elicitation and Documentation with Expert Stakeholders

Kelsey LaMere[a*], Samu Mäntyniemi[b], Jarno Vanhatalo[c,d], and Päivi Haapasaari[e]

Stakeholder Alias	Organization Type	Nation
A	Transnational Management Agency	Finland
B	Government Ministry	Finland
C	County Management Agency	Sweden
D	University	Sweden
E	NGO	Finland
F	County Management Agency	Sweden
G	NGO	Sweden
H	NGO	Finland
I	NGO	Sweden
J	County Management Agency	Sweden
K	NGO	Finland

Table A.1: Each stakeholder's pseudonym (stakeholder alias), the type of organization they work for (organization type), and the nation in which they work (nation).

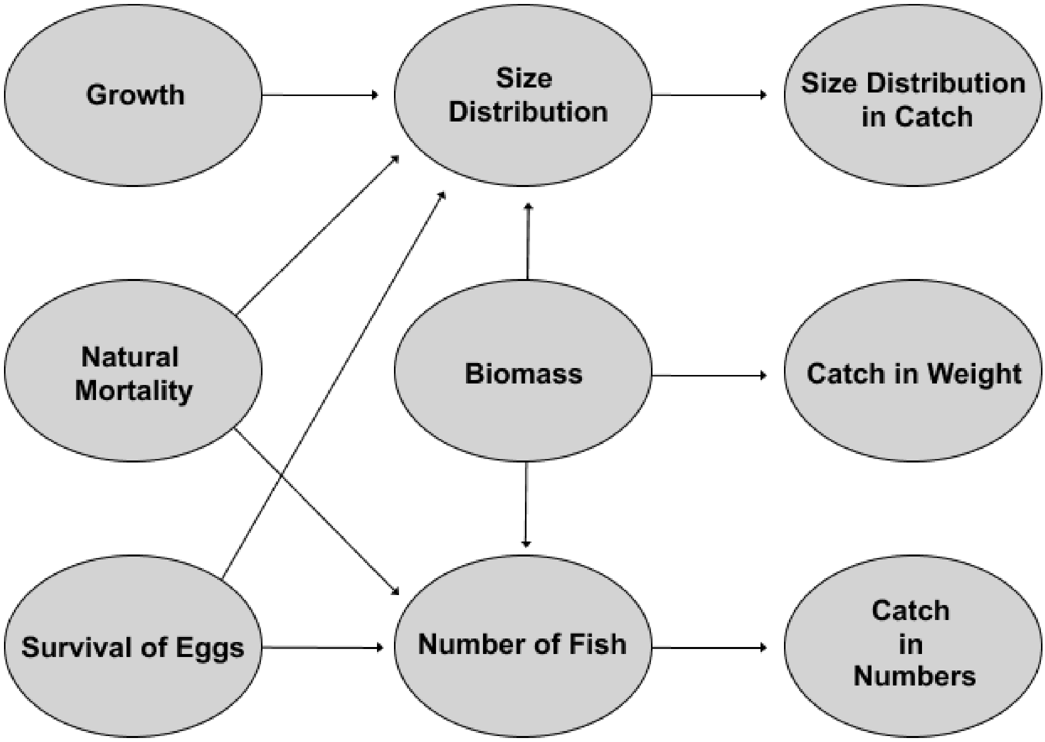

Fig. A.1: The core biological model. Originally published by Haapasaari et al. (2012). *(Single column fitting image)*

Salmon Stakeholder Questionnaire

The following is the complete questionnaire administered to participating stakeholders following the direct elicitation phase of the REA. The stakeholders' responses to the eight questions related to the substantive, normative, instrumental, and educational functions of participatory modelling are discussed in the main text of this article.

1. Are specific Baltic salmon stock important to you?
2. If you answered "yes," which stock(s) are important to you? Of more than one stock is important to you, please list the three most important. If you answered "no," please answer the following questions only for "Baltic salmon in general."
3. How satisfied are you with the current status of Baltic salmon stocks? 1 = Dissatisfied, 5 = Satisfied.
4. Referring to the previous question – Why/ Why not?
5. Referring to the previous question – Why/ Why not?
6. How important is it to consider the effect climate change may have on natural resources in making management decisions? 1 = Unimportant 5 = Important
7. How likely is climate change to have an effect on salmon in the foreseeable future? 1 = Unlikely 5 = Likely
8. How significant will these effects be? 1 = Insignificant 5 = Significant
9. When will these effects become evident?
10. Overall, will climate change be positive or negative for Baltic salmon? 1 = Negative, 5 =Positive
11. Please explain your answer.
12. If the effects climate change will have on Baltic salmon are negative, how much can management mitigate these effects? 1= Not at all, 5 = A lot
13. If we had a better understanding of how climate change may influence salmon, could we make management decisions to help prepare the fishery for the future? 1 = No, definitely not, 5 = Yes, definitely

14. Have you thought about the effects of climate change on salmon before?
15. Should the results of stakeholder mind mapping activities be used to help determine future goals for the salmon fishery? 1 = No, definitely not, 5 = Yes, definitely
16. Referring to the previous question – Why/Why not?
17. Would mind mapping be useful in reaching consensus about how to manage the fishery? 1 = No, definitely not, 5 = Yes, definitely
18. Referring to the previous questions – Why/Why not?
19. Would you feel more satisfied with management decisions if the results of stakeholder mind mapping activities were considered during the decision making process? 1 = No, definitely not, 5 = Yes, definitely
20. Referring to the previous question – Why/Why not?
21. Do you believe the results of mind mapping exercises with salmon fishery stakeholders would be valuable to decision makers when determining how to manage the fishery? 1 = No, definitely not, 5 = Yes, definitely
22. Referring to the previous questions – Why/Why not?
23. Would attending stakeholder mind mapping events with researchers who give recommendation for salmon fishery management make you feel more invested in the scientific process? 1 = No, definitely not, 5 = Yes, definitely
24. Referring to the previous question – Why/Why not?
25. Would sharing the results of stakeholder mind mapping activities with decision makers help ensure stakeholder values are represented in the decision making process? 1 = No, definitely not, 5 = Yes, definitely
26. Referring to the previous question – Why/Why not?
27. If you were facilitating this mind mapping activity, what would you do differently and what would you keep the same?
28. Was this experience helpful in organizing your thoughts and opinions about salmon and climate change? 1 = No, definitely not, 5 = Yes, definitely

29. Could mind mapping be useful in solving fisheries related problems? 1 = No, definitely not, 5 = Yes, definitely

30. Additional Comments:

CHAPTER III

Kelsey LaMere, Samu Mäntyniemi, Päivi Haapasaari

THE EFFECTS OF CLIMATE CHANGE ON BALTIC SALMON: FRAMING THE PROBLEM IN COLLABORATION WITH EXPERT STAKEHOLDERS

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The effects of climate change on Baltic salmon: Framing the problem in collaboration with expert stakeholders

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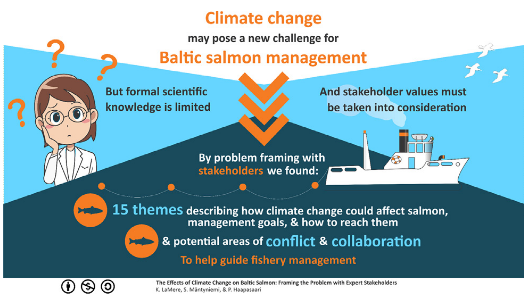
HIGHLIGHTS

- Climate change may pose a challenge for Baltic salmon management.
- We frame the problem using a participatory approach.
- Stakeholders' mental models form the basis of the problem framing.
- 15 key themes holistically describe this problem and its context.
- Understanding areas of conflict and collaboration between stakeholders is crucial.

GRAPHICAL ABSTRACT



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ABSTRACT

In the Baltic Sea region, salmon are valued for the ecological, economic, and cultural benefits they provide. However, these fish are threatened due to historical overfishing, disease, and reduced access to spawning rivers. Climate change may pose another challenge for salmon management. Therefore, we conducted a problem-framing study to explore the effects climate change may have on salmon and the socio-ecological system they are embedded within. Addressing this emerging issue will require the cooperation of diverse stakeholders and the integration of their knowledge and values in a contentious management context. Therefore, we conducted this problem framing as a participatory process with stakeholders, whose mental models and questionnaire responses form the basis of this study. By framing the climate change problem in this way, we aim to provide a holistic understanding of the problem and incorporate stakeholder perspectives into the management process from an early stage to better address their concerns and establish common ground. We conclude that considering climate change is relevant for Baltic salmon management, although it may not be the most pressing threat facing these fish. Stakeholders disagree about whether climate change will harm or benefit salmon, when it will become a relevant issue in the Baltic context, and whether or not management efforts can mitigate any negative impacts climate change may have on salmon and their fishery. Nevertheless, by synthesizing the stakeholders' influence diagrams, we found 15 themes exemplifying: (1) how climate change may affect salmon, (2) goals for salmon management considering climate change, and (3) strategies for achieving those goals. Further, the stakeholders tended to focus on the riverine environment and the salmon life stages occurring therein, potentially indicating the perceived vulnerability of these life stages to climate change. Interestingly, however, the stakeholders tended to focus on traditional fishery management measures, like catch quotas, to meet their goals for these fish considering climate change. Further, social variables, like "politics," "international cooperation," and "employment"

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comprised a large proportion of the stakeholders' diagrams, demonstrating the importance of these factors for salmon management.

1. Introduction

1.1. The Baltic salmon – climate change case study

In the Baltic Sea region in Northern Europe (Fig. 1), Atlantic salmon (*Salmo salar L.*) are popular among recreational fishers, support a commercial fishery (ICES, 2019), and act as a keystone species, providing irreplaceable ecosystem services in both marine and freshwater environments (ICES, 2019; Ignatius and Haapasaari, 2018; Kulmala et al., 2012). These fish are also, in many cases, woven into the cultural heritage of the nations along the Baltic Sea's shore (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Kulmala et al., 2012; Leeming, 2005; Lönnrot, 2009). Therefore, rapidly declining salmon populations in the 1970s–90s, associated with decades of

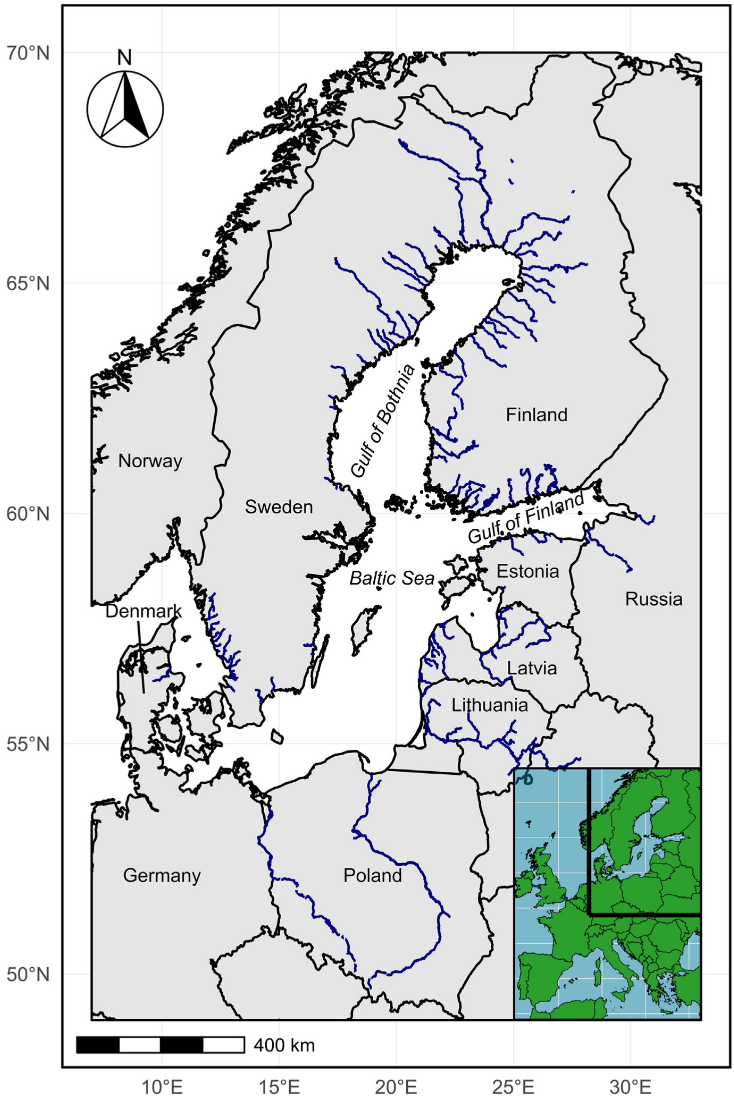

Fig. 1. Salmon rivers in the Baltic Sea Region. Map displaying the Baltic Sea Region and all the salmon rivers therein (dark blue). The inset in the lower right-hand corner depicts the position of the Baltic Sea Region relative to Europe as a whole.

overfishing, M74 syndrome,[1] and reduced access to spawning rivers (ICES, 2019; Romakkaniemi et al., 2003) were cause for alarm.

Despite the often-contentious nature of the salmon fishery, this concern precipitated the international adoption of the Salmon Action Plan (SAP) in 1997. Under its directive, nine stakeholder nations agreed to aid in the recovery and re-establishment of wild Baltic salmon. Their dedication to this task is often linked to the rebounding salmon populations observed in recent years (Reusch et al., 2018; Romakkaniemi et al., 2003). However, despite these successes, salmon are still considered threatened (HELCOM, 2011; ICES, 2019). Therefore, it is critical that collaborative, multinational management efforts continue to promote the longevity, sustainability, and health of salmon stocks in the Baltic Sea, including prompt action to address emergent threats.

We believe climate change could present a new challenge for Baltic salmon management, as this phenomenon has been shown to compromise the well-being of salmonid species around the world (Eliason et al., 2011), including wild populations of Atlantic salmon[2] outside the Baltic Sea (Almodóvar et al., 2018; Jonsson et al., 2016; Otero et al., 2014).

Like other regions where climatic shifts have affected salmonids, climate change is also occurring in the Baltic region (Bolle et al., 2015; HELCOM, 2013; Räisänen, 2017), where warming is expected to exceed the global average (HELCOM, 2013; Räisänen, 2017). Further, the region's riverine and marine environments, which are both relevant to the survival of anadromous fish, like salmon (ICES, 2019), are expected to change. For example, the scientific community has projected changes in river flow (HELCOM, 2013; Sonnenborg, 2015), further reductions in the extent and duration of sea ice cover, further increases in sea surface temperatures,[3] and shifting sea salinity and acidity (Bolle et al., 2015). Naturally, such changes in the physical environment affect the biological environment as well. As such, studies have acknowledged the potential for climate change to affect, for example, the Baltic Sea food web (Niiranen et al., 2013), the reproductive periods of flora and fauna (Bolle et al., 2015), Baltic fish stocks (Bolle et al., 2015; Koster et al., 2005) and the invasion (Engström-Öst et al., 2015) and proliferation (O'Neill et al., 2017) of harmful cyanobacteria species. New research suggests climate change may also affect the region's social environment, in terms of the mitigation and adaptation challenges that the society will face. For example, by downscaling the global Shared Socioeconomic Pathways (SSPs) for the Baltic Sea, Zandersen et al. (2019) acknowledge the role socio-economic development will play in climate change in the region.[4] Unsurprisingly, given the multitude of changes expected or currently underway in the Baltic Sea Region, we anticipate that salmon will be affected in some way as well.

However, although research about the effects climate change may have on the region's interlinked physical, biological, and social environments is diverse and growing, its effects on salmon and the socio-ecological system they are embedded within[5] are still poorly understood. The research community has produced several articles describing how environmental change affects the Baltic salmon life history (Huusko and Hyvärinen, 2012; Jokikokko et al., 2016; Jutila et al., 2005; Kallio-Nyberg et al., 2004; Snoeijs and Häubner, 2014), which build the foundational theory linking changes in salmon populations to climate change. However, few of these articles consider the issue directly or comprehensively. Further, to the extent that this body of research does consider climate change, it is primarily concerned with changes in the interactions between salmon and their physical and biological environments, leaving out the social environment altogether. At present, to the best of our knowledge, this topic has not been addressed in the literature.

We consider this to be an important area for development because, per the ecosystems approach to fisheries management, we view the physical, biological, and social environments surrounding fisheries issues as interconnected and interdependent (De Young et al., 2008; Ignatius and Haapasaari, 2018). Therefore, to comprehensively understand the problem climate change may pose for the salmon system, it is crucial to acknowledge each of these environments. Hence, the existing research, though vital, only represents a piece of the larger picture. To help develop this knowledge base, this study aims to directly address climate change and assist in producing a more robust, holistic understanding of its effects on the salmon system to advise fishery management.

1.2. The role of participatory methods in the salmon management context

However, while a comprehensive scientific knowledge base is one requirement for addressing large-scale emergent issues, like climate change, a functional fisheries management system is also a necessity. Since the end of the SAP in 2010, salmon management has become increasingly contentious, particularly at the level of the European Union (EU), where stakeholder interests conflict, leading to political stalemate (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014). These issues seem to be related to two interconnected struggles: (1) the marginalization of different stakeholder groups, their values, and their role in the fishery management process (Ignatius et al., 2019; Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014) and (2) a tendency to ignore the complex socio-ecological context in which salmon management takes place (Linke and Jentoft, 2014).

To meet these challenges, we suggest salmon management must become more inclusive throughout its process, from beginning to end, and consider salmon-related issues from a more holistic perspective. The EU's Common Fisheries Policy (Regulation (EU) No 1380/2013) also acknowledges the importance of involving stakeholders early in the fisheries management process and the value of their diverse knowledge, both of which it considers to be prerequisites for developing sustainable fisheries.

For these reasons, we believe the conversation about the effects of climate change on the salmon system must be inclusive from the outset as well. Therefore, for this study, we chose to use participatory methods, which integrate fishery stakeholders into the scientific process to ensure their views were taken into consideration and that the factors they found relevant were represented. This choice was also beneficial because, in complex, data-poor contexts like this, consulting expert stakeholders is often the best way to build substantive knowledge (Krueger et al., 2012; Kuhnert et al., 2010; Özesmi and Özesmi, 2004; Sutherland, 2006), particularly when action should not be delayed while more formal scientific information is generated (Kangas and Leskinen, 2005; Knol et al., 2010).

1.3. Study goals & aims

As such, the goals of this study were twofold. First, to develop the knowledge base about the effects of climate change on the salmon system in a holistic and socially accountable way to advise fishery management. Second, to provide insight, which could help fishery management efforts meet with success. To meet these goals we conducted a participatory problem framing study, which aimed to (1) improve understanding of the causal relationships between climate change, salmon, and other relevant aspects of the physical, biological, and social environments which comprise the salmon system; (2) identify goals for the management of the salmon system considering the effects of climate

[1] M74 is a diet-related thiamine deficiency syndrome (Keinänen et al., 2017), which causes mortality during the yolk-sac fry developmental stage (Bengtsson et al., 1999).

[2] In this article, the terms "Baltic salmon" or simply, "salmon" refer to Atlantic salmon populations spending the duration of their lives within the Baltic Sea.

[3] The greatest rises in sea surface temperature are expected to occur during summer in the Bothnian Bay and the Bothnian Sea. The majority of the salmon in the Baltic region are born in rivers emptying into these basins (ICES, 2019).

[4] Zandersen et al. (2019) downscaled SSPs to address changes in fish consumption and fisheries management in the region.

[5] From here on we refer to salmon and the socio-ecological system they are embedded within as the "salmon system." Additionally, we refer to the issue climate change may pose for the salmon system as the "salmon-climate change problem."

change; and (3) define potential actions that could be taken to reach those goals. Further, the study aimed to clarify whether or not the climate change issue warrants management action and the sources of conflict and consensus that may develop between stakeholders if it does.

2. Theoretical framework

2.1. Problem framing

To build knowledge about the potential salmon-climate change issue we used an approach known as problem framing. In the context of socio-environmental problem solving, problem framing is a strategy for clearly defining a problem and developing a holistic understanding of it and its context, based on information about, for example, relevant physical, biological, and social factors (Bardwell, 1991; Clark and Stankey, 2006; Haapasaari et al., 2012). By first developing a thorough understanding of a problem in this way, those engaged in a problem-solving effort, i.e. problem solvers,[6] can come to better, more workable solutions. As such, problem framing is an appropriate first step in problem-solving efforts, particularly in complex, uncertain, and even "wicked" contexts (Bardwell, 1991; Haapasaari et al., 2012; Verweij and van Densen, 2010), like the salmon-climate change problem. We perceived problem framing to be an advantageous approach for reaching the goals of this study because the process:

1. *Develops better problem solvers* – During problem framing, problem solvers closely examine and learn about the problem and the surrounding context, developing their conceptualization of the issue. Central to this process is considering the problem from multiple perspectives (Bardwell, 1991; Brugnach et al., 2008), which helps ensure important elements and linkages within the problem system have not been overlooked (Briggs, 2008; Haapasaari et al., 2012) and exposes the personal biases, beliefs, heuristics, and values on which those perspectives are based (Glynn et al., 2017). By framing and re-framing a problem from different perspectives, problem-solvers can relate to the problem in new ways, moving past previously perceived barriers and toward new solutions (Bardwell, 1991). Problem framing also helps direct problem-solvers toward information they lack, by exposing weaknesses in their conceptualizations of the problem (Kaplan and Kaplan, 1982). Further, examining a problem in this way also helps to determine its bounds and scope, which delimits what is and is not possible, what is most important, and what will and will not be addressed. All of which can help break a large, seemingly intractable problem into smaller, more manageable pieces (Briggs, 2008; Kaplan and Kaplan, 1982).
2. *Produces alternative solutions* - Alternative frames, built on alternative perspectives, lead to alternative actions, or solutions (Bardwell, 1991; Brugnach et al., 2008). For example, Tversky and Kahneman, 1981 found that framing an economic problem from the perspective of gains encouraged risk-averse behavior, whereas framing the same problem for the perspective of losses encouraged risk-seeking behavior. Similar examples exist within the natural resource management field (see Brugnach et al. (2008)). As such, the way we define a problem, i.e. the way we perceive it, is critical in determining where the outcomes of problem-solving efforts will ultimately lead (Bardwell, 1991; Pahl-Wostl, 2007). Hence, by problem framing, problem solvers can explore a range of potential solutions that might not have been considered otherwise.
3. *Addresses Conflict* – In collaborative problem-solving contexts, conflict is often unavoidable, as many, often competing, interests must be taken into account (Bardwell, 1991). Indeed, different understandings of a situation are typically the underlying reasons for disputes in environmental management (Haapasaari et al., 2012; Verweij and van Densen, 2010). Therefore, exploring perspectives about an issue and the different concerns, interests, and values they include, helps identify both areas of conflict and consensus that might either hinder or aid management efforts. In this way, problem framing helps determine the correct question(s) to address and ultimately, move toward mutually agreeable solutions as well (Bardwell, 1991). Additionally, understanding different perspectives and the rationale behind them can help bridge gaps in understanding between conflicting groups (Cronin and Weingart, 2019), which may ease conflicts associated with environmental management.
4. *Empowers problem-solvers* - The act of problem-framing itself bolsters a problem solver's sense of competency, as they learn more about the issue, their role in it, and become capable of shifting their perspective (Bardwell, 1991). The sense of self-efficacy these new skills and knowledge bring, in turn, help improve motivation to solve difficult problems (Bardwell, 1991; Biggs and Tang, 2011).

The way a problem is framed subsequently determines the issues and solutions presented to decision-makers (Kueffer et al., 2012; Rittel and Webber, 1973), which reflect not only scientific facts, but also the problem-solvers' values, the tradeoffs they are willing to make, and the risks they are willing to accept (Bardwell, 1991). Therefore, we believe, in the context of natural resource management, including salmon management, problem framing should include all relevant stakeholders' to ensure their knowledge and values are reflected in the decision-making process (Haapasaari et al., 2012; Ignatius et al., 2019). This is particularly true where natural resources are considered common-pool and are managed for the benefit of current and future generations. Further, stakeholders should be included in the problem-framing process, so they too can contribute their perspectives, improve their understanding of themselves, the problem, and others, and address conflict. These outcomes may indeed prove critical for legitimizing and implementing management decisions later on (Fiorino, 1990; Jones et al., 2009), and empowering stakeholders to help tackle complex problems.

2.2. Problem frames as mental models

Central to the problem framing process is understanding, collecting, and building upon the cognitive structures people use to reason, often referred to as mental models, or cognitive maps (Johnson-Laird, 2010; Jones et al., 2011; Nersessian, 2002). Mental models can be thought of as a person's "internal representation of an external reality" (Jones et al., 2011), which encodes their understanding of a system's causal dynamics (Moray, 1998). In problem-solving situations, people automatically access their mental models to interpret and respond to the situation, using it as a reservoir of information from which to draw conclusions (Bardwell, 1991). Studies suggest this kind of informational structure is key for effective problem solving, as problem solvers with more comprehensive and accessible mental models are better able to find effective solutions (Bardwell, 1991).

Naturally, mental models reflect perspective (Johnson-Laird, 2010; Jones et al., 2011). As such, they provide clear insights into the way a person frames and therefore, addresses a particular problem by displaying their hypotheses about a system's causal dynamics (Krueger et al., 2012), what they believe is relevant to the problem, and what they believe is possible within the problem space (Bardwell, 1991). When elicited and aggregated, individual mental models allow for the co-production of systems knowledge (Olazabal et al., 2018)

[6] In this article, we use the term "problem solver" in the same sense as it is used by Bardwell (1991). Although Bardwell (1991) does not define the term explicitly, it is meant to denote a person who is engaged in the process of developing and synthesizing knowledge to identify or create solutions for a given issue. We consider fisheries management and the production of knowledge to support it to be a problem-solving process at its core and therefore, consider those stakeholders who are actively involved in this process to be problem solvers. In this study specifically, the problem solvers include both the authors of this article and the participating expert stakeholders.

and ultimately, a synthesized problem frame. For these reasons, to understand the way stakeholders frame the problem climate change poses for the salmon system, we chose to elicit their mental models about it.

3. Methods

Before describing the methodology used to conduct this problem framing study, we would like to alert the reader to our article LaMere et al. (2020), which describes in greater detail the process we used to elicit and prepare the stakeholders' mental models for analysis, as well as our protocol for administering the questionnaire. While the focus of that previous article was the development of the mental model elicitation methodology, this article focuses on the analysis of the stakeholders' models and the subsequent results.

3.1. Stakeholder selection

For the purpose of problem framing, we studied the mental models of 11 expert stakeholders of the salmon-system from Finland and Sweden. Expert stakeholders from these two nations were targeted because most natural Baltic salmon reproduction occurs in these two nations, they jointly receive approximately 70% of the total commercial catch quota, and the majority of recreational fishing takes place in their waters (ICES, 2019). We only invited experts on the salmon system to participate in this study because we judged this group to have the most extensive knowledge regarding the effects of environmental change on the salmon and their fishery. Those with domain-specific expertise like this have richer pre-existing mental models about the problem (Nersessian, 2002) and should, therefore, be more adept at problem framing about the topic (Bardwell, 1991).

Currently, the distinction between experts, stakeholders, and expert stakeholders is often unclear in the literature (Krueger et al., 2012). For clarification, here we define them as individuals who can be described both as “experts,” based on the extent and depth of their experience with the salmon system (Fazey et al., 2006), and “stakeholders,” who are considered to be those who will be influenced by the effects climate change may have on the system (Carney et al., 2009; Durham et al., 2014). From here on, the “expert stakeholders” participating in the study will be simply referred to as “stakeholders.”

We identified suitable stakeholders for this study via snowball sampling (Matthews and Ross, 2010); first, we reached out to known contacts with suitable expertise and then asked that they pass our request for participation on to other experts. The 11 responding stakeholders we selected demonstrated appropriate contributory and interactional expertise (McBride and Burgman, 2012) regarding the salmon system via their diverse professional backgrounds. These included a transnational management agency, a government ministry, a university, three county management agencies, and five non-government organizations. We assigned each participating stakeholder a letter pseudonym, for example, “stakeholder K,” to conceal their identities and respect their privacy. Assuring anonymity is common practice in social scientific research (Bernard, 2018; Marvasti, 2004) because it allows participants to express their true thoughts without fear of retribution or ridicule. This was particularly important for our study given that field of Baltic salmon experts is relatively small and many of our study's participants likely knew one another and because salmon management and climate change may both be perceived as controversial.

3.2. Elicitation: from mental models to influence diagrams

Mental models are internal and therefore, to study them they must be elicited and represented physically. As such, we elicited the stakeholders' mental models as influence diagrams, a type of causal diagram (Haapasaari et al., 2012). These “visualized mental models” clearly articulate the causal relationships between variables within the model by linking them with arrows, which also serve to indicate the direction of the effect (Haapasaari et al., 2012) (see Figs. 3 and 7 for examples). In addition to displaying causal relationships between variables, influence diagrams also acknowledge stakeholders' uncertainty about these relationships, expressed as degrees of belief, which can be elicited either qualitatively (Haapasaari et al., 2012; Varis and Fraboulet-Jussila, 2002; Varis and Lahtela, 2002) or quantitatively as joint probability distributions (Mäntyniemi et al., 2013). Risk assessment models can be easily developed from influence diagrams, when degrees of belief are recorded quantitatively (Haapasaari et al., 2012; Mäntyniemi et al., 2013). However, we chose a qualitative approach for this problem framing study, where uncertainty is represented by the thickness of the arrows drawn between variables (thicker arrows represent more certain relationships) (Haapasaari et al., 2012; Parviainen et al., 2019). Whether quantitative or qualitative, engaging with their mental models by creating influence diagrams, encourages stakeholders to think deeply about the problem, clearly articulate their thoughts, and reflect (Lynam et al., 2007; Marcot et al., 2001; Uusitalo, 2007), which is an essential element of problem framing and helps to improve problem-solving competence as described in Section 2.1.

For this study, the stakeholders' mental models were elicited via the Rich Elicitation Approach (LaMere et al., 2020), which combines direct and indirect mental model elicitation methodologies (Jones et al., 2011; LaMere et al., 2020). The direct portion of the elicitation consisted of an “elicitation session,” which is a one-on-one semi-structured interview (Matthews and Ross, 2010) between a stakeholder and a facilitator, during which the stakeholder's mental model is documented as an influence diagram. We used the three following interview prompts during each elicitation (Haapasaari et al., 2012; LaMere et al., 2020):

1. What variables and causal relationships do you think should be considered when determining the impacts of climate change on Baltic salmon and their associated fishery?
2. What goals do you have for salmon and their fishery in the future considering climate change?
3. What management strategies or actions can be undertaken to achieve those goals?

We asked the first question to elicit the stakeholders' mental models of the direct and indirect causal relationships between climate change and the salmon system. Answers to this question were recorded as uncertain variables in the influence diagrams. Collectively, the responses to this question help produce a more comprehensive understanding of the effects climate change may have on the salmon system as perceived by the stakeholders. It also assisted in deepening our understanding of the stakeholders' perspectives of problem, including the elements of the system they are familiar with or find important. The second question elicits the value stakeholders place on salmon and other aspects of the salmon system, which may help to determine potential areas of future conflict or collaboration when managing salmon in the context of climate change. Answers to this question were recorded as goals[7] in the influence diagrams. The third question identified actions[8] that could be taken to reach the aforementioned goals, which broadens the potential pool of solutions for addressing the climate change problem and again, indicates potential areas of conflict and consensus. Answers to this final question were referred to as action variables. Audio was recorded during each elicitation session.

Following direct elicitation, each stakeholder was sent a link to an anonymous online questionnaire, which included questions intended to provide more context for problem framing, determine the utility of the problem framing and mental model elicitation processes, and improve the implementation of those processes. The questionnaire

[7] Referred to utility, loss, or preference of decision nodes in the Bayesian modeling literature (Haapasaari et al., 2012).

[8] Often conceptualized as management options in the Bayesian modeling literature (Haapasaari et al., 2012).

consisted of 18 multiple choice and scoring questions. The majority of these were followed by an open response question asking the stakeholders to elaborate on their answers if desired. Additional information about the implementation of the questionnaire and the questionnaire itself are available in LaMere et al. (2020).

Next, the audio recordings collected during the elicitation sessions were transcribed and the transcriptions were coded. Using the coded transcriptions and notes taken on the transcriptions, each influence diagram was enhanced via indirect elicitation to reduce information loss and oversimplification, which may have occurred during direct elicitation (LaMere et al., 2020). These enhanced versions of the influence diagrams were then sent back to the stakeholders to ensure their thoughts were still represented accurately. Lastly, the terminology used within each influence diagram was standardized (LaMere et al., 2020) to improve their comparability.

3.3. Problem framing analysis & synthesis

After the elicitation process, we conducted two types of analysis, one semi-quantitative and the other, qualitative. Then, we synthesized the results to produce a collective framing based on the individual stakeholders' perspectives.

3.3.1. Semi-quantitative analysis

During the semi-quantitative phase, we deconstructed the influence diagrams and sorted each variable into a hierarchical categorization scheme. We, the co-authors of this article, decided on the categories by observing the data and deliberating about how to categorize them appropriately among ourselves. The variables were sorted into these categories according to our discretion in an effort to decompose the vast amount of information contained in the influence diagrams into more meaningful and easily interpreted themes. For example, using these categories, we were able to identify frequently described categories of variables (i.e. themes) to better understand the areas of the salmon system the stakeholders focused on when considering climate change, and the types of interventions and goals they supported.

Our final categorization scheme included 1st, 2nd, and 3rd order categories, where the first-order categories were the narrowest and 3rd order, the broadest. The 3rd order categories corresponded with the three types of variables included in the influence diagrams: uncertain, goal, and action. We identified five types of uncertain variables, (1) those related to the salmon themselves (salmon-specific)[9]; (2–4) those related to either of the three environments that comprise the salmon system, the physical,[10] biological,[11] and social environments,[12] and (5) those specifically related to the knowledge and uncertainty about the salmon-system that stakeholders wished to represent directly in their influence diagrams.[13] Each of these 3rd order categories was broken down further into more and more specific categories developed according to the variables the influence diagrams contained and our expertise about salmon, the system they inhabit, and the way it is typically managed. An example of our categorization of a specific variable, "volume of high flows" is as follows: 3rd order – "uncertain: physical;" 2nd order – "hydrologic cycle," 1st order – "flow."

We also categorized the variables according to the salmon life stages and environments they were associated with. A variable was placed into a particular "environment category" if it was either 1) a quality of that environment, 2) occurred in that environment, 3) was a quality of something that occurred in that environment; or 4) was specifically intended to impact that environment. For example, the variable "volume of high flows" was classified as related to the riverine environment. The variables that met the requirements for two or more environments were categorized as belonging to both, i.e. a variable related to both the riverine and marine environments was classified as riverine/marine.

Similarly, variables were classified as related to a particular life stage if they: 1) referenced a specific life stage, 2) were a quality or state of a specific life stage, or were 3) a behavior occurring during a specific life stage. Variables related to more than one life stage were labeled as such. For example, some variables pertained to all life stages occurring within the marine environment, therefore these were labeled as "marine phase." Variables, which were not related to a specific environment and/or life stage were given a categorization of "not applicable" (NA) in these areas. For example, life stage was deemed "not applicable" for the "volume of high flows" variable. A full categorized list of all the variables included in the stakeholders' influence diagrams is available as supplementary material associated with this article.

3.3.2. Qualitative analysis & narrative building

For the qualitative analysis portion of this study, we used a conventional content analysis approach (Hsieh and Shannon, 2005). This is an appropriate strategy for concept development or model building (Hsieh and Shannon, 2005), when existing knowledge about the phenomenon in question is limited (Hsieh and Shannon, 2005), as it is for the salmon-climate change problem. The approach's utility in these areas made it a good fit for our problem framing study. Specifically, we used this approach to analyze the transcripts from each stakeholder's elicitation session in conjunction with their influence diagrams, and their responses to the open response questionnaire questions. In practice, this involved identifying and coding concepts within the text and diagrams, then grouping them into larger themes (Hsieh and Shannon, 2005). During this phase, we also produced short narratives summarizing the main concepts included in each stakeholder's frame (see Appendix, Section A.1).

3.3.3. Synthesis

Then, we developed descriptions of each of the primary themes discovered between the stakeholders (see Appendix, Section A.3), using the results of the semi-quantitative analysis to support this process. Those themes which four or more stakeholders contributed to were considered primary. Then, the influence diagrams, transcripts, and narrative summaries were scrutinized again to determine which themes the stakeholders considered to be related and the direction of the causality between them. We documented any causal relationship between primary themes that we found sufficient evidence for within these materials. Lastly, we produced a synthesized influence diagram including the primary themes discovered and the causal relationships we observed between them.

Fig. 2 summarizes the connections between the concepts described in Sections 2.1–3.3.

4. Results

4.1. Influence diagrams

We present the influence diagram one stakeholder produced to represent his mental model of the effect climate change may have on the salmon-system in Fig. 3. However, all 11 of the stakeholders' influence diagrams are available in the supplementary material associated with this article.

[9] Examples of uncertain – salmon-specific variables: "number of smolts" or "egg mortality."

[10] Examples of uncertain – physical variables: "precipitation," "sea temperature," and "flow."

[11] Examples of uncertain – biological variables: "sprat" or "number of seals."

[12] Examples of uncertain – social variables: "national policy" or "commercial fishing effort."

[13] Examples of uncertain – knowledge & uncertainty variables: "uncertainty about food web dynamics" or "data collection."

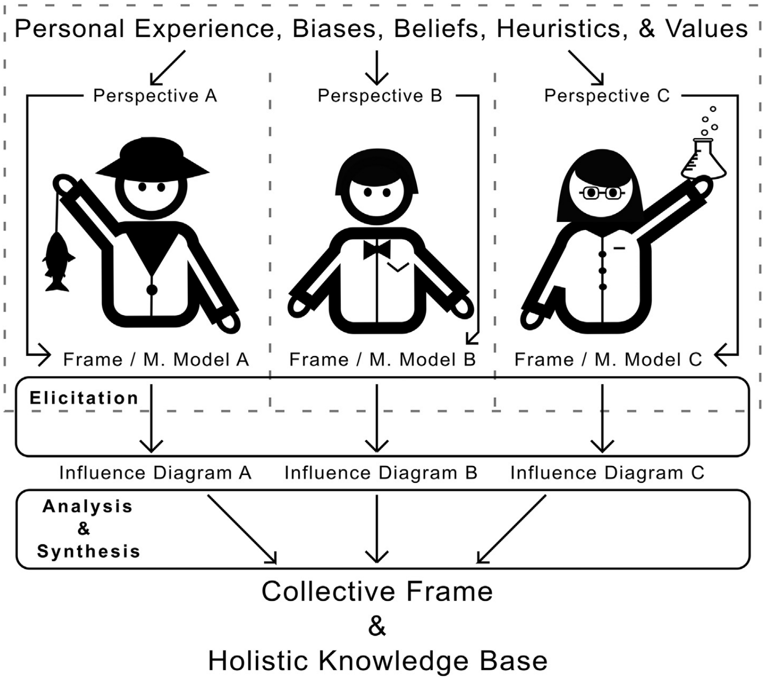

Fig. 2. A synthesis of the study approach. Diagram representing the connection between the concepts described in Sections 2 and 3. The figures represent three hypothetical stakeholders. The arrows can be understood as representing the word "affects" or "influences." Processes occurring internally, in the stakeholders' minds, are within the dashed borders. M. Model stands for "mental model."

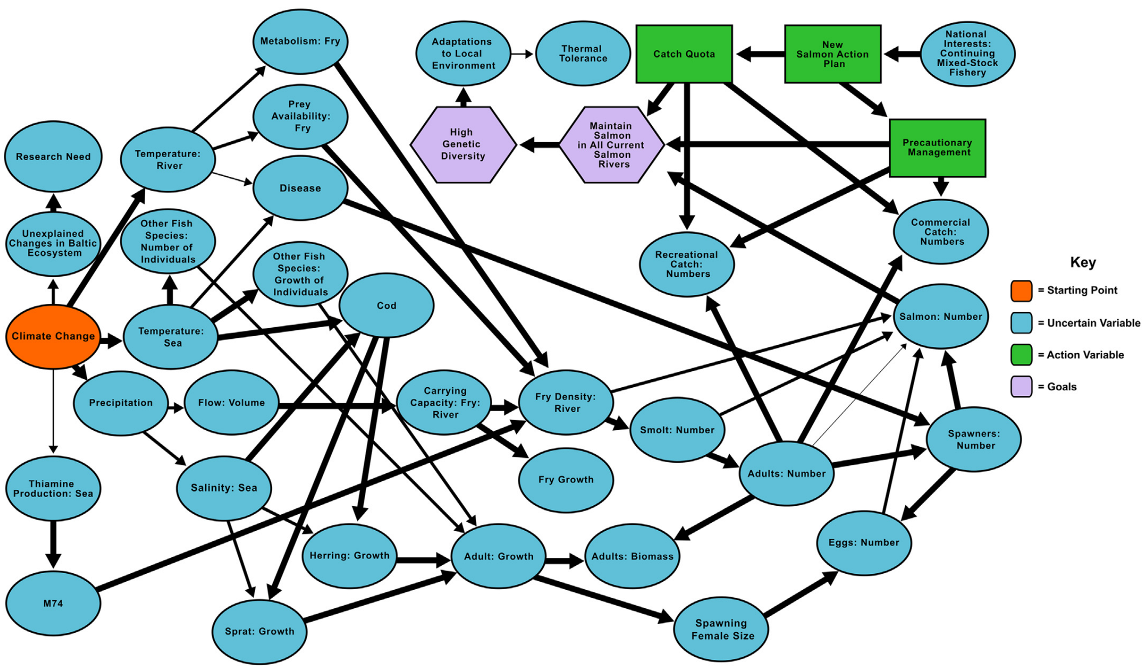

Fig. 3. An example of a stakeholder's influence diagram. Depiction of an influence diagram representing stakeholder F's mental model of the salmon-climate change problem developed using the Rich Elicitation Approach. Each node represents either an uncertain variable, action variable, or goal within the model (see key) and arrows represent causal relationships between variables. Thicker arrows indicate stronger causal relationships.
This figure was adapted from figure 3 in LaMere et al. (2020).

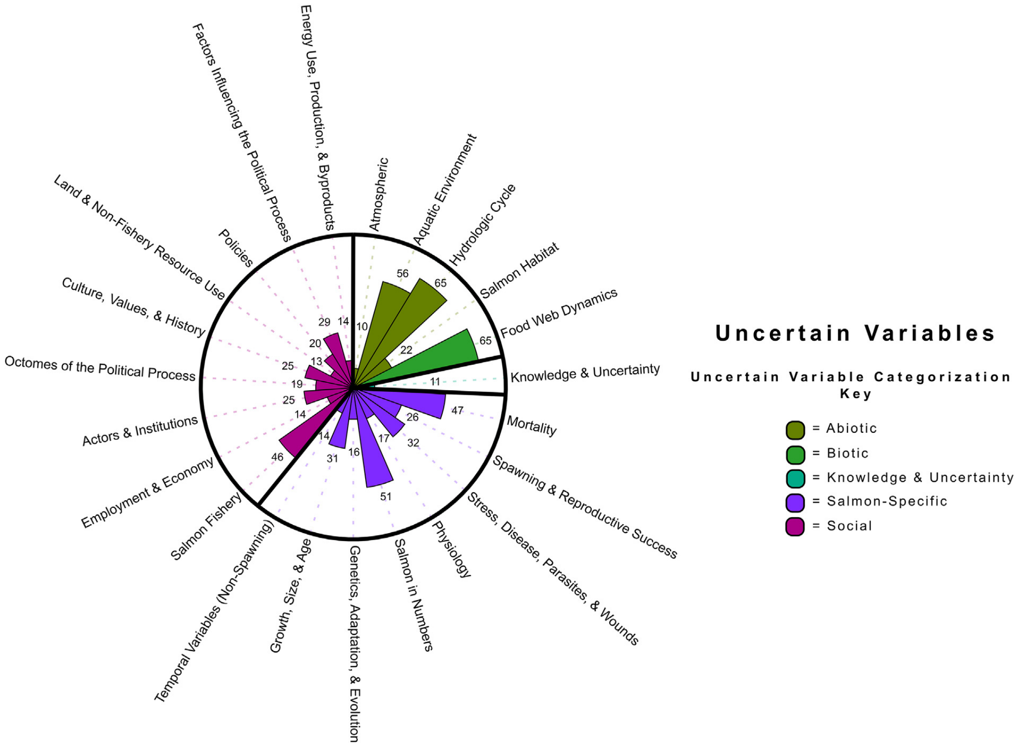

Fig. 4. Categorized uncertain variables. Representation of the 2nd order categories (text) of uncertain variables grouped by the 3rd order categories (color, see key) they fall within. Each 2nd order category is labeled with the number of individual variables it contains. Only the 2nd order categories including ≥10 variables are included in this diagram. These results were produced during the semi-quantitative phase of data analysis.

4.2. Qualitative results

The narratives developed to summarize each stakeholder's influence diagram and elicitation session notes are available in the Appendix, Section A.1.

4.3. Semi-quantitative results

Combined, the 11 stakeholder influence diagrams contained 718 uncertain variables. From Fig. 4 we can see the prominence of different ideas or themes within the stakeholders' influence diagrams. For example, food web dynamics and the hydrologic cycle are represented strongly, with each of the two categories containing 65 variables from across the 11 influence diagrams. Bear in mind, these are not numbers of "unique" variables. Meaning that in many cases the same variable may have been reiterated by several stakeholders. Unsurprisingly, the greatest number of uncertain variables are included in the salmon-specific variables category. However, the social variables category contains the second most and the highest number of 2nd order categorizations, indicating greater diversity in the stakeholders' conceptualization of this portion of the salmon system.

Table 1 depicts the uncertain variables most frequently used across the 11 influence diagrams. All the uncertain variables included in five

Table 1
The uncertain variables most frequently included in stakeholders' influence diagrams.

Uncertain variable	1st order categorization	2nd order categorization	3rd order categorization	Number of stakeholders
Temperature: river	Water temperature	Qualities of aquatic environment & influencing processes	Uncertain: physical	11
Temperature: sea	Water temperature	Qualities of aquatic environment & influencing processes	Uncertain: physical	10
Smolt: number	Number	Salmon in numbers	Uncertain: salmon-specific	6
Spawners: number	Number	Salmon in numbers	Uncertain: salmon-specific	6
Spawning migration: timing	Spatial & temporal spawning variables	Spawning & reproductive success	Uncertain: salmon-specific	5
Adults: number	Number	Salmon in numbers	Uncertain: salmon-specific	5
Egg mortality	Natural mortality	Mortality	Uncertain: salmon-specific	5
Eggs: number	Number	Salmon in numbers	Uncertain: salmon-specific	5
Hydropower	Energy production	Energy use, energy production, & byproducts	Uncertain: social	5
Ice cover: river	Ice	Hydrologic cycle	Uncertain: physical	5
Parr: number	Number	Salmon in numbers	Uncertain: salmon-specific	5
Spawning female size	Size	Growth, size & age	Uncertain: salmon-specific	5
Temperature: air	Air temperature	Atmospheric	Uncertain: physical	5

or more diagrams are included in the table. River and sea temperature occurred most frequently and the number of salmon at different life stages was frequently mentioned as well.

The uncertain variables most frequently (≥5 times) included in stakeholders' influence diagrams and their 1st, 2nd, and 3rd order categorization. The "Number of Stakeholders" column indicates how many stakeholders included the variable in their influence diagrams. These results were produced during the semi-quantitative phase of data analysis.

Altogether, the 11 influence diagrams included 48 goals. These were divided into three 2nd order categories; 1) biological, which included goals related to the salmon and the ecological community, like "protect biodiversity" and "climate change adaptation;" 2) knowledge, which contained goals related to improving the state of knowledge, for example, "improved reliability of catch statistics" and 3) socioeconomic, which included goals like "societal wellbeing" and "achieve fishery sustainability." Fig. A.1 depicts all 1st order goal categories grouped by the 2nd order categories described above. The figure shows that the influence diagrams contained a nearly equal number of biological and socioeconomic goals, 22 and 23, respectively. The biological goals were more uniform, however, again demonstrating higher diversity among the stakeholders regarding their mental models of the social portion of the salmon system.

The influence diagrams also included 122 actions that could be taken to reach the aforementioned goals. These actions were divided into nine 2nd order categories (Fig. A.2). The largest of these categories was action related to salmon fishery management and regulations, with catch quotas and bag limits being the tools the stakeholders most frequently described to achieve their goals for the salmon system in the context of climate change.

As depicted in Fig. 5, the most frequently described environment was the riverine environment, followed by the marine environment. Some variables like those related to fishing generally were categorized as riverine/marine, as fishing for salmon occurs in both these environments, and in the absence of further information, these could not be reliably classified as belonging to one environment or the other. The spawning phase was the most often mentioned salmon life stage and in total, the riverine phases of the salmon lifecycle were more frequently mentioned than the marine phases (Fig. A.3).

The data set containing the hierarchical, environment, and life stage categorizations for each variable from all 11 influence diagrams is available as supplementary data associated with this article.

4.4. Questionnaire results

The majority of stakeholders acknowledged that specific stocks were important to them and identified eight salmon groups of interest (Table 2). These included both specific stocks, those originating from a particular river, and broader salmon groups potentially comprised of multiple stocks. Like, for example, "weak stocks" or salmon in the "Gulf of Bothnia" generally.

The stakeholders also rated their satisfaction with the current management of Baltic salmon generally and of the specific salmon groups they chose, and their satisfaction with the current status of Baltic salmon generally. Typically, stakeholders were neutral or positive about the management of the Finnish and Swedish stocks they named, except Simojoki, whose management was perceived as satisfactory by some and not by others. Those interested in weak Baltic salmon stocks or the Gulf of Bothnia stocks more generally, were dissatisfied with their management. Their feelings about the management of Baltic stocks as a whole, were either neutral or dissatisfied. The stakeholders' responses about their satisfaction with the current status of Baltic salmon were mixed, ranging from dissatisfied to satisfied.

Several stakeholders also chose to submit short written responses about their satisfaction with the current management and status of Baltic salmon stocks. Typically, they focused on their reasons for dissatisfaction, although a few did mention that some stocks have been improving, indicating satisfactory management. Their reasons for dissatisfaction included the following: poaching and misreporting by countries other than Finland and Sweden, continued mix-stock fishing in the Baltic proper, a lack of effective river restoration, a lack of positive development for smaller stocks compared to larger ones, a lack of a common salmon management plan between Finland and Sweden, the need for more reliable catch statistics, a lack of a long-term

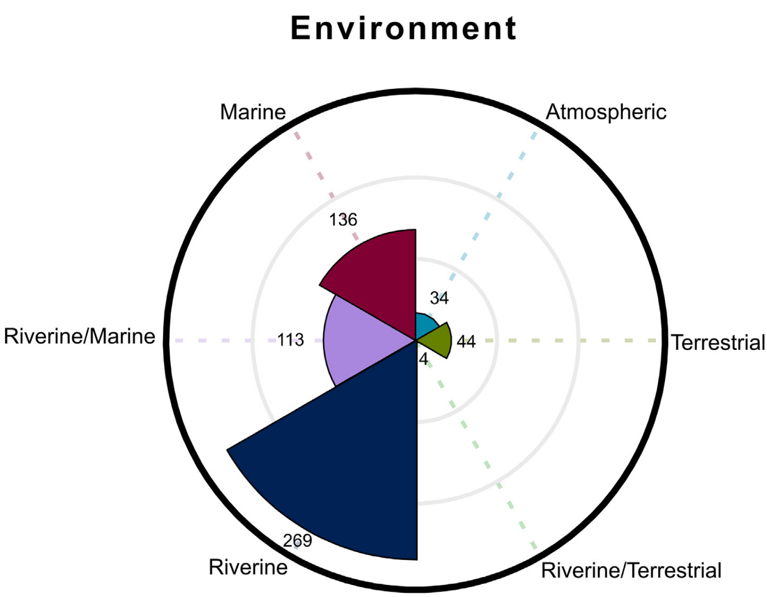

Fig. 5. Frequency of different environments occurring within stakeholders' influence diagrams. Those variables related to two environments are designated with a "/," i.e. any variables related to both the river and sea are categorized as "Riverine/Marine." These results were produced during the semi-quantitative phase of data analysis.

management plan (SAP), a short, intensive fishing seasons requiring large amounts of salmon to be sold at once for a low price, the need for more fishing gear regulations in some areas, and a lack of stock-specific management plans.

In answers to the open response questions, most stakeholders acknowledged that the status of salmon in the Baltic is currently good or at least improving, particularly in the cases of the Tornionjoki and Simojoki stocks. However, despite this positive outlook, most acknowledged that many stocks are still in poor condition and that there is plenty of work to be done to improve the status of Baltic salmon overall. Most commonly, stakeholders described riverine issues, in particular, the need for habitat restoration and the removal of hydroelectric dams. Fishing pressure was also described as a threat to Baltic salmon, specifically mixed-stock fishing, which occurs when fishing in the Baltic proper where adult salmon from multiple stocks mix as they feed. There was some indication that fishery management was working well in Finland and Sweden, but perhaps not in other countries. Disease and lack of a SAP were also described as threats to salmon.

The stakeholders were also asked a suite of questions regarding salmon and climate change (Table 2). Most agreed it is important to consider the effects climate change will have on natural resources when making management decisions and all eleven reported they had previously thought about the effects climate change could have on salmon. Most believed it is likely that climate change will affect salmon in the foreseeable future and that these effects will be significant. However, the stakeholders' views about whether these effects would be negative or positive were mixed, although there were more negative than positive responses. The stakeholders' conceptualizations of the foreseeable future were also likely diverse because their beliefs about when the effects of climate change on salmon would become evident were mixed, spanning from "they already are" to "in 20–50" years. When asked whether or not management would be able to mitigate negative effects of climate change, the stakeholders' responses were fairly evenly distributed; with some reporting that management can mitigate these effects and others reporting that it cannot. Despite this, most stakeholders agreed that if we had a better understanding of how climate change may affect salmon, management could make decisions to better prepare the fishery for the future.

Table 2. The stakeholders' responses to questionnaire questions regarding (A) their satisfaction with the status and management of Baltic salmon, and (B) the importance and relevance of climate change to salmon management. In Section A, the stakeholders were asked to write in the specific stocks that were important to them (specified stocks) and provide a rating of their satisfaction with the management of those stocks specifically and Baltic salmon generally. Questionnaire questions and the raking scale used for each question are italicized. Response options are in bold. Each X represents one stakeholder's response. Xs in the NR column indicate stakeholders who chose not to respond to the question.

When asked to explain their answers regarding whether or not will climate change be positive or negative for Baltic salmon, some stakeholders suggested that salmon production could increase, particularly in the northern Baltic, perhaps as the result of a longer growing season and a faster lifecycle. However, others mentioned that climate change

Table 2
The stakeholders' responses to questionnaire questions regarding (A) their satisfaction with the status and management of Baltic salmon, and (B) the importance and relevance of climate change to salmon management. In Section A, the stakeholders were asked to write in the specific stocks that were important to them (specified stocks) and provide a rating of their satisfaction with the management of those stocks specifically and Baltic salmon generally. Questionnaire questions and the raking scale used for each question are italicized. Response options are in bold. Each X represents one stakeholder's response. Xs in the NR column indicate stakeholders who chose not to respond to the question.

A. Satisfaction with Salmon Management in General & for Specific Stocks										
Questions:	NR	Yes	No							
Are specific Baltic salmon stock important to you?		XXXXXXXXX	XX							
How satisfied are you with the current management of the Baltic salmon stocks you specified & Baltic salmon in general? (1 = Dissatisfied, 5 = Satisfied)										
Specified Stocks:	**NR**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Tornionjoki/Torneå						XX		XX		X
Simojoki				XX		X		X		
Kalix						X		X		
Råne								X		
Mörrumsån						X				
Gulf of Finland: Weak Stocks		X								
Weak Stocks		X		X						
Gulf Of Bothnia				X						
Baltic Stocks in General				XXXX		XXXXXXX				
How satisfied are you with the current status of Baltic salmon stocks? (1 = Dissatisfied, 5 = Satisfied)			X	XXXX		X	XX	XXX		
B. The Importance of Climate Change for Salmon Management										
Questions:	**NR**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
How important is it to consider the effect climate change may have on natural resources in making management decisions? (1 = Unimportant 5 = Important)				X		XX		XXX		XXXXX
How likely is climate change to have an effect on salmon in the foreseeable future? (1 = Unlikely 5 = Likely)				X		X		XXX		XXXXXX
How significant will these effects be? (1 = Insignificant 5 = Significant)	X			X		XX		XXXXX		XX
Overall, will climate change be positive or negative for Baltic salmon? (1 = Negative, 5 =Positive)	XX	XXX	X			XXX		XX		
If the effects climate change will have on Baltic salmon are negative, how much can management mitigate these effects? (1= Not at all, 5 = A lot)		XX		X	X	X	X	XXX		X
If we had a better understanding of how climate change may influence salmon, could we make management decisions to help prepare the fishery for the future? (1 = No, definitely not, 5 = Yes, definitely)				X		X		XXXXX		XXXX
	NR	**Yes**	**No**							
Have you thought about the effects of climate change on salmon before?		XXXXXXXXXXX								
	NR	**They already are**	**In <5 years**	**In 5–10 years**	**In 10–20 years**	**In 20–50 years**				
When will (the effects of climate change on salmon) become evident?		XXXX	X	X	XXXX	X				

may also worsen conditions for salmon in the southern Baltic. Stakeholders described potential changes in water temperature, runoff, river flow, drought, the Baltic food web, feeding areas, disease, and temporal shifts in lifecycle phases (spawning, migrating, and hatching). A few stakeholders found it difficult or even impossible to speculate about the effects climate change could have on Baltic salmon.

4.5. Primary themes from the problem-framing process

Fifteen primary themes became evident from the stakeholders' frames. These themes are each described in the appendix, Section A.3, and are depicted in Fig. 6 below. Fig. 6 shows which theme each stakeholder discussed and the total number of stakeholders that discussed each theme. In the figure, each theme is represented by an abbreviated name (see Appendix, Section A.3).

4.6. Synthesis

The influence diagram in Fig. 7 represents a synthesis of the 15 primary and the causal relationships between them as described by the stakeholders. In this synthesized view, climate change could affect food web dynamics, create phenological mismatches between salmon and their prey, accelerate the salmon lifecycle, cause heat stress in the riverine environment, change disease prevalence, alter river flow, and cause changes in fishing, each of which affects salmon.

In addition to the effects of climate change, during their elicitation session and in their questionnaire responses the stakeholders also described other drivers of ecological change they believe will affect the future status of Baltic salmon. The greatest proportion of these was related to the degradation of the riverine environment caused by anthropogenic factors, like forestry practices, peat mining, water usage, and hydropower. The "human impacts on the riverine environment" node in Fig. 7 represents this idea.

Three themes are depicted as goals in Fig. 7. The first of these, increase salmon populations, is a reflection of all 11 stakeholders' unsurprising desire to see Baltic salmon populations continuing to grow and thrive into the future. However, the stakeholders did describe different motivations for suggesting this goal including to support predator populations, for the intrinsic value of salmon themselves, for the wellbeing of future generations of people, and to support fisheries. As such, this goal is tightly coupled with the second, to ensure the economic security and wellbeing of fishers and their communities. The majority of stakeholders of all different backgrounds, described the importance of maintaining strong fish stocks, which generate revenue via the commercial fishery and increasingly, the recreational fishery as well. In particular, the stakeholders described the importance of this income source in northern Baltic towns, where employment opportunities are often limited. However, most stakeholders acknowledged that salmon must be protected from overfishing nevertheless, which is still a concern despite the increasing size of several stocks. The stakeholders considered the protection of genetic diversity, the last of the goal-related themes, to be crucial, as it provides the best chances for adaptation to ecological change, including climate change. Central to this goal was maintaining and strengthening weak and vulnerable stocks, which they frequently

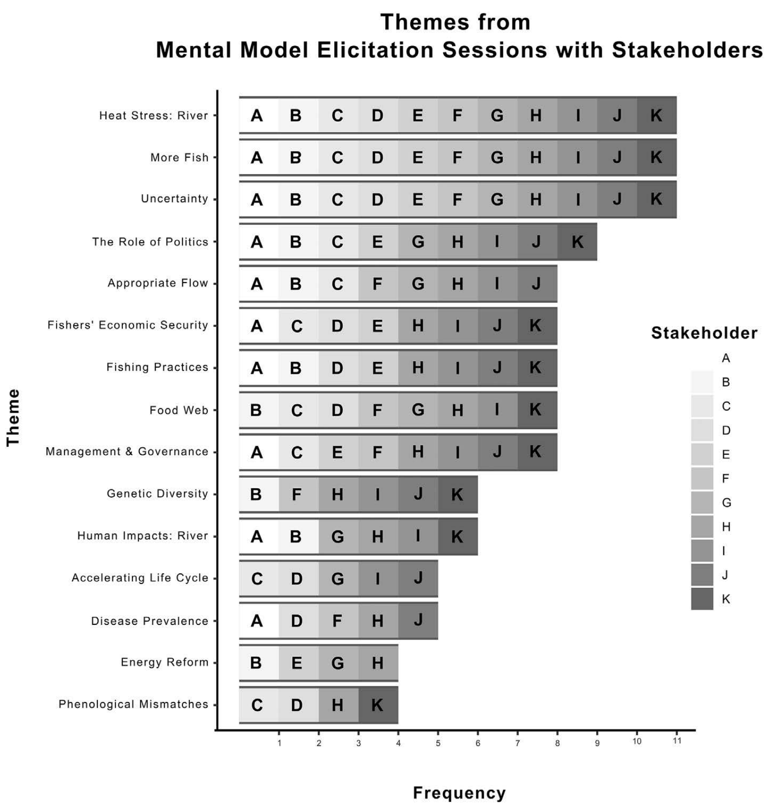

Fig. 6. The number of stakeholders discussing each of the 15 primary themes detected across the 11 influence diagrams. Themes considered to be 'primary' were described by ≥4 stakeholders. The stakeholders contributing to the theme are represented by their letter pseudonyms (key). These results were obtained during the synthesis phase of our analysis.

described as those originating in the southern Baltic region. According to several stakeholders, those stocks are both currently in worse condition than the northern stocks and are more likely to be negatively affected by climate change-driven environmental changes, like reduced flow and rising river temperatures in the near term.

Throughout the stakeholders' elicitation sessions we found three overarching strategies for reaching the goals described above. The first of these was continuing to improve salmon management and governance. Many of the stakeholders were concerned about, for example, the threat of overfishing, fishing opportunity inequalities between nations, and overly lenient regulations on the growing recreational fishery. As such, the stakeholders described a variety of measures, primarily via adjusting quotas and catch reporting requirements, which should be implemented. Additionally, to protect and strengthen individual stocks according to their unique circumstances, several stakeholders suggested stock-specific management plans and banning mixed-stock fishing, to reduce fishing pressure on weak salmon stocks. Instead, they argued, salmon should be fished close to their natal rivers, as is the current practice in Finland and Sweden, to ensure only those stocks strong enough to support a harvest are fished. A few stakeholders also urged precautionary management in the face of the uncertainty that climate change brings and others suggested adaptive management strategies. For example, ending the fishing season early if environmental conditions like water temperature become too taxing for salmon to support fishing as well. Unlike fishery management reforms, most stakeholders did not view political action, the second action-related theme, as within their direct control, although most described the importance of the political system and how it ultimately affects fisheries management, energy, and land-use decisions. However, some stakeholders did suggest their role in advocates. In some cases, stakeholders described the governance process, how to influence it, and the importance of doing so in detail. Notably, the stakeholders described the importance of policy in reforming energy use and energy production strategies, the third action-related theme. According to some stakeholders, changing energy use and production practices is the only route society truly has to influence the progression of climate change. Further, changes in policy also affect decisions about whether to build or remove hydropower plants.

Lastly, all the stakeholders expressed their uncertainty about how climate change will affect the salmon system, with some even adding uncertainty as a variable in their influence diagrams. Therefore, we

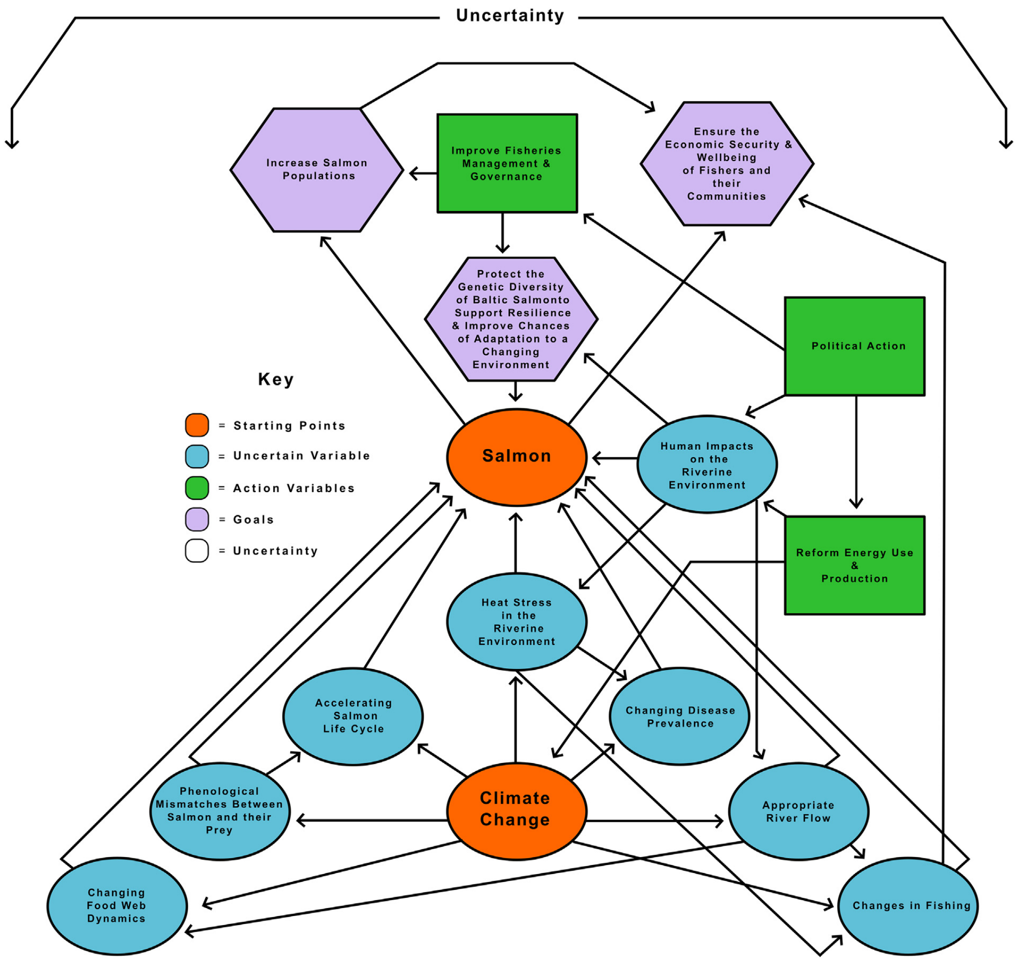

Fig. 7. Synthesis influence diagram. The diagram describes the causal relationships between the 15 primary themes found within the 11 individual stakeholder influence diagrams. See Section 3.2 for information about interpreting influence diagrams. The results were obtained during the synthesis phases of our analysis.

placed uncertainty outside the synthesized influence diagram to represent the uncertainty the stakeholders felt about how climate change could affect the salmon system.

5. Discussion

5.1. Synthesis discussion

Most of the climate change-induced effects listed as variables in Fig. 7 (the 15 themes) have been previously described as potential threats to either Baltic salmon specifically (HELCOM, 2011), or Atlantic salmon more generally (ICES, 2017; Jonsson and Jonsson, 2009). For example, in their 2017 report, ICES discusses many of the same concepts addressed by the stakeholders, including the impacts of climate change on disease prevalence and age at maturity (accelerating life cycle), among others. Multiple reports also describe the importance of maintaining the genetic diversity of salmon (ICES, 2017, 2019; Reusch et al., 2018). Further, Lassalle and Rochard, 2009 found that under conditions predicted for 21st-century climate change, salmon populations are likely to diminish to some extent in the southern Baltic, a concern held by the stakeholders as well. Researchers have also already extensively studied and documented the impacts of anthropogenic activities in the riverine environment and catchment areas on salmon (Elliott et al., 1998; Rivinoja et al., 2001; Romakkaniemi et al., 2003; Young et al., 2011).

As such, the existing literature supports the stakeholders' biological and environmental thinking on a broad level. Indeed, existing literature may have informed the stakeholders' mental models about the effects of climate change on the salmon system. However, even if this is true, the stakeholders specifically applied this information to the Baltic context, where literature about the effects of climate change on salmon is still limited. The stakeholders' influence diagrams also provided a more detailed account of the causal relationships between these ideas than documented previously. The causal chains they created in their influence diagrams can be thought of as alternative hypotheses about how different variables within the salmon system interact. The primary themes within these causal chains are represented within the synthesized influence diagram, Fig. 7. For example, Fig. 7 suggests that, according to the stakeholders, climate change could cause changes in fishing practices. The interested reader can view the influence diagrams and narrative summaries (included in the supplementary material and appendix, respectively) of those stakeholders who discussed this topic (see Fig. 6) for more insight into their hypotheses about the relationship between these variables. This study leaves us with a great number of new questions and hypotheses about the mechanisms by which variables affect one another within the context of the salmon-climate change problem, but this is progress nevertheless, as it presents a foundation to build upon.

The stakeholders' knowledge also provides a more holistic view of the climate change issue in the Baltic context than has been produced previously, as it includes not only the physical and biological environments but their connections with the social environment as well. Although Zandersen et al. (2019) have laid the foundations for investigating the interconnected implications of climate change and societal development of fisheries in the Baltic Sea area, we believe the stakeholders' knowledge could help define this issue more precisely. For example, the stakeholders describe specific changes in the effectiveness of certain gear types and fisher behavior that may occur as climate change continues (see Section A.3.10). As such, this may be an interesting line of inquiry for future studies.

Along these lines, we would also like to draw the reader's attention to the importance and prevalence of social variables within the stakeholders' conceptualizations of the climate change problem. As depicted in Fig. 4, the 3rd order categorization, uncertain: social variables, was the second-largest, following the category for uncertain: salmon-specific variables. The social variables category also contained the highest number of 2nd order categories, indicating the greatest diversity in the variables described. Put another way, the stakeholders had the most divergent perspectives about the social system relative to the other variable categories. Although each influence diagram contained different proportions of each 3rd order category, all contained at least some description of the social system, indicating its integralness to the stakeholders' understandings of the climate change-salmon system issue. This finding reiterates the central role of the social system in fisheries management (De Young et al., 2008), including Baltic salmon management (Linke and Jentoft, 2014), which must not be forgotten when addressing the climate change issue.

The greatest proportion of the environment-related variables included in the influence diagrams concerned the riverine environment and the greatest proportion of the life phase-related variables concerned the spawning stage, which occurs therein. The spawning phase, in combination with the other life stages occurring in the river, comprises the majority of the life phase-related variables. This information may indicate the stakeholders found the riverine environment and riverine phases of the salmon life cycle to be most relevant in the context of climate change or potentially, the most vulnerable to its effects. Alternatively, it could also reflect the greater complexity of the portions of the salmon life cycle occurring within the riverine environment or the state of the stakeholders' knowledge. As such, we encourage future studies to address this topic directly, which may be useful for prioritizing management efforts and allocating resources.

The importance of promoting Baltic salmon's resilience dominates the management actions proposed by the stakeholders. It appears they, as a group, believed the best way to address the effects climate change may have on the salmon system is to reduce other stressors as much as possible, perhaps as determined on a stock-by-stock basis. Therefore, it seems reasonable that the most frequently described action variables were catch quotas and bag limits (Fig. A.2), as fishing has historically had a strong influence on the size of the Baltic salmon population (Romakkaniemi et al., 2003). However, we find it interesting that although the greatest number of variables in both the individual and synthesized influence diagrams represented the riverine environment and described climate change-induced stressors therein (Fig. 5), few action variables targeted rivers. Of course, fishing occurs within rivers as well as the sea. Nevertheless, comparatively few actions addressed the climate change-related stressors salmon may face in the riverine environment. The action variables most directly linked to the riverine environment are included in the “salmon habitat management” and “land use and catchment area” categories in Fig. A.2. We believe this omission may reflect past reliance on catch regulations to manage the fishery, however, climate change may necessitate the expanded use of a broader arsenal of management tools, like riverine habitat protection and restoration, including collaborative efforts with, for example, the forestry, agricultural, and hydropower industries. Further, options for mitigating stressors primarily experience in the riverine environment, like high water temperatures, have been suggested, including increasing tree cover in riparian zones (Blann et al., 2002) and protecting groundwater sources (Carlson et al., 2017), both of which may serve to keep water temperatures low.

5.2. Conflicts & collaboration

In addition to producing a more holistic picture of the effects climate change may have on the salmon system, this study also provided insight into the areas of conflict and consensus that incorporating climate change into the salmon management discussion might encourage. Although there may be disagreement about the specifics, synthesis influence diagrams like ours (Fig. 7), could be used to illustrate broad areas of consensus within problem framing groups to help to drive discussion forward productively. However, as the previous sections describe our participants' synthesized frame and hence the concepts they tend to agree on, we will use the remainder of this section to describe the potential areas of conflict we found between them.

First, although most stakeholders believed climate change will affect salmon significantly, opinions about whether those effects will be negative or positive were more mixed (Table 2). Further, while most believed climate change will affect salmon in the foreseeable future, they disagreed about when that foreseeable future will arrive. For example, some stakeholders believed the effects of climate change on salmon are already evident, while others felt they would become evident later, or even much later (Table 2). As such, whether or not climate change is indeed a threat to Baltic salmon may be in question. If it is a threat, whether or not it is currently relevant might also prove controversial.

Along these lines, during their problem framing sessions, some stakeholders alluded that while climate change is a problem, other issues like overfishing and anthropogenic habitat degradation are more pressing and therefore, more resources and effort should be allocated to correcting them. The stakeholders' attention to anthropogenic impacts on the riverine environment and improving regulations to prevent overfishing in their influence diagrams also emphasize that at least some of them may view these stressors as more relevant than climate change, at least for the time being. Räisänen (2017) came to similar conclusions, stating that in the future, the effects of climate change may be overshadowed by other anthropogenic changes in the Baltic region. On the other hand, the stakeholders' inattention to managing the effects of climate change directly could also have less to do with its low position on their lists of fishery management priorities, and more to do with feelings of helplessness. Perhaps, stakeholders are more apt to focus on stressors they believe they have more control over, like the overfishing. The mixed responses we received about the efficacy of fishery management to mitigate the effects of climate change could indicate the perceived futility some stakeholders feel about managing the effects of climate change on fisheries. However, the results of our study do not decisively conclude how the stakeholders would rank other anthropogenic impacts in comparison with climate change as priorities for salmon management, nor do they define their rationale behind these rankings. This matter should be investigated further by future studies to help fishery management prioritize its efforts according to the values and expertise of fishery stakeholders. Despite the pertinence of other threats to the salmon system, many stakeholders did believe that climate change would have negative impacts on salmon and that a better understanding of its effects could help prepare fishery management for the future, as described previously (Table 2). At the very least, climate change represents an additional environmental stressor that may compound the issues associated with other anthropogenic stressors and is likely to increase in importance into the future (Räisänen, 2017). Therefore, the issue warrants investigation now.

Another potential conflict we envision is about the management of weak salmon stocks in the Southern Baltic, which some stakeholders consider to be the key to safeguarding genetic diversity. While several stakeholders reported they were neutral or satisfied with the management of Finnish and Swedish stocks, two reported they were dissatisfied with the management of weak stocks and all were either neutral or dissatisfied with the management of Baltic salmon in general. Additionally, during their elicitation sessions, several stakeholders described the importance of protecting and improving the management of the southern stocks. This indicates that some Finnish and Swedish stakeholders may not be satisfied with the southern Baltic nations' salmon management strategies or perceive that changes will become necessary as climate change continues. If the nations surrounding the Baltic Sea decide to discuss the climate change issue collectively, under, for example, the directive of a new SAP, this issue should be considered thoroughly ahead of time, and statements should be structured to promote constructive problem solving rather than unproductive criticism. Further, if ending mixed stock fishing were suggested as a strategy to avoid overfishing weak stocks, thoughtful, perhaps creative concessions for those southern nations who would then be excluded from the fishery should be proposed.

Continuing with international relations, several stakeholders described strong relations between Finland and Sweden regarding salmon management. They viewed the proliferation of the Tornionjoki/Torneå salmon stock as a joint management success and seemed pleased that both nations had decided to stop longline fishing targeting mixed salmon stocks feeding in Baltic Main Basin. However, some stakeholders did call for improved cooperation between Finland and Sweden and even a joint salmon management plan. In particular, one stakeholder discussed the importance of changing regulations to equalize competition between Finnish and Swedish commercial fishers (see Appendix, Section A.1.1). Although this concern is not directly related to climate change, strong cooperative relationships between nations can only be beneficial for addressing complex problems like environmental change.

Additional conflicts may arise surrounding increased competition between salmon and humans for riverine resources. For example, climate change may increase the demand for renewable energy, including hydropower. Indeed hydropeaking, the practice of releasing pulses of water to meet electricity demand, has increased in Nordic rivers in recent years, indicating rising consumption of hydroelectric power (Ashraf et al., 2018). Hydroelectric dams reduce salmon's access to spawning grounds, even when fishways are available (Rivinoja et al., 2001) and also affect the quality and quantity of both downstream and upstream habitat. Specifically, because hydropeaking influences fish behavior (Scruton et al., 2003; Young et al., 2011), mortality (Saltveit et al., 2001; Young et al., 2011), and spawning (Haas et al., 2016; Vollset et al., 2016; Young et al., 2011). To reduce the conflicting interests between increasing hydropower demand and salmon habitat, we suggest the timing and magnitude of hydropeaking-related water discharge fluctuations should be adjusted to be as sensitive as possible to salmon requirements (Harnish et al., 2014). Stakeholder G suggested an alternative strategy to manage the trade-off between salmon and hydropower. He proposed the creation of a few high-efficiency hydroelectric dams on large Swedish rivers and removing less efficient, older dams from smaller rivers. Then, rehabilitating the small rivers to provide suitable habitat for salmon (see Appendix, Section A.1.7). In addition to hydropower, increasing municipal and industrial demand for water could exacerbate increasingly prevalent drought conditions in some areas.

Lastly, as described previously, the stakeholders recognized the importance of balancing the health of salmon stocks with the economic security and wellbeing of fishers and their communities. Measures to protect salmon stocks from overexploitation, like reduced quotas and ending the mixed stock fishery, could reduce profit margins for fishers or exclude them from the fishery altogether, creating conflict. Climate change could exacerbate this pre-existing problem, either by diminishing salmon stocks or by inciting proactive management to reduce salmon mortality or conserve weak populations on grounds of protecting genetic diversity. Either way, for these reasons, including climate change in the fisheries management conversation could be perceived as a threat to the livelihoods of commercial and recreational fishers, necessitating careful negotiation and creative problem-solving.

5.3. Participatory modeling in Baltic salmon management

In addition to a better understanding of the problem climate change poses for salmon, this study also demonstrates how stakeholder knowledge and values can be incorporated into problem framing, which should serve as the first step in solving fishery management-related problems (Bardwell, 1991). Including stakeholders at this early stage is especially important in the context of Baltic salmon management because, despite the encouraging outcomes of collaboration under the SAP (1997–2010), salmon management has been a contentious issue since times immemorial (Ignatius et al., 2019). Today, a diverse array of stakeholders at both the national and EU levels, including decision-makers, commercial fishers, recreational fishers, scientists, managers, and environmental non-governmental organizations, must regularly address divisive questions about salmon management (Ignatius and Haapasaari, 2018). The answers to these questions, which are deeply and understandably tied to stakeholders' values and beliefs, tend to clash, leading them to struggle against one another (Ignatius and Haapasaari, 2018). Unfortunately, efforts to reduce such conflicts and give the stakeholders a voice in salmon management have often been imperfect, leaving them feeling embittered and unheard (Ignatius and Haapasaari, 2018; Linke and Jentoft, 2014).

These issues are at least partially responsible for the difficulty in establishing a long-term management plan for Baltic salmon stocks (Linke and Jentoft, 2014) and may therefore also inhibit any future multinational attempts to address the problem climate change poses for salmon management. However, research indicates that providing stakeholders with meaningful opportunities to participate would improve management outcomes. For example, (Haapasaari et al., 2007) found that offering such opportunities to Baltic salmon fishers would improve their commitment to sustainable fishing practices. Therefore, we believe participatory co-management of Baltic salmon is essential and that all relevant stakeholders must be meaningfully included. Further, making certain that problem-solving related to salmon management begins with participatory problem framing, like the process described here, could ensure the problem is considered from all relevant perspectives, thus producing a more holistic knowledge base from which to develop better informed and more mutually acceptable solutions. Problem framing could also help address the conflict between stakeholders, which is particularly relevant in the Baltic salmon management context (Linke and Jentoft, 2014).

5.4. Methodological considerations

This study contains a few limitations worth noting. First, analyzing the large, complex influence diagrams, and elicitation sessions notes via the methods we used here is time-consuming, limiting the feasible number of study participants. Fuzzy cognitive mapping (FCM), a method for creating semi-quantitative cognitive maps similar to the influence diagrams presented here, could provide a solution (Gray et al., 2014, 2015; Olazabal et al., 2018; Özesmi and Özesmi, 2004). FCM provides streamlined methodological options for aggregating stakeholders' conceptual models (Aminpour et al., 2020; Gray et al., 2014; Özesmi and Özesmi, 2004), which are more conducive to including a large number of stakeholders in the problem framing process. FCMs also allow the calculation of several useful metrics, for example, the centrality index, which represents the relative importance of specific concepts within the conceptual model (Gray et al., 2014). Relevant nodes can also be collapsed into themes, helping deconstruct large, complex maps (Olazabal et al., 2018). Further, FCMs can be used to model how changes in one or more of the system variables affect the states of other variables in the model (Aminpour et al., 2020; Olazabal et al., 2018). We believe that like the influence diagrams, FMCs could be easily converted into Bayesian risk assessment models, making FMC and Bayesian modeling compatible partners for natural resource management. Hence, we recommend the FMC approach for further problem framing effort, particularly those including a higher number of stakeholders.

Second, many of the stakeholders did not complete the task of adding effect strengths to their influence diagrams, which is why we have not included this information in the results presented here. Additionally, we suspect the stakeholders may have interpreted the effect strengths in different ways, with some conceptualizing them as degrees of uncertainty and others, as the magnitude of impact. As such for future studies, we suggest facilitators use clear language to explain which information is expected from the stakeholders. We discuss these issues and others related to mental model elicitation in more detail in LaMere et al. (2020).

Third, we believe including all relevant stakeholders is crucial for effective fisheries management (De Young et al., 2008). However, we recognize that representatives from some key stakeholder groups, like commercial fishers, were absent from our problem framing due to the limited reach of our snowball sampling strategy. Therefore, we suggest that as the climate change conversation matures in the Baltic salmon management context, an additional problem-framing study should be conducted, paying special attention to include any groups that were absent from this first round of problem framing.

Lastly, as this portion of the problem framing draws to a close, we should plan a follow-up meeting to discuss the results with the participating stakeholders. Such a meeting would give them a chance to comment and adjust the frame as they see fit. Perhaps most importantly, however, a group meeting would provide them a forum to learn about and discuss the different individual frames collected during this study. Thereby expanding their mental models and allowing them to grow as problem solvers who can approach the problem from multiple perspectives themselves (Bardwell, 1991).

Additional methodological considerations about the mental model elicitation process are presented in greater depth in LaMere et al. (2020).

5.5. Future directions

Based on the results of this study and the concerns expressed in the existing literature (HELCOM, 2011; ICES, 2017, 2019), we assert that while climate change is not the only factor influencing Baltic salmon populations, its effects are nevertheless imminent. As such, we urge ICES to incorporate climate change effects into their existing stock assessment model (Michielsens et al., 2008) expediently to ensure stock projections remain as realistic as possible. The accuracy of these projections is crucial, as they form the basis of ICES' advice to the EU (Kuikka et al., 2014) and thereby enable informed management decisions.

The problem-framing results presented here can assist ICES in determining which concepts and variables to incorporate into their model and the individual stakeholder influence diagrams can serve as alternative hypotheses about the causal dynamics operating within the salmon system. Further, as a next step, stakeholders could build directed acyclic graphs (DAGs), connecting the concepts and variables defined in this study with the relevant aspects of the current stock assessment model, via a process similar to the one described by (Haapasaari et al., 2013). Instead of the effect strengths collected for the influence diagrams presented here, parameterized DAGs include quantified joint probability distributions and define whether two variables are positively or negatively correlated (Jensen and Nielsen, 2007). Owing to these attributes, parameterized DAGs can be integrated into one stock assessment model via Bayesian model averaging (Mäntyniemi et al., 2013). Developing parameterized DAGs would also allow Value of Information (VoI) analysis to be conducted (Mäntyniemi et al., 2009). VoI determines the maximum amount a decision-maker should be willing to pay to obtain more information before making a decision. Therefore, VoI is a central concept in determining what data to collect to assist cost-efficient decision-making.

5.6. Conclusions

In summary, we framed the problem climate change poses for Baltic salmon management by combining the individual perspectives of salmon stakeholders. Through this approach, we identified 15 common themes describing the effects climate change may have on the salmon system, acceptable goals for the system considering climate change, and actions that could be taken to reach those goals. In addition to developing this common ground, problem framing also allowed us to approach the climate change issue from a variety of perspectives to define causal linkages within the system that might have otherwise been missed, explore the context surrounding the issue, and identify potential areas of conflict. We believe participatory problem framing efforts like this are particularly important in the context of contentious natural resource issues, like the salmon fishery, to ensure all relevant stakeholders are meaningfully included in the management process from the outset. We hope this study begins the process of developing the knowledge base necessary for integrating climate change into Baltic salmon management and encourages the use of problem framing in complex fisheries management situations to address emergent threats for the benefit of both the fish and the people who value them.

CRediT authorship contribution statement

Kelsey LaMere: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration, Funding acquisition. **Samu Mäntyniemi:** Conceptualization, Methodology, Writing - review & editing. **Päivi Haapasaari:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140068.

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Appendix

The Effects of Climate Change on Baltic Salmon: Framing the Problem in Collaboration with Expert Stakeholders

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A.1 Narrative Summaries of Stakeholder Frames

A.1.1 Stakeholder A

Stakeholder A approached the salmon-climate change problem primarily from the perspective of the Torniojoki River and was particularly concerned with securing the well-being and economic security of anglers (both commercial and recreational) and communities along the river's banks. For A, achieving these goals meant ensuring successful salmon management, via strong cooperation between Finland and Sweden and by producing reliable catch statistics to support adaptive management. In A's opinion, an improved fishery management system would likely make it easier to address other challenges, like climate change. For example, a strong, internationally supported adaptive management system could be used to intervene mid-fishing season if the fish were found to be struggling as the result of prevailing environmental conditions. A described one challenge currently disrupting fishery management relations between Finland and Sweden in detail: because Swedish fishers begin fishing earlier than their Finnish counterparts do and as there is low demand for Baltic salmon among Swedish consumers, Swedish fishers can flood the Finnish market with their catch, thereby outcompeting Finnish fishers. Presumably, resolving such conflicts would improve cooperation between Finland and Sweden, thus improving their ability to jointly address emerging management challenges. A also discussed the environmental portion of the salmon system more directly, by describing the potential effects climate change could have on the riverine system in terms of changing river temperature, flow, and ice cover. For example, A suggested that high water temperatures, likely the most important climate-related factor, and low summer flows could stress the salmon, increasing their susceptibility to disease, and making them more difficult to catch. Changes in flow could also affect fishers, as flow affects the efficiency of flow net fishing gear and high flows unleash debris, making fishing with lures difficult. If salmon become more difficult to catch due to warmer temperatures or difficulty using lures, this could impact the recreational fishing industry and deprive local economies of an important source of revenue. According to A, changes in peak flows resulting from changing snowmelt patterns could ultimately affect river pH, again affecting salmon's stress levels. Interestingly, A did not discuss changes in river ice cover in terms of its direct impact on salmon, but on the public’s perception of the salmon’s wellbeing. Reduced ice cover could expose ill, exhausted, and dying post-spawn salmon, which may be alarming to the public.

A.1.2 Stakeholder B

According to Stakeholder B, more important issues than the politically unpopular topic of climate change are currently facing Baltic salmon. For example, disputes over fishing rights ownership and fishery management. However, B did suggest that climate change will affect salmon, although these effects will be highly complex and often indirect. According to B, protecting the small, weak Southern Baltic stocks is particularly important in the context of climate change because they are likely to be affected first and as a source of genetic diversity, their persistence improves the odds that Baltic salmon as a species will adapt to changing conditions. The challenges B believed will face the southern stocks were primarily riverine and related to changes in the hydrologic cycle, specifically reduced flow, which could increase salmon mortality and reduce the suitability of spawning habitat. Despite these assertions, seemingly in contrast with most other participating stakeholders, B believed that climate change will have a stronger impact on the marine phase of the salmon’s life cycle than the riverine. For example, climate change could impact food web dynamics and therefore, prey availability at sea, which may, in turn, lead to higher mortality rates, particularly for smolts from both hatchery and wild origins. Changing food web dynamics may also lead to a diet at sea richer in sprat than herring, which could ultimately increase the prevalence of thiamine deficiency syndrome, M74. Further, changes in sea temperature could affect the timing of the spawning migration or changes in the migration route, affecting the fishers' ability to catch them. B suggested that if salmon populations begin to decline significantly, the conversation surrounding salmon management may move away from fishing rights disputes and toward conservation, at least for those stakeholders whose livelihoods are not directly dependent on salmon sales. Despite this conceivable change in attitude, B warns that if salmon populations appear to be beyond saving, they may lose their standing as a conservation priority and political will could be directed toward damming salmon rivers as a source of renewable energy instead.

A.1.3 Stakeholder C

Stakeholder C steadfastly believed in the efficacy of well-informed salmon management, whose goal is to safeguard salmon for their own sake, for future generations, and for their utility as a commercial and recreationally popular species. According to C, with perfect knowledge about the salmon system, management can be adapted to handle any stressor, including climate change. However, C acknowledged that unfortunately, a great deal of uncertainty exists with regard to the effects of climate change on salmon, which are undoubtedly complex and often indirect, making them difficult to understand. To make the climate change problem less complicated, C chose not to address the human component of the salmon system, reflected by the low proportion of social variables included in the influence diagram. One of the overarching themes C described was the importance of timing throughout a salmon's life, which may be disturbed by climate change. For example, C suggested that changes in air temperature, river temperature, and the hydrologic cycle could ultimately affect both the timing of the emergence of fry from the river bottom and their prey, creating a phenological mismatch between them. Two additional themes within C's diagram were the prominence water of temperature and the hydrologic cycle. C suggested that increased water temperatures could be stressful for salmon, particularly within their riverine habitats because, in the river, fish cannot dive in search of suitable temperatures. However, rising water temperatures could also stimulate growth, accelerating the salmon lifecycle, resulting in potentially large populations. On the other hand, C suggested that increased precipitation and higher flows could increase the amount of dissolved organic material reaching the sea, affecting the sea's microbial loop, which may ultimately affect the amount of energy available for higher trophic level organisms, like salmon, reducing their numbers. Changes in flow could also affect the size and timing of the plume of river water extending into the sea, influencing the salmon's ability to smell their natal river and complete their spawning migration. Despite these negative consequences of a changing flow regime, C also suggested it may have some benefits for salmon. For example, higher flows and increased precipitation may dilute the Baltic, reducing the amount of energy salmon must spend to adapt to saltwater, and in turn, their stress levels as they enter the sea environment. Another potential benefit of climate change could be less riverine ice cover, which would reduce the frequency of ice scraping the river bottom in spring, which disturbs eggs.

A.1.4 Stakeholder D

Like stakeholder C, stakeholder D also chose to focus primarily on the salmon lifecycle and the climate change-related problems the fish may face during each stage, largely choosing to ignore the human element of the salmon-system. However, D's diagram does include both commercial and recreational fishing effort and timing. Naturally, these variables impact salmon mortality, but interestingly, D saw a direct connection between them and climate change, suggesting that changes in precipitation, cloud cover, and air temperature could affect fisher behavior, and therefore, fishing effort and timing. The importance of fishing was also prominent in the goals D included in the diagram, which hint at the importance of maintaining a consistent livelihood for fishers while avoiding the salmon stocks' collapse. According to D's diagram, sea and river temperatures will be the main drivers of change for Baltic salmon. In both of these environments, water temperature affects the prevalence of salmon diseases and parasites. In the river, water temperature affects dissolved oxygen concentration, and therefore, egg mortality. Further, in conjunction with cloud cover, water temperature changes also affects primary production in both the river and sea, which results in cascading effects within the food web including, changes in predator and prey abundance, and their phenological distribution. Such changes affect the growth and mortality of both juvenile and adult salmon. D's diagram also describes how climate change may indirectly influence salmon adaptation, by suggesting that changes in natural and fishing mortality will drive adaptation, which could result in changes in the salmon's life history strategy, like the probability of smoltification. The actions included in D's diagrams suggest that scientifically determined catch quotas are the tools to be used to affect the salmon-climate change problem.

A.1.5 Stakeholder E

From stakeholder E's diagram two main points are clear: 1) the wellbeing and economic security of fishers and residents in the northern Baltic region must remain secure and 2) it is imperative to protect biodiversity, of which, salmon are a part. E sees securing these goals, particularly biodiversity protection, as highly social and largely international matters. To these ends, E suggests that all nations and all people must honor their commitments to international agreements like the Paris Climate Accord and the Rio Convention on biological diversity. Honoring these agreements also entails regulating industrial practices and coal use to manage climate change itself. NGOs and individual citizens have the further responsibility of ensuring decision-makers adhere to these commitments. On a smaller scale, effective cooperation between Finland and Sweden is important for Baltic salmon management. Beyond the conversation focused on the human portion of the salmon-system, E also explained that climate change may increase the difference in temperature between the river and sea, causing salmon to pause for longer in the estuary to acclimate before resuming their spawning migration. The resultant higher mortality rates may be further exacerbated by river temperatures, which may stress the fish and lead to further mortality. During this pause, salmon will be more vulnerable to both fishing pressure and seal predation. River temperature specifically may also influence the timing and duration of spawning, which could affect fishing opportunities.

A.1.6 Stakeholder F

Stakeholder F's diagram began with a discussion about the riverine phases of a salmon's life cycle, which may be impacted by both changes in river flow and temperature. Reduced flow could prove negative for salmon fry, by constricting the livable, foraging area and hence, effectively reducing the carrying capacity of the river. River temperature could also change both the amount of available prey for fry and fry metabolism, which if disproportionate could affect the density of fry in the river. Temperature both, in the river and at sea could also have an impact on disease. Along these lines, F also suggested that climate change may affect the production of thiamine in the Baltic Sea through uncertain mechanisms, which could affect the prevalence of M74. Moving on to the sea phase of the salmon life cycle, F described the confounding changes climate change induces, in terms of its influence on the Baltic food web and ultimately, on salmon. F discussed how increased precipitation may result in poor growing conditions for sprat and herring, resulting in less food to fuel salmon growth. Conversely, however, lower salinity and warmer sea temperatures could reduce the cod population, resulting in less competition for prey for salmon. Such changes could improve conditions for other potential competitors, like pike and pike perch though. Faced with this type of complexity and uncertainty, F recommended a new Salmon Action Plan focused on precautionary fishery management and the conservation of all salmon stocks to safeguard salmon genetic diversity.

A.1.7 Stakeholder G

According to stakeholder G, weather patterns will likely become warmer and more extreme in the coming years, resulting in increased water temperatures, more prevalent storms, and increasingly unpredictable precipitation patterns. G believed warmer water temperatures alone are not likely to decimate salmon, at least not in the short term, considering they are capable of living as far south as France. However, warmer water temperatures could affect how quickly salmon smoltify, leading to smaller, younger smolts. Consequently, smaller smolts may be at a higher risk of mortality. Changes in river temperature paired with changes in flow (including high flows and droughts) may also affect the riverine food web. Specifically, such changes could alter both the amount of available prey, particularly insects, and the number of predators. Changes in river flow may also have consequences for the salmon’s reproductive success, as river flow must be amenable to facilitate this process. G was also concerned about changes in the food web in the marine environment, suggesting that changes in temperature and salinity could lead to influence zooplankton production and therefore, sprat and herring production as well. Like several other stakeholders, G expressed concern about how changes in sprat production could influence the prevalence of M74. If the Baltic Sea were to become more dilute as a result of a greater influx of freshwater, the energy required for osmotic regulation could decrease, reducing smolt mortality and increasing the amount of energy available for growth. G suggests that the salmon's ability to adapt to changing conditions will prove critical for their survival. In addition to discussing the ecological components of the salmon system in depth, G also described humanity's role in it. While, like many other participating stakeholders, G believes that catch quotas can be used as a tool to help manage the salmon fishery under conditions of climate change, G tended to focus on more large-scale strategies to influence the salmon system. For example, G said reforming energy consumption is the best and only true strategy to manage climate change. To these ends, G described his ideas for solutions to this problem, suggesting increasing home solar cell use, wind energy, and nuclear energy. He also described a strategy for Sweden in particular, which would involve damming a few large rivers and constructing high-efficiency power plants. With the installation of proper infrastructure, excess hydropower could be exported to other European nations with less access to renewable energy sources. Smaller, less efficient dams would be removed in Sweden to improve the quality of those habitats for salmon. G also suggested that political will is required to both reform energy use, mandate environmentally-friendly industrial practices and set fisheries policy. As such, understanding the political agenda, context, and how to influence it is vital. G suggests that while science does inform policy, it is not enough. To make real change in favor of environmental causes requires effective advocacy, which is related to factors such as the receptiveness of decision-makers, strong coalitions, personal qualities like credibility and adept social skills, and stakeholder support. According to G, most people do want salmon to thrive, they are not controversial in the way that other species like wolves are. However, the wellbeing of salmon could easily be overshadowed by other issues related to climate change, like climate refugees.

A.1.8 Stakeholder H

According to Stakeholder H, climate change is rarely discussed within the fisheries context at the EU level. This is in part because professionals involved in fisheries management do not have strong traditions of speaking about climate change, are perhaps poorly informed about it, and may not see its relevance to fisheries. Fisheries and climate change are dealt with within separate branches of the EU and little cross-pollination between these branches exists, which may also contribute to climate change's absence from the fisheries discourse. H suggested increased contact between these branches may help the fisheries discussion evolve and he suspected this is more likely to occur as climate change becomes more and more prominent on the EU agenda. A similar disconnect between fisheries and climate change exists at the national level. Despite climate change’s increasing prominence on the EU stage, it is not perceived as a strong threat in Northern Europe because temperatures in the region are cool in comparison to other areas within Europe. However, H stated that the Finnish meteorological community has warned that Finland will experience the effects of climate change and soon. According to H, some have suggested that climate change may increase the abundance of salmon’s prey species, which could increase salmon productivity, but otherwise described primarily negative possible consequences for salmon. Within the riverine environment, changing water temperatures could become less suitable for eggs. Changes in precipitation, ice cover, and the rapidity of snowmelt, could also cause flooding, consequently harming salmon eggs. Further, at warmer temperatures salmon concentrate around cold water refugia, which could increase the prevalence of disease and make them more vulnerable to predation. Warmer temperatures could also increase more heat-tolerant invasive species' (like rainbow trout) competitive advantage for resources like spawning sites and prey. As the sea temperature changes, it may become more vulnerable to the establishment of invasive species. These, H suggested, are likely to come from the Caspian or the Black Sea via the Russian canal system. Other issues related to climate change threaten the marine environment as well, including nutrient runoff from agriculture and forestry, which may increase as precipitation increases. If salmon numbers decrease, this would be highly problematic for commercial and recreational fishers, predators, and the Baltic ecosystem as a whole. Therefore, helping salmon to achieve a favorable conservation status is imperative. Favorable conservation status entails a large number of salmon distributed across their native geographic range with access to quality habitat. This achievement would help sustain predators and fishers alike. Reductions in the number of salmon could be particularly problematic for communities in Lapland, which rely heavily on the revenue recreational fishing and associate tourism, bring in. Changes in temperature could also alter salmon migration patterns within the Baltic making them more difficult or impossible to catch for both recreational and commercial fishers. H offered several strategies that could be undertaken to manage salmon in the face of climate change, most centered around reforming land-use practices. For example, changing forestry and peat mining practices, protecting bogs and mires, and remaining committed to reducing agricultural runoff. These practices should help decrease nutrient loading and stabilize the hydrologic cycle, increasing its resilience should precipitation increase. H also described the importance of groundwater protection, which helps regulate river temperature. A variety of legislative tools including an updated Finnish Water Act and the Polluter Pays Principle could help further ease threats to riverine habitats. Lastly, owing to their cultural significance, H suggested salmon could be used as a flagship or poster species to help promote efforts to mitigate the effect of climate change on behalf of other, less charismatic species.

A.1.9 Stakeholder I

Stakeholder I expects differential changes in precipitation between the northern and southern Baltic, with less precipitation resulting lower flows in the south and more precipitation resulting in higher flows in the north. Higher flows in the north, particularly during summer, could be positive for salmon, increasing their ability to reach previously inaccessible small streams and tributaries. The opposite may be true in the southern Baltic on the other hand. Human water use for municipal, industrial, and hydropower needs could reduce flow as well, creating competition between people and salmon for water, particularly if drought becomes more prevalent. In the south, river temperatures may become too high for salmon, whereas in the north, warmer river temperatures could spur juvenile feeding and growth, allowing salmon to smoltify earlier. Earlier smoltification could lead to larger salmon populations, however, if this shift occurs too quickly, it could increase smolt mortality. Increasing fish populations could increase fishing pressure as well. Climate change could also impact the Baltic food web, as reduced ice cover could lead to a longer growing season for algae, which could increase the prevalence of anoxic "dead zones." The presence of these anoxic zones could negatively impact the salmon's prey species and ultimately salmon growth. I believes increasing the number of salmon, particularly from weaker stocks is an important goal for the system. More salmon could then improve their likelihood to adapt to changing conditions as climate change progresses and provide better experiences for recreational anglers, ultimately raising the value of the fish. According to I, fishing pressure, particularly fishing the mixed stock in the Baltic Proper, is the greatest threat to salmon. Therefore, he encourages appropriate quotes and suggests that fishing the mixed stock, which could heavily impact weaker stocks, should be banned.

A.1.10 Stakeholder J

As climate change progresses, Stakeholder J expects higher temperatures in both the river and sea, changes in river flow, and potentially, longer production seasons due to warmer water temperatures and less ice cover. J does not expect these changes will be particularly detrimental for salmon, at least not in the short term. Higher winter flow could be beneficial for fry because this would provide larger production areas and reduce the chance of anchor ice, which can affect fry mortality. J also suggested that warmer river temperatures and longer production seas could lead to more rapid egg and fry development and growth. This could result in smoltification at an earlier age, resulting in more productive salmon populations. On the other hand, rising temperatures could leave salmon more susceptible to disease. Presently, Ulcerative Dermal Necrosis (UDN), is of concern. This disease, suspected to be of viral origin, causes lesions on the skin, which are then infected by Saprolegnia fungus. Saprolegnia infections are common in salmon post-spawning when salmon are covered in wounds from migrating and fighting. However, UDN and the co-morbid Saprolegnia infections can kill salmon before spawning, thus diminishing the population. The Swedish Veterinary Authority is currently researching the causes of UDM. J suggests that changing temperatures at sea could affect the timing of the spawning migration, which would impact the duration of the fishing seas and could also affect the amount of time salmon spend in the river, which might affect their risk for disease. Despite these possible climate-related effects, J believes the greatest threat to salmon is overfishing. This, he suggested, has been dealt with quite successfully in recent years, particularly since Finland and Sweden stopped mixed-stock fishing. Nevertheless, improvements to fisheries management should continue. For example, J suggested a new online-based catch reporting system and gill tags, which could help to generate more accurate catch statistics. Additionally, since the end of Finland and Sweden's mixed-stock fishing practices, there is more certainty about which stock is being fished, opening the possibility for stock-specific management plans. Ensuring the survival of all stocks, with particular emphasis given to protect the weak ones is important as they are a source of genetic diversity. Genetic diversity provides salmon with the best chances to adapt to climate change and resilience to disease. All stocks are also intrinsically valuable. J also described the structure and role of politics in fishery management, including the EU's role in setting and partitioning catch quotas and the role of national governments in determining national fisheries management strategies. J suggested that because salmon is such a popular species, the more salmon there is the more conflict there will particularly with fishers, who may press for regulation changes, including an increased quota. However, J sees this as a positive problem, compared to having very few salmon left.

A.1.11 Stakeholder K

Stakeholder K suggests climate change could lead to increased precipitation, which will increase runoff from catchment areas to rivers. Increased runoff subsequently increases sedimentation and nutrient loading. This is particularly problematic during the autumn, winter, and spring months because this is a critical time for salmon eggs and fry nestled within the river's gravel beds. Sediments and nutrients reduce the flow of clean, oxygenated water the young salmon need to develop, grow, and survive, essentially suffocating them. Ditches used to drain land to promote tree growth for forestry and clear-cut forestry are major contributors to the runoff problem, however correcting it is difficult because forestry is a culturally and economically significant industry in Finland, with strong political ties. K explained that indoctrination into the forestry culture or the belief that making one's living from the land is a good thing begins early with school-age children and may have its roots during from the post World War Two era, when the heavy use of natural resources was necessary to fuel industry and ultimately, to pay off Finland’s war debts. Peat mining and agriculture also contribute to sedimentation and nutrient loading and are also entrenched in Finnish culture. Fortunately, now there are several measures to help control sedimentation. Beyond changing river flows, changing river temperatures could also create a phenological mismatch between fry and their prey. In essence, eggs could hatch before there is any food available for the fry, leading to mortality. Temperature could also alter the species composition within rivers, resulting in more predators and thus higher parr mortality. Further, high river temperatures could kill adult salmon, which would lead to less production overall. In Finland, salmon still have limited access to rivers due to obstructions like dams. Only two wild and one semi-wild salmon rivers exist in Finland. This reduces the resilience of Finland's salmon; losing one wild salmon river due to an accident or disaster would have a massive effect on the population overall. Therefore, historic salmon rivers need to made accessible restored, and their populations rehabilitated to mitigate this risk. The restoration of historic salmon rivers could include dam removal or the construction of fishways (the more natural the better), the creation of spawning sites, and via egg stocking. Restoring these historic rivers and protecting existent ones could also increase salmon genetic diversity, which would help them to adapt to a changing environment. Better legal protection for existing salmon rivers and their catchments could also support the stability of salmon populations. Improving the stability of the species in this way would also help to secure the fishery and the economic value it produces. Moving away from the salmon's riverine habitat and toward the sea, K described how increased runoff would be detrimental there as well. In the sea, runoff containing nutrients could increase eutrophication, which could result in more anoxic zones in the sea, which may impact fish species like cod. Changes in the Baltic food web via this and other climate-related means could alter the amount of prey available for salmon. If sprat becomes a more significant part of the salmon diet, it could increase the prevalence of M74, leading to fry mortality. Climate change could also lead to further reductions in sea ice in the Gulf of Bothnia, which could change the duration and opening date of the fishery. Fishing practices may change in the Baltic as a whole as well if salmon migration patterns change. Particularly, if they stop migrating south to feed. K also mentioned that after sustainable fishing quotas were put in place, salmon populations increased markedly. Therefore sustainable quotas must remain in place for the salmon and also for other fish species connected to them via food web interactions. According to K, fishing mortality is currently sustainable, at least for the northern salmon stocks. However, stock-specific management would be a further improvement. That said, K understands that some southern fishers are still dependent on fishing the mixed stock, which makes stock-specific management unlikely. Further, the growing recreational fishery, requires some management improvement, particularly better catch reporting.

A.2 Categorized Variables

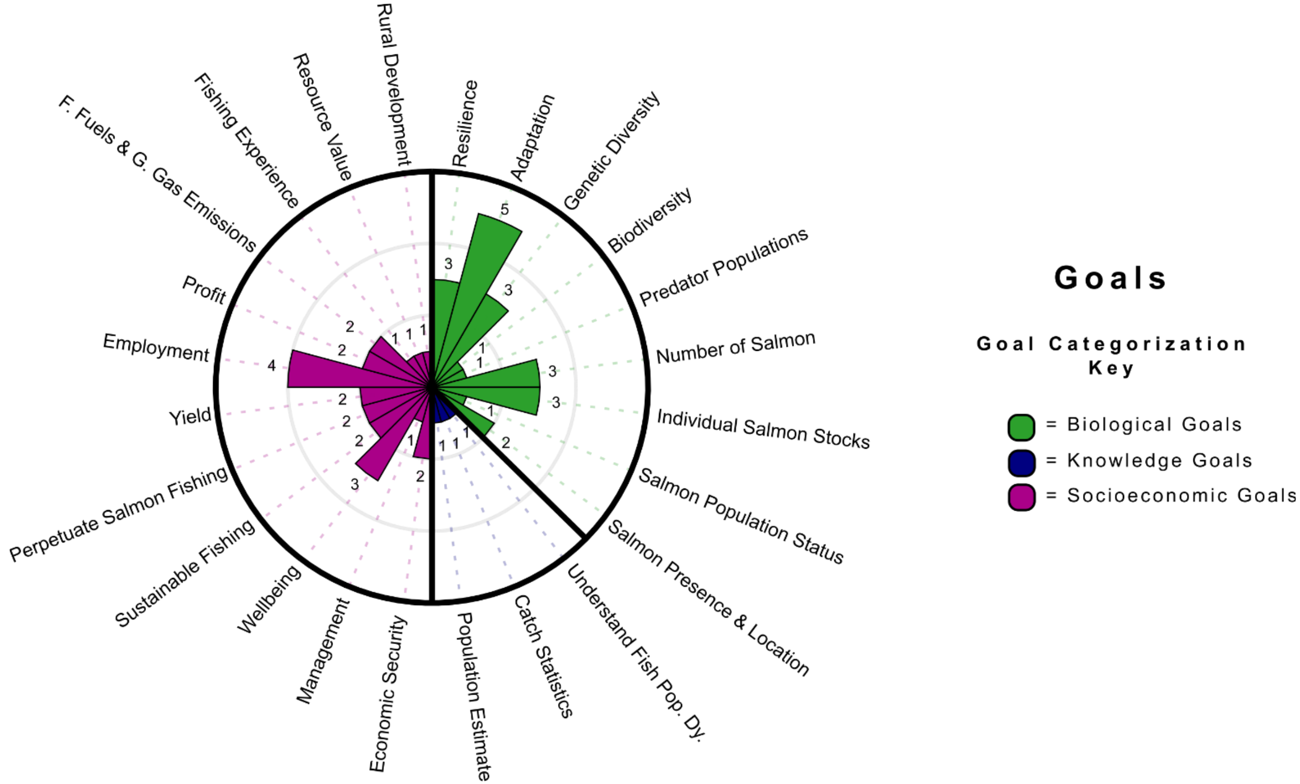

Fig. A.1. Categorized goals. Representation of the 1st order categories (text) describing the goals included in the stakeholders' diagrams grouped by the 2nd order categories (color, see key) they fall within. Each 1st order category is labeled with the number of individual goals it contains. Pop. Dy. = Population Dynamics; F. Fuels = Fossil Fuels; and G. Gas = Greenhouse Gas. These results were produced during the semi-quantitative phase of data analysis.

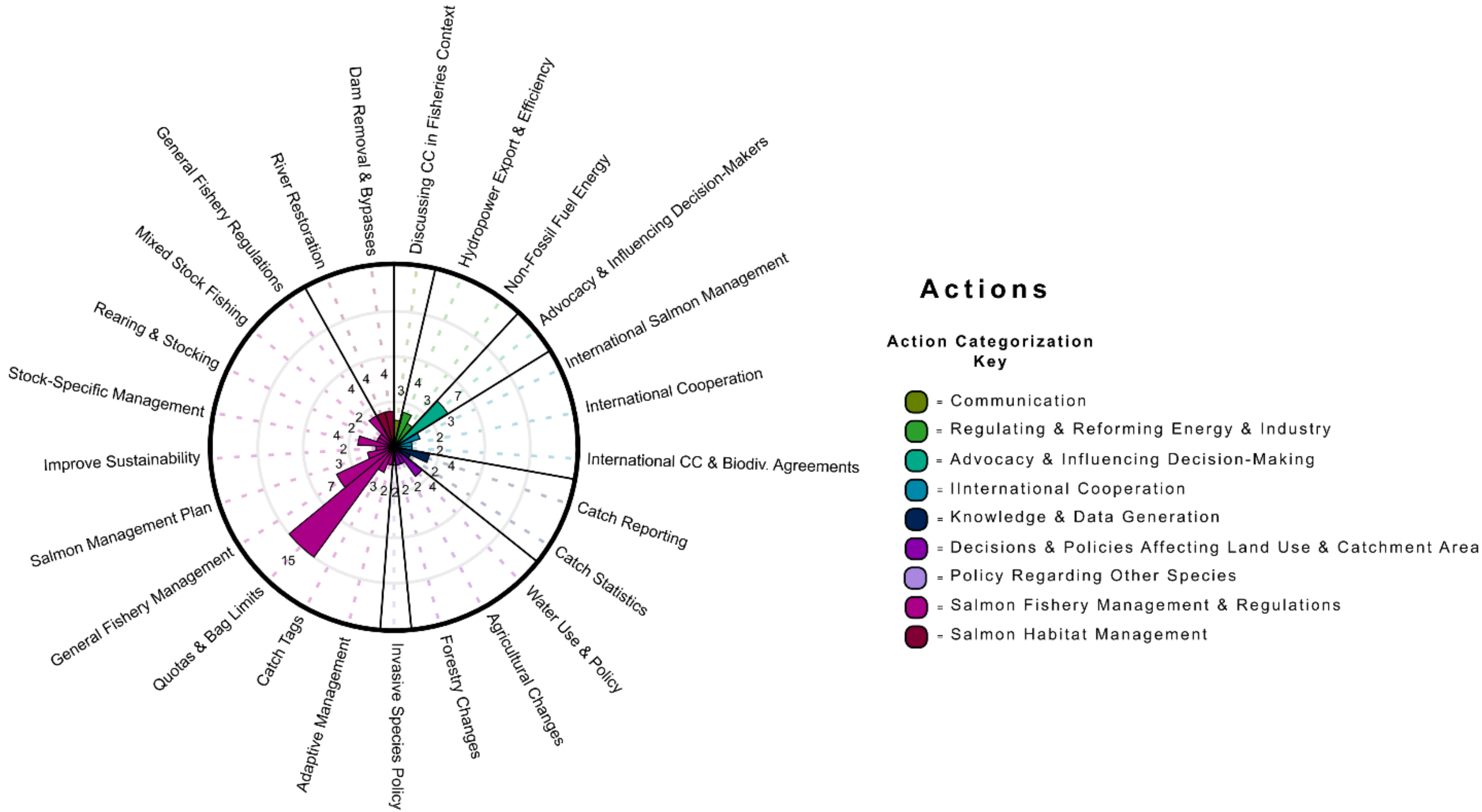

Fig. A.2. Categorized action variables. Representation of the 1st order categories (text) describing the actions included in the stakeholders' influence diagrams grouped by the 2nd order categories (color, see key) they fall within. Each 1st order category is labeled with the number of individual actions it contains. Only 1st order categories containing ≥2 actions are included in this diagram. These results were produced during the semi-quantitative phase of data analysis.

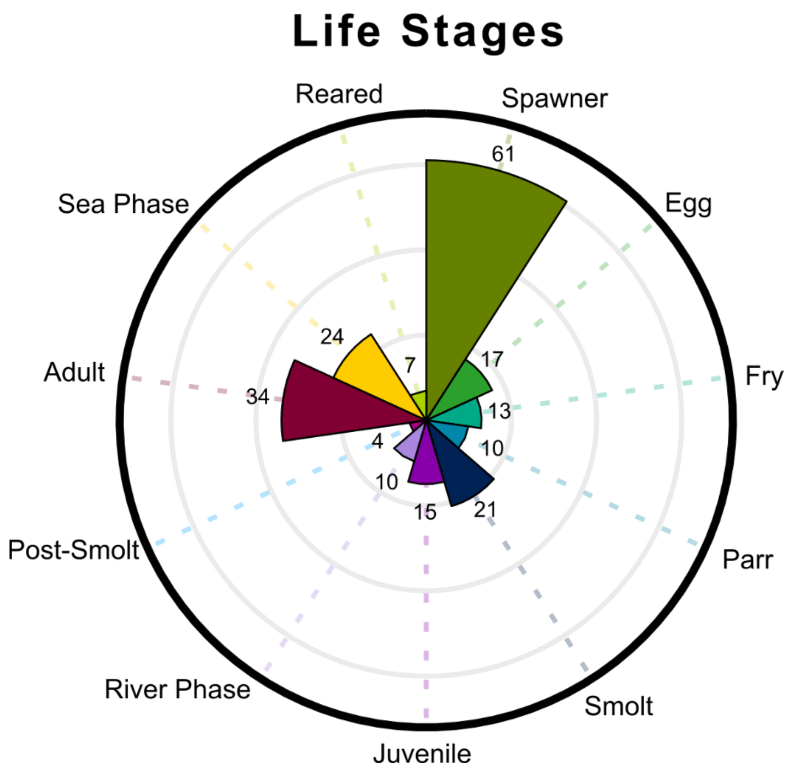

Fig. A.3. Frequency of different life stages occurring within stakeholders' influence diagrams. The number of variables related to reared, i.e. stocked salmon are also included. These results were produced during the semi-quantitative phase of data analysis.

A full spreadsheet containing all the variables included in the stakeholders' influence diagrams and their 1st, 2nd, and 3rd order categorization are available as a spreadsheet in the supplementary material associated with this article.

A.3 Descriptions of the 15 Primary Themes Derived from Stakeholders' Elicitation Sessions and Questionnaire Responses

A.3.1 The More Fish the Better (More Fish)

Unsurprisingly, all 11 stakeholders would have found common ground in their desire for greater numbers of salmon in the Baltic Sea or at least in the hope that the current population size remains stable. Each, either directly or indirectly, stated the importance of this idea. Those discussing this theme directly included large or increasing salmon populations as a goal in their influence diagrams (stakeholders I and J). For others, the achievement of their goals was frequently linked with the number of salmon or catch. For example, stakeholder A's described the "societal wellbeing" of towns along the Northern Baltic coast as linked with the profitability of the recreational fishing industry, which is directly linked to the Baltic salmon catch. As an additional example, H's goals were to achieve a favorable conservation status for salmon and ensure that there would be enough salmon to sustain themselves while supporting predator populations and both a recreational and commercial fishery, all of which were predicated on the number of Baltic salmon.

A.3.2 Uncertainty

Uncertainty was also an overarching theme for all eleven stakeholders. Again, some expressed their uncertainty by directly including it in their influence diagrams in some form (stakeholders A, B, C, D, E, F, G, J, and K). Each also expressed uncertainty while creating their influence diagrams, using phrases like “I don't know” or “it is so difficult to guess” when trying to determine how climate change could affect the salmon-system. This type of uncertainty during the problem-framing sessions often required the facilitator to reassure the stakeholders that the exercise was to create a better understanding of the problem based on their current knowledge and that they were not expected to know the answer to this question for certain. Uncertain was also apparent in the short answer portions of the questionnaires, where for example, one stakeholder responded that it would be "impossible to answer" whether climate change will be positive or negative for Baltic salmon and why presumably due to the high degree of uncertainty inherent in answering this questions.

A.3.3 Heat Stress in the Riverine Environment (Heat Stress: River)

River water temperature was incorporated as a variable in all eleven influence diagrams and most seemed to believe it would increase over time. Frequently, however, stakeholders asserted that rising water temperatures are a greater or at least more urgent threat to salmon stocks originating from rivers in the Southern Baltic and some suggested that rising temperature may even be beneficial in the Northern Baltic. Although the effects rising water temperatures could have on salmon and the riverine ecological community were often described differently, all stakeholders mentioned that if they were to exceed a certain threshold, rising water temperatures could either stress, increase disease amongst or kill cool water-dependent salmon. Several stakeholders (C, D, F, G, H, I, and J) also suggested that rising river temperatures could influence prey availability, which would have implications for salmon mortality or growth and others (A and E) suggested that salmon may become less active when suffering from heat stress, making them harder for anglers to catch. The stakeholders often focused on different life stages as vulnerable to heat-related problems, however, all life stages inhabiting the riverine environment were mentioned by at least one stakeholder. As depicted in table 1, sea temperature was also often included in the influence diagrams, however, its role in the salmon-system varied more between the stakeholders although it was often thought to have some impacts on the Baltic food web, salmon growth, or their migration timing and spatial distribution.

A.3.4 The Importance of Appropriate Flow (Appropriate Flow)

River flow was also frequently discussed in the context of the climate change problem, evidenced by the size of the 2nd order "hydrologic cycle" category (fig. 4), which was largely comprised of variables linked to flow. Typically, stakeholders described possible changes in flow driven by climate change and related to changes in precipitation, and snow and ice melt patterns. Although the stakeholders frequently described appropriate flow as vital to the salmon-system, they presented a more diverse set of effects related to flow than to river temperature. Drought (A, B, G) was linked with salmon stress and mortality and low flows (I and C) more generally were described as an impediment to river passage and spawning. Like high river temperatures, droughts and low flows were expected to be more problematic in the Southern Baltic. Several stakeholders (F, I, and J) also linked flow with habitat area, as higher flow conditions effectively increase the size of the rivers, potentially increasing their carrying capacity for salmon. Other less frequently described effects of changing flow were, for example, changes in flow net fishing efficiency, difficulty fishing with lures due to floating debris in high flow conditions, changes in the amount of dissolved organic carbon entering the sea, changes in sea salinity, egg removal from river bottoms due to flooding, and changes in the extent of the river water plume in the sea, which salmon need to find their home river.

A.3.5 The Integral Role of Politics (The Role of Politics)

Most stakeholders described politics and decision-making as integral components of the salmon-system. Although they tended to approach this topic from different perspectives and with differing levels of specificity, all those who discussed this topic viewed politics and decision-making as drivers of the fisheries management system. Most stakeholders described the political structure and specific legislation either existent or wished for, which ultimately affect fisheries management (see stakeholders G, H, and J for examples). Some stakeholders also the role of politics and decision-making in regulating energy use, which ultimately impacts climate change itself (For example, stakeholders E and G). Others described decision-making in the context of industrial, agricultural, forestry, peat mining, groundwater use, and hydropower relations, and the causal chain via which these regulations ultimately impact salmon and their stakeholders (for example stakeholders I and K). The most common actor incorporated in the models were the stakeholder's national government, the EU, and the Finnish and Swedish national governments as cooperative partners. However, some stakeholders also included the globally international political treaties like the Paris Climate Accord and the role of individual stakeholders, NGOs, advocates, and etcetera in influencing the political process. A few stakeholders (for example, G, H, and K) developed highly nuanced descriptions of the political system and included specific strategies, conditions, and characteristics, that could be leveraged to influence it. As such, several stakeholders viewed decision-making and political change as tools to influence the salmon-system and the effects of climate change on it.

A.3.6 Changing Food Web Dynamics (Food Web)

Descriptions of potential changes in food web dynamics both in the riverine and Baltic Sea environments were common amongst the stakeholders. Their descriptions of the Baltic food web was more consistent than their descriptions of changes in riverine food webs, however. Typically, stakeholders described the Baltic Sea food web as including herring and sprat as prey, and cod as an interspecific competitor for those prey resources. Prey availability at sea was typically expressed as affecting salmon mortality, growth, spawning age, and their migration routes within the sea. Additionally, stakeholders B, G, and K were concerned that changes in the proportion of sprat in the salmon's diet, perhaps driven by changes in cod predation on these fish, would increase the prevalence of M74. Cod, herring, and sprat were most commonly thought to be directly affected by changes in sea temperature and salinity and perhaps changing disease prevalence of disease and parasites, and worsening anoxic zones. Some stakeholders, like stakeholder C, chose to include a more complete picture of the Baltic food web, however, which ultimately impact these fish species and salmon as well. For example, changes in river flow could increase the amount of dissolved organic carbon available in the sea and reduce sunlight penetration, which coupled with changing temperature, could affect the sea's microbial loop, leading to further changes within the food web. Food web changes within the riverine environment. Generally, changes in either river or air temperature were thought to affect prey availability, ultimately affecting juvenile growth and mortality. Additionally, some thought climate change could bring about changes in interspecific competition, by inferring a competitive advantage to those species more tolerant to new environmental conditions than salmon. Along these lines, stakeholder H suggested that invasive species may find new conditions in both the Baltic and riverine environments more favorable than previously, establish themselves, and compete with salmon for food and other resources.

A.3.7 The Economic Security of Fishers and their Communities (Fishers' Economic Security)

Fishers' employment and economic security and the subsequent wellbeing of their communities was a priority for the majority of the stakeholders. All those describing this concept included some version of it as a goal in their influence diagrams. As shown in fig. 4, goals related to this topic are prominent among the socio-economic goals (purple). Rural areas, particularly in the northern Baltic, were of particular concern because as stakeholder J described, as other sources of employment in those areas, like mining, close, the more important revenue from fishing, particularly recreational fishing, becomes. Attaining goals related to this category was typically linked with the availability of fish, the ease of catching them, and the fishing restrictions implemented by fisheries management as mandated by policy. The availability of fish and the ability to catch them were both typically thought to be affected by climate change and in some cases, policy mandates were also thought to be responsive to changes in fish populations due to climate change. More often, however, fisheries management decisions were described as more of a political problem and less strongly coupled with environmental change. Although these goals were important to the stakeholders, the majority described the need to strike a balance between achieving them and maintaining thriving salmon populations. For example, stakeholder C believed having enough fish to keep fishing should be a goal, but made it clear that if there are not enough, we absolutely must stop.

A.3.8 The Importance of Improving Fisheries Management and Governance (Management & Governance)

According to the questionnaire results, while stakeholders were generally satisfied with the management of the specific Baltic salmon stocks that interested them, they were neutral or dissatisfied with the management of Baltic salmon as a whole. Those who reported they were interested in weak Baltic salmon stocks were not satisfied with their management. These feelings played out in the stakeholders' influence diagrams as well, where the majority described the management actions that could or should be changed to meet their goals for the salmon-system considering climate change. Indeed fisheries management and regulations form the largest group within the actions category in the semi-quantitative results (fig. A.2). During their elicitation sessions, stakeholders A, C, and K described the utility of adaptive management, which could restrict or halt fishing mid-season in response to changing environmental conditions. A, C, and J also advocated for improved catch reporting and subsequently better catch statistics and population estimates to help make more informed management decisions. Ending the practice of fishing the mixed salmon stock was also recommended by I and J to protect weaker stocks from over-exploitation. When all the Baltic stocks congregate in the Baltic Proper to feed, it is impossible to distinguish a fish from a strong stock versus a weak one. However, if one fishes nearer to the river mouths, they can be more certain about which stock they are fishing. This improved certainty would lend itself to stock-specific management, which stakeholders C, J, and K each suggested. The need for continued and strengthening joint management between Finland and Sweden was suggested by stakeholders A and E, and A, F, H, and K, each discussed the need for a new Salmon Action Plan. Several other management improvements were also suggested including, more precautionary management practices, national fishery regulations reflecting the EU's Common Fishery Policy and other international agreements, increased regulations for the recreational salmon fishery, discussing climate change more within the context of fisheries policy, and reducing salmon rearing. Many of the same ideas about fishery management reform were also received via the questionnaire (see section 4.3)

A.3.9 The Importance of Protecting Genetic Diversity (Genetic Diversity)

Six stakeholders explained that safeguarding the genetic diversity of Baltic salmon improves the species' resilience and ability to adapt to changing environmental conditions related to, for example, disease or climate change. Most explained that the smaller, weaker salmon stocks in the Southern Baltic, in particular, must be protected on the basis of the genetic diversity they contribute to Baltic salmon as a whole. The actions that should be taken to ensure their protection were more diverse but included for example: ending the mixed stock fishery to reduce pressure on weaker stocks and reduce uncertainty about which stocks are fished, precautionary management, changing catch quotas, instituting sustainable fishing practices, and stock-specific management. Stakeholder H also suggested that salmon rearing negatively affects genetic diversity and K suggested that protecting Baltic salmon's adaptability also ultimately helps to secure its fishery.

A.3.10 Changes in Fishing (Fishing Practices)

Beyond changing the amount of fish available, climate change may also affect the ease with which fishers find and catch salmon. Most commonly the stakeholders discussing this topic suggested that migration routes and timing could be influenced by climate change, in turn, affecting fishers' ability to catch them. For example, changes in environmental cues like river or sea temperature could impact spawning migration timing, route, duration, and the amount of time spent in the estuary before entering the river, each impacting their probability of capture. The availability and migration routes of prey could also be driven by climate change, influencing the salmon's migration within the Baltic as well. Stakeholder K suggested that if Baltic salmon would cease to migrate to the southern Baltic, those nations relying on fishing the mixed stock which has traditionally congregated there to feed could be excluded from the fishery. Further, change in salmon growth at sea could affect the number of years they spend at sea before returning to spawn, thus impacting the probability that they are captured before spawning. On a smaller scale, changes in flow may affect the amount of floating debris, making fishing with lures more difficult. Changing flow may also impact the efficiency of fishing with flow nets. Changes in river conditions like temperature and dissolved oxygen may also stress fish, making them less active and therefore less likely to strike bait. Changes in environmental conditions could also affect fisher behavior. According to stakeholder D, changes in air temperature, cloud cover, and precipitation could influence fishing effort and timing. Lastly, changes in policy made in response to climate change-induced changes in the salmon-system could also affect fishing.

A.3.11 Human Impacts on the Riverine Environment (Human Impacts: River)

The impacts humans have on the riverine environment was another strong theme apparent within the stakeholders' influence diagrams. Although this theme was rarely directly linked with climate change, it was described as a factor that could exacerbate or improve deteriorating environmental conditions and ultimately, outcomes for salmon. Hydropower was the most frequently described impact within this theme and was described as a threat to salmon because hydroelectric dams block access to rivers and thus, reducing spawning success. However, hydropower was also often described as a renewable energy source, which may be necessary to implement to reduce fossil fuel usage and ultimately mitigate climate change, thus pitting salmon conservation and hydropower as competing interests. Stakeholder G described a solution to this conundrum in great dealing, explaining that a few large rivers should be dammed for hydropower, while all smaller and less effective dams should be removed to make way for salmon. Some also explained that forestry drainage ditches, clear-cutting, and peat mining negatively impact the riverine environment, by delivering runoff to rivers, thus increasing flooding, sedimentation and nutrient loading. If the climate becomes wetter, these problems could become worse, leading to low dissolved oxygen concentration and stress, and dislodging or suffocating spawning gravel and eggs on the river bottom. Ultimately nutrient loading may affect eutrophication in the sea as well. Stakeholder I also explained that municipal and industrial water use could reduce river flow, diminishing habitat area and impeding fish passage. Further, stakeholder H explained that groundwater protection is essential because groundwater inputs regulate river temperature, and overuse could exacerbate warming river water temperatures as climate change continues. On the positive side, river restoration efforts could also be undertaken to improve riverine conditions for salmon, by, for example, removing dams and restoring spawning gravel.

A.3.12 An Accelerating Life Cycle (Accelerating Life Cycle)

Five stakeholders suggested that rising water temperatures paired with adequate prey availability could accelerate growth and maturity, effectively accelerating the salmon life cycle. According to some stakeholders, this could increase the size of salmon populations, as more fish would essentially have "less time to die" between hatching and spawning, and more rapidly smoltifying populations would more quickly vacate space and resources for young fish in the rivers. However, stakeholder G suggested that warmer river temperatures could also lead to earlier smoltification at a smaller size, which may negatively impact smolt survival. Additionally, Stakeholder I suggested, that a more productive salmon population could result in increasing fishing pressure, which may dampen population growth.

A.3.13 Changing Disease Prevalence (Disease Prevalence)

Several stakeholders also suggested that as a result of climate change, altered environmental conditions may lead to changes in the prevalence of disease in salmon populations. The changes were discussed by all five stakeholders describing this theme in the context of the riverine environment and by two in the context of the marine environment. Changes in the prevalence of disease were generally attributed to changes in water temperature, which may stress fish, or, in the context of the riverine environment, in changes in population density. Further, changes in environmental conditions could also increase the prevalence of disease in prey species, ultimately affecting the amount of prey available for salmon. Stakeholder J discussed changes in the prevalence of ulcerative dermal necrosis (UDN), which leads to open wounds on the fish's bodies. These wounds are then infected with Saprolegnia, a fungus, ultimately leading to death. Saprolegnia infections are common for fish following injuries acquired during the spawning process, however, UDN ultimately leads to fungal infections before spawning. Stakeholder J suggests the prevalence of UDN and other diseases may change in response to changing river temperature, population densities, and the amount of time adult fish spend in the river before spawning.

A.3.14 Energy Use and Production Reform (Energy Reform)

Among the stakeholders' influence diagrams, the only factor influencing climate change was energy use and production reform. Stakeholder E suggested that from the international level to the individual, society must honor the commitments made to, for example, the Paris Climate Accord, and reform the way we use energy personally and industrially, and regulate municipal coal use. G offered solutions to reduce greenhouse gas emissions by suggested increased wind, solar, nuclear, and hydropower energy use. As described above, he suggested in the Swedish context, a few larger rivers should be damned and the rest should be rehabilitated for salmon habitat. B also described the tradeoff between the renewable energy produced by hydropower and salmon habitat. Further, G said an ultra-high voltage power line should be put into place within Europe to allow excess green energy from countries where it is more readily available to be transferred to countries where it is less readily available. Stakeholder H also described how burning peat for energy emits greenhouse gases and also reduces the flood control services that peat bogs provide. Lastly, H also described an eco-energy certification system in Finland, which collects money to pay for environmental restoration projects, like river restoration, to offset the environmental impacts of renewable energy.

A.3.15 Phenological Mismatches

Four stakeholders also suggested that climate change could cause phenological mismatches between salmon and their prey. For example, stakeholder C, K suggested that rising river temperatures (C and K) and changes in flow (C) could cause eggs to develop faster. This would then lead to the salmon fry emerging from the river gravel before their prey is available, leaving them starving. Stakeholder H suggested a similar mismatch could occur if smolts enter the sea before their prey are available and D explained that a shifting climate could lead to both phenological and spatial differences between salmon and their prey at sea, ultimately leading to salmon mortality.