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Transdisciplinary research for climate change adaptation: learning from an aquaculture knowledge exchange workshop

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ABSTRACT
Climate action is urgently required in aquaculture systems. Emerging monitoring tools, production practices, raw materials, and technologies could help the industry adapt to changing environmental conditions. Yet, the complexity and uncertainty of climate-related stressors, impacts, and responses, combined with diverse stakeholder values and priorities, demand collaborative and transdisciplinary research approaches. Building shared awareness, articulating common goals, and envisioning ways of working together to realize climate action will be key to transdisciplinary approaches. To explore these dynamics, participants at two knowledge exchange workshops on aquaculture and climate change were asked to share their perspective of climate change to gain a better understanding of shared goals and interests between researchers and industry, as well as government and non-governmental organizations. Participant groups agreed that climate change is already impacting the aquaculture industry and that we are not well prepared to respond. Knowledge, funding, and motivation were recognized as important factors for adaptation. Participants also recognized the need for collaboration beyond knowledge sharing, and the role of communication, funding, and common goals in improving collaboration. Shared perspectives on the need for climate change action and knowledge production among workshop participants suggest that there may be opportunities for deeper collaboration between research and the aquaculture industry.

KEYWORDS Aquaculture; transdisciplinary; interdisciplinary; climate change; adaptation

CRITICAL INSIGHTS SUMMARY

Preparing Aquaculture for Climate Change Starts with Collaboration

Climate change is no longer a future concern for aquaculture. Researchers, industry representatives, policymakers, and NGOs attending two climate workshops held in Norway largely agreed that the sector is already experiencing climate-related impacts, yet many believe aquaculture remains underprepared to respond effectively. Concerns over marine heatwaves, disease risks, harmful algal blooms, and uncertainty around adaptation strategies are increasingly shaping conversations across the industry.

To explore these perspectives, researchers from the University of Stirling and Nofima organized climate-focused knowledge exchange workshops in Norway in 2024 and 2025. Participants from research institutes, seafood companies, government agencies, and non-governmental organizations took part in interactive engagement sessions to identify challenges and opportunities related to climate adaptation in aquaculture.

Across stakeholder groups, participants expressed concern about the impacts of climate change on aquaculture and limited preparedness within the sector. Many participants highlighted uncertainty around climate information, lack of funding and resources, competing priorities, and gaps in leadership as barriers to adaptation. Participants also emphasized the importance of communication, shared objectives, and partnerships between research and industry.

Going forward, the aquaculture sector may need to move beyond traditional research models toward more transdisciplinary approaches that combine scientific expertise with industry experience and stakeholder participation. The findings suggest that building resilient aquaculture systems will depend not only on scientific knowledge, but also on stronger collaboration across sectors working to address climate-related challenges affecting food production and aquatic ecosystems.

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1. Introduction

As emphasized by the Intergovernmental Panel on Climate Change (IPCC) and World Meteorological Organization (WMO), there are widespread and rapid changes occurring in the atmosphere, cryosphere, land, and ocean due to anthropogenic climate change [1,2]. Despite these repeated warnings and escalating concerns over the unprecedented rates of change and increasingly severe consequences, progress on both climate adaptation [3] and mitigation [4] remains alarmingly slow. The challenge of accelerating climate action is compounded by additional crises facing the planet, including a critical need to increase the availability of healthy, nutritious, and sustainably produced food. At the same time, climate change is affecting global food production, including aquaculture [5]. These climate change and food-security challenges are represented in the United Nations' Decade of Ocean Science for Sustainable Development (the Ocean Decade), which calls for advancement of "the science we need for the ocean we want" [6]. In particular, Ocean Decade Challenge 3: Sustainably nourish the global population, recognizes the importance of aquatic foods, and the unique potential for growth in the role of aquaculture in providing sustainable and nutritious food for a growing global population [7].

These overlapping food system and climate crises mean that intensified efforts to counteract or stabilize global warming at 1.5 °C is urgent, but the need for food systems (including aquaculture), to adapt to climate change is equally important. New raw materials, production methods, and technology could help secure future aquaculture production in a changing environment but only if they are developed and implemented in a sustainable way and avoid other negative consequences [8]. The Ocean Decade points to the role of science in not only understanding current conditions but supporting the implementation and evaluation of interventions. It also recommends interdisciplinary and co-created science that includes different knowledge brokers as a pathway to achieve these objectives [7]. Therefore, the development, implementation, and evaluation of aquaculture climate change adaptations will require collaboration between researchers and industry to ensure grounded and meaningful research insights and tools that strengthen the resilience of aquaculture systems.

1.1. From applied research to transdisciplinarity in aquaculture

Aquaculture research is found across multiple fields of science, albeit with varying levels of integration and participation depending on the questions and topics under investigation (Figure 1). Research has long been an important component of aquaculture development, with early objectives tied to identifying suitable areas, controlling diseases, and configuring aquaculture systems [11]. A range of independent disciplines have and continue to create knowledge that informs aquaculture practices, which is indicative of multidisciplinary research and reflects the multifaceted nature of farming. Climate change is also a multifaceted challenge requiring input from multiple disciplines; however, it is also a wicked problem characterized by its complexity, high degree of uncertainty, and the competing values and priorities of stakeholders [12–14]. In aquaculture, climate change presents integrated technological, infrastructural, ecological, and biological challenges that will require changes to industry and governance practices [15,16]. For example, new adaptative practices could range from coping strategies to system transformation supported by the development of new raw materials and technologies [17]. The development and implementation of those solutions could affect individual people and animals, communities, and companies which hold different values and prioritize different types of actions and outcomes. Therefore, each solution to climate change recontextualizes the problem itself, and different stakeholders may interpret any negative consequences (maladaptation; see Falconer et al. [8]) differently. There is no one-size-fits-all approach to adaptation, and no single response or action is likely to address the multiple challenges presented by climate change. Wicked problems like climate change require integrated approaches, moving from multidisciplinary to interdisciplinary research that breaks down barriers between disciplines and ways of knowing [18].

In addition to private research and development, aquaculture firms throughout the supply chain collaborate with academic and public research institutions [19]. This might include sharing data, facilitating fieldwork, co-developing projects, and acting as key informants or participants. These approaches represent the combination and exchange of academic and nonacademic knowledge that characterize participatory research [10] (Figure 1). Participatory research can be disciplinary or multidisciplinary [10], and the degree of participation and sharing of power between participants may range on a continuum from minimally participatory to fully egalitarian [20]. The importance of this type of information sharing between researchers and producers has long been recognized as a vital part of aquaculture development (e.g. 11]. It should also be noted that academic aquaculture-related knowledge is not restricted to academic or research institutions. For example, private companies are responsible for more than half of reported research and development funding within the Norwegian aquaculture sector [21]. Therefore, it is important to recognize that people employed in the aquaculture industry often hold academic knowledge and have research expertise. Likewise, there are also people who have worked in industry that then move into academic roles, or in some cases there

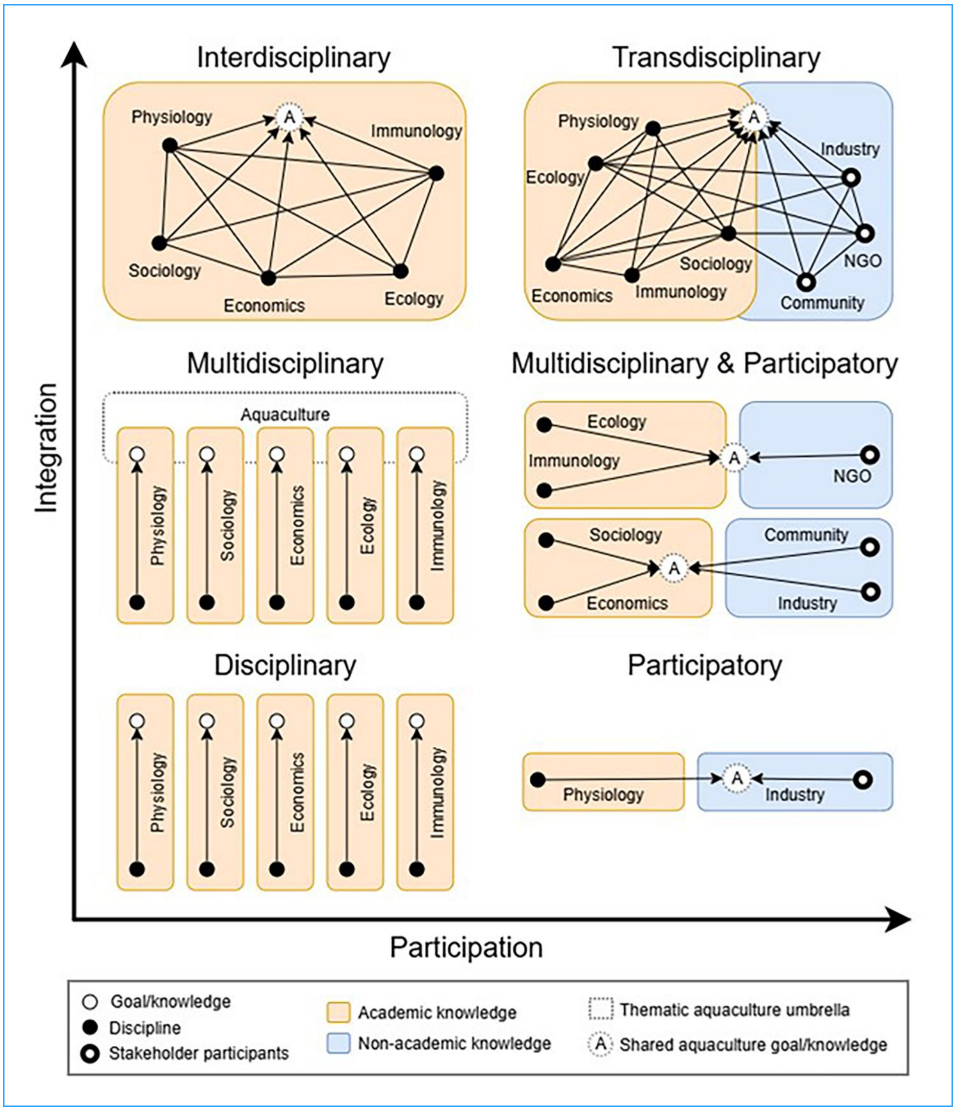

Figure 1. Types of aquaculture research ranging from low to high integration and with or without stakeholder participation. Figure adapted from Morton et al. [9] and Tress et al. [10] for an aquaculture research context. Orange represents the role of academic knowledge, and discipline labels (physiology, sociology, economics, ecology, and immunology) are used to provide an example of how different disciplines contribute to different types of knowledge creation; many more disciplines than those included in these examples contribute to aquaculture knowledge. Interdisciplinary aquaculture knowledge may be generated by one person working across multiple disciplines, or by multiple people working across multiple disciplines. For example, a single person may create knowledge in multiple disciplines (multidisciplinary); if that person integrates knowledge from those disciplines, they are conducting interdisciplinary research. Likewise, multiple specialists might contribute separately to disciplines that create knowledge under the thematic umbrella of aquaculture (or a sub-theme of aquaculture); integration of the knowledge created by those specialists represents interdisciplinary research. When stakeholder knowledge is included in disciplinary or multidisciplinary research, that research becomes participatory; when stakeholder knowledge is included in interdisciplinary research, that research becomes transdisciplinary.

are people with dual positions working across academia and industry. Hence, if strict categories are applied to types of knowledge, the production of interdisciplinary knowledge might include contributions from both academic- and industry-employed researchers when the contributed knowledge is academic in nature. When knowledge contributed by industry-employed researchers is nonacademic in nature, that is, practical or experiential knowledge, that knowledge represents a contribution to participatory research. In reality, the line between academic and nonacademic knowledge is much blurrier, and a single researcher or practitioner may have access to and contribute both types of knowledge in participatory (or transdisciplinary) research settings.

When the participation of stakeholders in research is combined with the integration of multiple disciplines as well as nonacademic knowledge, research can become

Table 1. Stereotypical perceptions of the perspectives associated with the cultures of aquaculture research, policy & management, and industry.

	Natural Science	Social Science	Policy & management	Industry
Valued action	Research, scholarship	Research, scholarship	Decisions, plans	Innovation, decisions, plans
Time frame	That needed to gather, analyze, and interpret evidence	That needed to gather, analyze, and interpret evidence	Immediate, short-term	Immediate, short-term
Goals	Increase understanding	Increase understanding	Manage problems, set policy	Manage problems, increase production
Basis for decisions	Empirical scientific evidence	Subjective (relativistic) evidence	Science, values, opinion, economics	Science, economics, experience & best professional judgment
Expectations	Understanding never complete	Multiple and context-specific understandings	Clear answers from science	Clear and actionable answers from science
Grain of interest	Focus on details	Focus on details	Focus on broad outline	Focus on both broad outline and details
World view	Primacy of biological, physical, chemical mechanisms	Primacy of social, psychological, economic, governance mechanisms	Primacy of social, political, economic mechanisms	Primacy of biological, market, production mechanisms

These stereotypical perceptions have been adapted from Bernstein et al. [24] for an aquaculture context and extended to include the culture of social science reflecting the range of epistemologies applicable in a post-normal science context. These are stereotypical perceptions of differences between stakeholders only, and do not necessarily reflect real or perceived differences in any particular inter- or transdisciplinary setting, highlighting the need for reflexivity when working across disciplines and types of knowledge.

transdisciplinary and create knowledge for science, industry, and wider society [10,22]. One of the key attributes of participatory, interdisciplinary, and transdisciplinary research is a shared goal across disciplines and sectors [9]. However, collaboration across disciplines and with industry partners may be challenging due to real and perceived cultural differences which contribute to difficulty identifying and agreeing on shared goals [23] (Table 1). For example, natural scientists may be stereotypically viewed as empirically minded researchers who recognize that understanding is never complete while social scientists may be viewed as relativistic thinkers who recognize multiple plural understandings, embracing the epistemological and ethical uncertainty associated with post-normal science [25]. Perceived cultural or paradigmatic differences between these two fields and/or the disciplines within are a barrier to interdisciplinarity, though they are also a strength, as integration could result in new approaches beyond the boundaries of any single discipline [26]. Similarly, cultural differences between researchers and stakeholders are a barrier to transdisciplinarity. For example, people working in policy, management, or industry might be viewed as prioritizing information that can be used to make decisions or take action while researchers could be viewed as prioritizing understanding [24]. While these differences represent potential stereotypes of different disciplines and stakeholders, and perspectives are unlikely to be as rigid as those represented in Table 1, it is still useful to understand potential cultural differences in addition to examining the assumptions and positionality that we each bring to inter- and transdisciplinary settings. This reflects the importance of reflexivity in inter- and transdisciplinary research, as recognition and self-examination of assumptions may support collaboration and transdisciplinarity [27,28].

1.2. An opportunity for collaboration

While transdisciplinary discourse has tended to focus on collaboration with communities and the third sector to create positive impact, there is also a case for working with the industries that hold the power to shape our society and impact our daily lives [29]. The aquaculture industry is expanding and taking a more important role in the global food system and human nutrition, with some parts of the sector, such as salmon farming, growing at an exceptionally rapid pace over the past decade [5]. The business of salmon farming has also increasingly become concentrated with the top 4 salmon farming companies (by production volume) now accounting for over half of all farmed salmon production, and the top 9 companies accounting for over 75% (calculated from FAO [30] and Mowi [31]). Farming companies are also increasingly vertically integrated [32] having invested in feed mills, hatcheries, and processing facilities which gives companies control across the supply chain. The concentration of power and influence of salmon farming within the aquaculture industry, and within the top producing salmon farming companies, means that the industry and its leading companies are positioned to have an outsized impact (whether positive or negative) on the environment and society. The need for climate action overlaps with this influence, presenting not only a need, but an opportunity to work toward transdisciplinarity in aquaculture research and make progress on critical challenges. The remainder of this paper will focus on this opportunity, with grounding in data collected at two climate change knowledge exchange events largely focused on the salmon aquaculture sector. Given the importance of shared goals in participatory and transdisciplinary research, the goals of the knowledge exchange workshops included (1) understanding the perceptions and experiences of people attending the workshop with climate change and aquaculture, and (2) engaging workshop participants and improving their understanding of the perceptions and experiences of others involved in aquaculture.

2. Materials and methods

Providing a venue for knowledge exchange and dialogue on the issue of climate change impacts, mitigation, and adaptation in aquaculture is an important component of collaboration and the identification of shared goals and interests. In this vein, we convened two one-day workshops on aquaculture and climate change. The workshops were both co-organized by the research institute Nofima (Norway) and the University of Stirling (UK) and took place in Ås, Norway in April 2024 and April 2025. Each workshop included presentations and panel discussions used to share insights and perspectives from scientists, industry, NGOs, and policymakers (Appendix B). The free workshop was advertised on LinkedIn and promoted through host networks.

In addition to providing information to the audience, an interactive engagement activity was used to help understand the perspective, and experience of workshop participants on climate change and aquaculture. We anticipated some barriers to more typical qualitative interpretivist methods that require open discussion at the workshop including hesitancy to speak in front of a group, privacy and confidentiality concerns, employee–employer relationships, and the potential primacy of academic knowledge due to the uneven split of researchers and other stakeholders in attendance. Therefore, to address our dual research and engagement goals, we used an anonymous and interactive tool to invite participation and collect information about audience perspectives.

Mentimeter is an interactive presentation and audience engagement tool [33]. It allows presenters to display a variety of question types, and audiences can respond to those questions anonymously and in real time using a smart phone or laptop. Responses are displayed live on a presentation screen. Mentimeter is increasingly used in educational settings where it has been shown to promote engagement, motivation, collaboration, participation, and active learning [34,35]. As part of the climate change workshops, Mentimeter was used to display questions about audience (1) experience in aquaculture, (2) understanding of climate change, and (3) challenges and opportunities for climate change adaptation and collaboration. Therefore, Mentimeter was not used as a traditional survey approach but as an exploratory research and engagement tool.

Everyone in attendance at the workshops was invited to take part in the Mentimeter activity. Mentimeter sessions were dispersed throughout the workshops in 5–10-minute segments, and an open-ended question was presented during some of the break periods. In total, 11 questions were presented in 2024 and 16 questions in 2026 which included a combination of closed and open-ended questions. Responses appeared live on the workshop presentation screen.

All workshop attendees were informed verbally and in writing that participation in the Mentimeter polling was optional and anonymous, and that participating in the Mentimeter activity would be interpreted as implied consent. This consent procedure and all research activity was approved by the University of Stirling General Research Ethics Board (GUEP 22024 17365 12134), as recording informed consent was not practicable in the workshop setting. No personal data were collected, and responses cannot be linked to identifiable individuals.

Data collected through Mentimeter were later segmented into stakeholder groups to support understanding of similarities and differences between groups. These segments include: (1) researchers, (2) industry, (3) government & NGOs, and (4) others. These groups reflect attendance at the workshops. As this is exploratory research with no specific hypotheses to be tested, descriptive and interpretivist analysis is used to explore perceptions and experiences of climate change and aquaculture within the specific context of two knowledge exchange workshops. Quantitative data are summarized using proportions and averages, and qualitative data are summarized based on interpretive analysis using either deductive (Table 2) or inductive (Table 3) categories.

3. Results

3.1. Aquaculture and climate change workshops

More than 70 people attended the 2024 workshop, and more than 80 attended in 2025. Approximately 25% of those attending in 2025 had attended in 2024, and over 60% of attendees responded to Mentimeter questions (2024, n = 52; 2025, n = 59). Most of the respondents worked with finfish, in particular salmon (88%, 81%), followed by rainbow trout (60%, 44%), cod (44%, 32%), and seabass/seabream (15%, 14%). However, lower trophic aquaculture species were also represented including seaweed (35%, 12%) and mussels/oysters (23%, 7%), as were freshwater fish (19%, 19%). Given the location of the workshop, almost all respondents work in or have work associated with Norway (96%, 92%). This was followed by Scotland (29%, 31%), Chile (25%, 24%), and Canada (21%, 22%), countries where salmon farming is also an important industry. Therefore, insight from audience feedback is largely a reflection of experience and perceptions of climate

Table 2. Summary of responses to open-ended questions to 2024 workshop participants: (1) "What are the barriers keeping the aquaculture industry from taking action on climate change and/or planning for climate change?" and (2) "What would enable the aquaculture industry to take more action on climate change and/or planning for climate change?"

Dimension of adaptive capacity	Description	Barriers	Enablers
Assets	Access to financial, technological, and service-related assets	Lack of funding, high costs of adaptation	
External context	Structure and function of institutions and the environment support adaptation	Regulations that restrict expansion to new areas or species	Legislation and regulatory pressure, market demand, incentives, crisis
Agency	Power and freedom to respond to climate change	Expectation that industry adaptation should receive public funds, regulations that limit responses	
Flexibility	Ability to switch between strategies	Low diversity of species, limited availability of solutions	
Vision	Long-term planning and prioritization of climate action	Shortsightedness, competing priorities, not willing to invest in solutions	
Knowledge	Capacity to recognize climate change, process information, and assess response strategies	Lack of knowledge, uncertainty, complexity, lack of acknowledgment of climate impact, shortage of competency	Clear objectives, relevant research

Results are organized into dimensions of adaptive capacity adapted from Cinner and Barnes [36].

Table 3. Summary of responses to open-ended question (1): "How can collaboration between industry, researchers, policymakers, and NGOs be improved?"

Themes	Researcher	Industry	Government & NGO	Other/Blank
Communication	• Better communication & knowledge sharing • Workshops, seminars, spaces to talk and plan • Less privacy	• Communication • Sharing interests/ challenges • Workshops/forums • Data sharing	• Meeting/talking	• Workshops
Incentives	• Funding/funding calls • Regulations • Urgency ("we get sufficiently scared")	• Funding	• Funding/providing grants	• Funding calls for joint projects
People/ expertise	• Third-party to coordinate collaboration • Training & education • Facilitators to translate results and support implementation			• Open-minded, inclusive, smart individuals
Research/ project structure and goals	• Ambitious research beyond observation & description • Active collaboration (beyond sharing knowledge) • Joint projects/project leads	• An aligned initiative where all parties collaborate		• Clear/common goals on a project that is as business-oriented as it is research/science-oriented • Research on topics the industry needs • Joint projects • Common goals

change in the salmon-farming industry and salmon-farming regions. Almost half the respondents were from research institutes/academia (46%, 46%). Representatives from industry (21%, 20%) and government and NGOs (19%, 12%) were also present (Appendix A).

3.2. Setting the scene and finding common ground

Workshop participants were asked a series of questions pertaining to their perceptions about the impacts of climate change and preparedness to respond to climate change. All stakeholders were largely in agreement that the aquaculture sector is already experiencing the effects of climate change, and this proportion also increased from the first to second workshop with 66% of participants in 2024 and 87% of participants in 2025 saying "definitely" (Figure 2A and B). Stakeholders were also largely in agreement regarding their concern about the impact of climate change on aquaculture with only one researcher and no participants from other groups saying they are "not at all concerned" (Figure 2C).

In general, participants also expressed concern about preparedness to respond to climate change; in 2024, only 12% of participants said that the sector "almost definitely" or "definitely" has the information it needs to respond to climate change, and only 24% said that policymakers "almost definitely" or "definitely"

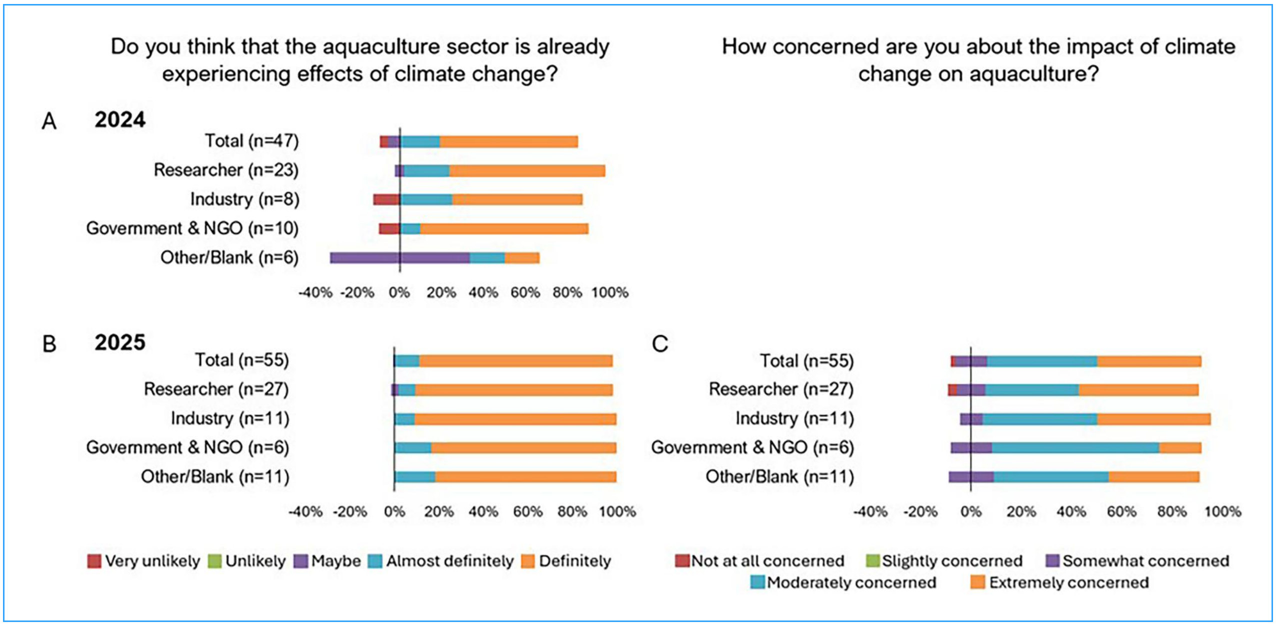

Figure 2. Proportional response to questions about perceptions about climate change and impacts on aquaculture, segmented by stakeholder group. Each bar represents the total of responses within each group, with different colors used to represent the proportion of responses for each of the five Likert scale categories; the lowest 2.5 Likert scale categories are represented by negative values, and the highest 2.5 Likert scale categories are represented by positive values.

have the information they need to respond to climate change (Figure 3A and B). In 2025, only one participant rated degree of preparation for climate change as "very prepared" and none as "prepared" (Figure 3C). Across all three questions about preparedness, researchers and industry were similar in their perception of poor preparedness, while the government & NGO group was slightly more optimistic. In 2024, the majority of people within the researcher (61%) and industry (67%) groups thought that it was either unlikely or very unlikely that the aquaculture sector has the information it needs to respond to climate change where more than half of the government & NGO group (57%) thought that the industry may, almost definitely, or definitely has the information it needs (Figure 3A). Similarly, the industry group was most positive about policymakers having the information they need to respond to climate change with most saying it was either unlikely or very unlikely (57%) followed by researchers (48%) and government & NGOs (40%) (Figure 3B). Regarding preparedness to respond to climate change, 44% of researchers responded that the sector is not at all prepared, followed by industry (27%) and government & NGOs (20%) (Figure 3C).

Participants were also asked about their general understanding of climate change and aquaculture on a scale from 1 to 100 (Figure 4). In 2024, the industry group rated their understanding the highest among groups with an average score of 72 followed by the government & NGO group (63), researchers (57), and others (49) (Figure 4A). In 2025, this question was expanded to collect information about understanding of different components of climate change including climate impacts, mitigation, and adaptation. This time, the government & NGO group rated their overall knowledge highest (82) followed by industry (72), researchers (70), and others (55). Among the different components of climate change, the government & NGO group (63), and the researcher group (59) rated their understanding of impacts highest, followed by understanding of climate change mitigation (54, 50) while the industry group was only slightly more confident about mitigation (73) than impacts (70). All groups rated their understanding of how aquaculture can respond to climate change (adaptation) lowest among the three components of climate change with an overall average of 50 compared with mitigation (54) and impacts (64) (Figure 4B). The industry group average rated understanding of mitigation was highest (60) followed by researchers (49) and the government & NGO group (48).

Responses to these questions suggest that researchers and people representing industry and government or NGOs attending the workshops are aligned in their understanding that climate change is affecting aquaculture, concern about impacts, and judgment that aquaculture is not well prepared to respond to climate change. Stakeholder groups also share some understanding about climate change and aquaculture in general but are less confident in their understanding of adaptation. This information could provide the common ground needed to develop shared research goals. In the next section, we use climate change adaptation to explore perceptions of

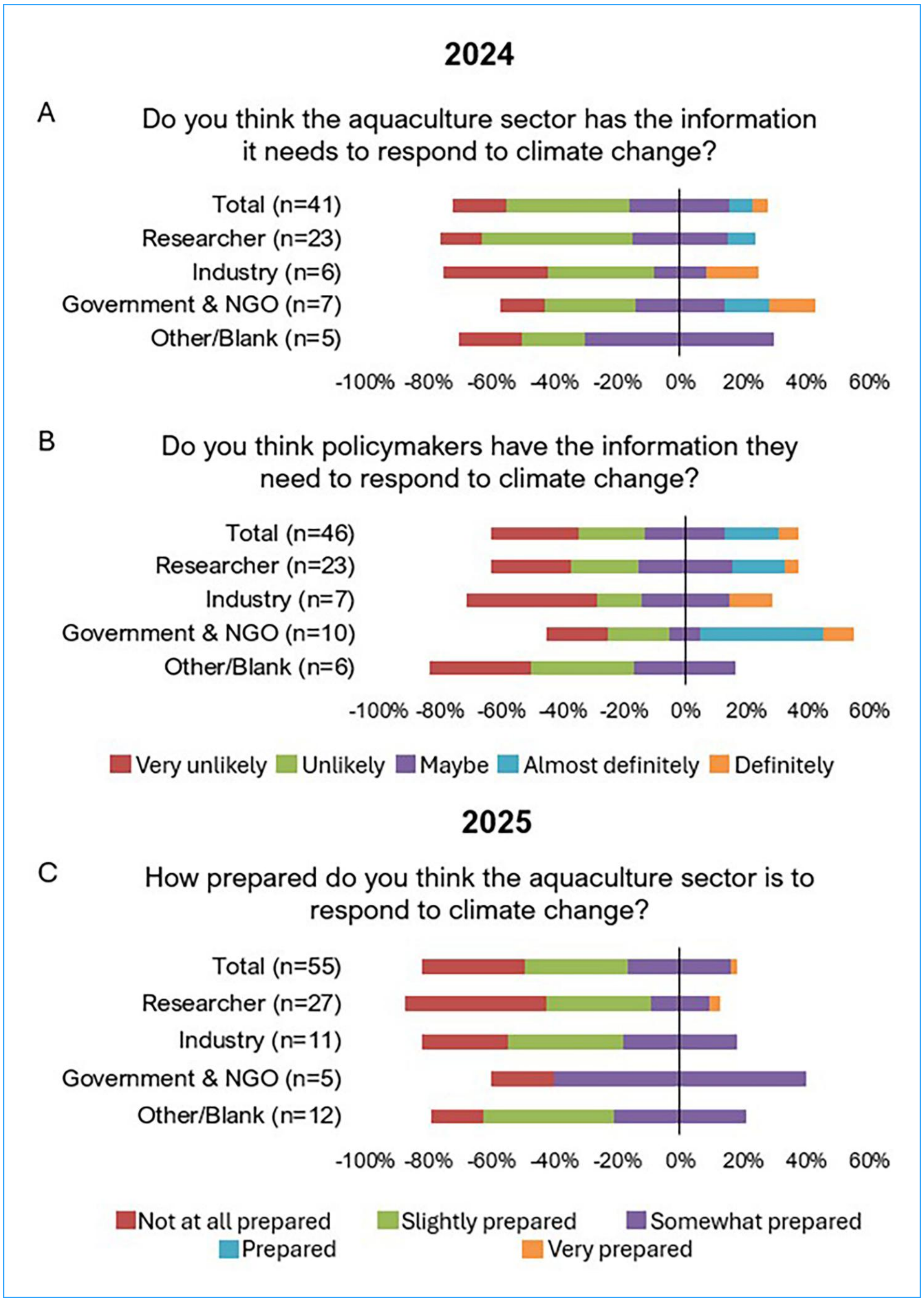

Figure 3. Responses to questions about perceptions about preparedness to respond to climate change, segmented by stakeholder group. Each bar represents the total of responses within each group, with different colors used to represent the proportion of responses for each of the five Likert scale categories; the lowest 2.5 Likert scale categories are represented by negative values, and the highest 2.5 Likert scale categories are represented by positive values.

barriers toward progress in an area that appears to be most lacking in understanding.

3.3. Challenges in aquaculture climate change adaptation

Given shared concern that the aquaculture sector is not well prepared to adapt to climate change, combined with relative lack of confidence in understanding of how aquaculture can respond to climate change, it is reasonable that shared research and knowledge goals could be developed around this area and be supported by participatory or transdisciplinary research. The next series of Mentimeter questions were used to develop an understanding of challenges in adapting to climate change. In 2024, we asked participants about barriers

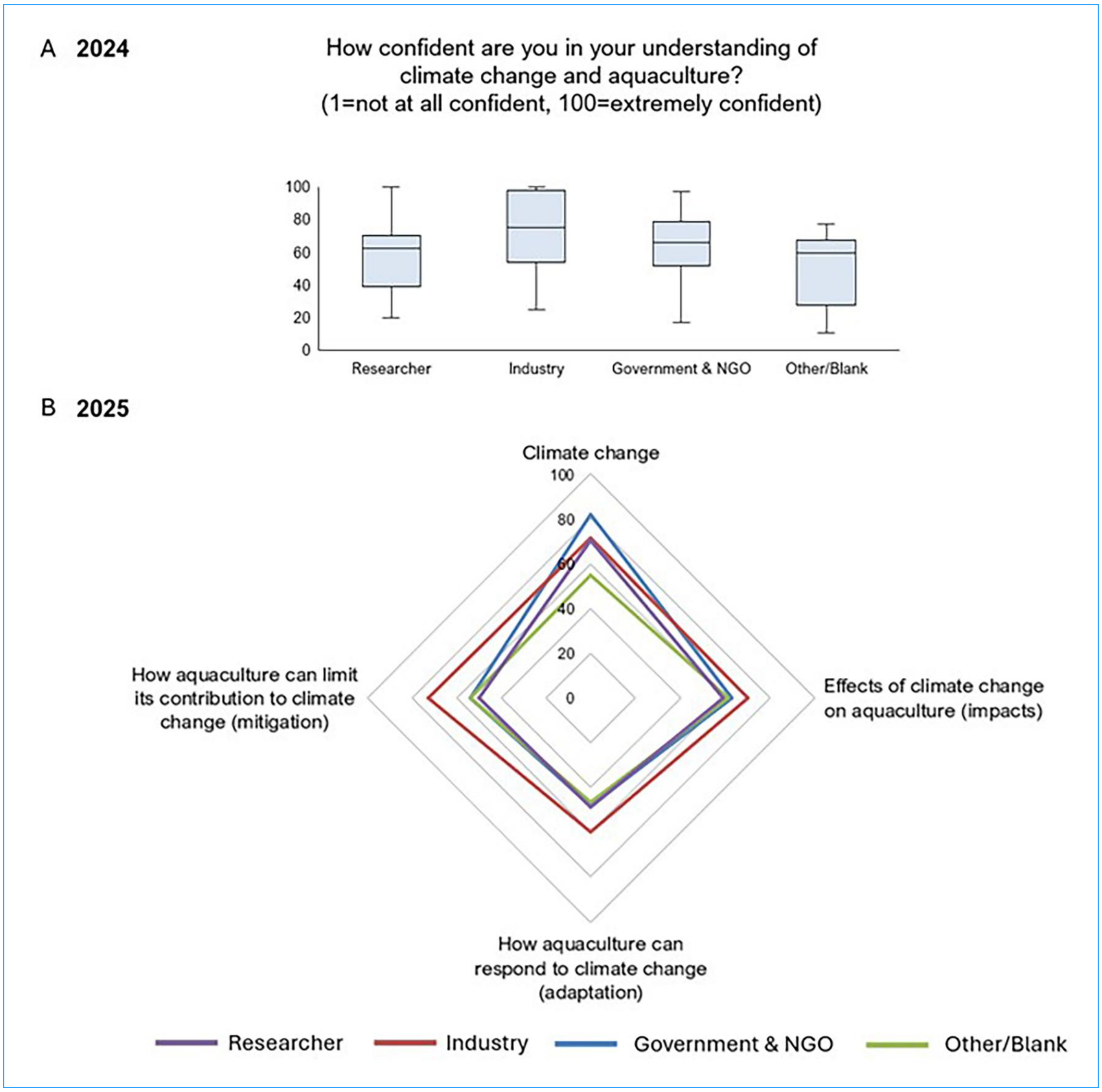

Figure 4. Response to questions about understanding of climate change and aquaculture, segmented by stakeholder group. In (A), boxplots are used to represent responses to a question about general understanding of aquaculture and climate change asked in 2024. Segmented groups in (A) include Researcher ($n = 24$), Industry ($n = 11$), Government & NGO ($n = 10$), and Other/Blank ($n = 14$). Mean responses to four questions about understanding of four components of climate change and aquaculture (general understanding, understanding of climate change impacts, understanding of climate change mitigation, and understanding of climate change adaptation) are displayed on a spidergram with different colors representing different stakeholder groups (B). Segmented groups in (B) include.

and enablers to climate action in general using open-ended questions. These results are summarized and grouped into dimensions of adaptive capacity (the ability to adjust to, cope with, and take advantage of changing conditions) that were adapted from Cinner and Barnes [36]. Barriers to adaptation included a lack of funding, regulatory restrictions, limited availability of solutions, a lack of knowledge, as well as motivational factors, among others. Enablers included regulatory pressure and other incentives, clear objectives, and relevant research (Table 2).

In 2025, we approached questions about challenges to adaptation differently. Questions were developed around Moser and Ekstrom's [37] framework to diagnose barriers to climate change adaptation. This framework divides the stages of adaptation into three stages and nine sub-stages, in recognition that barriers may differ across stages of adaptation. These segments include *understanding* [detect problem, gather/use information, (re)define problem], *planning* [develop options, assess options, select option(s)], and *managing* (implement option, monitor option and environment, evaluate). Participants were presented with questions about each stage and given a list of options from which to choose their top 2 challenges.

Some of the data already presented here suggest some agreement in the "detect problem" sub-stage of *understanding* as respondents have generally acknowledged that climate impacts are occurring, and that the sector does not have the information needed to adapt

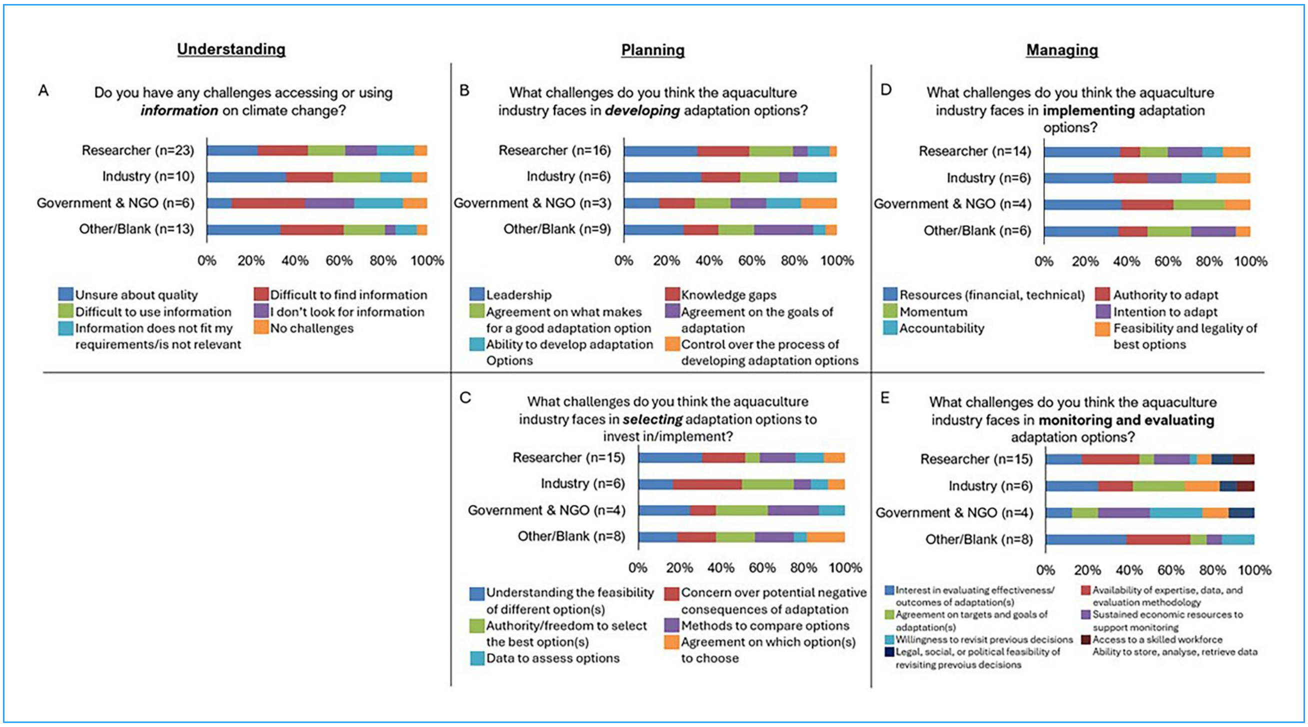

Figure 5. Proportion of each response option for questions about challenges in the understanding, planning, and managing phases of adaptation. Participants at the 2025 workshop were asked to select their top 2 challenges for each question.

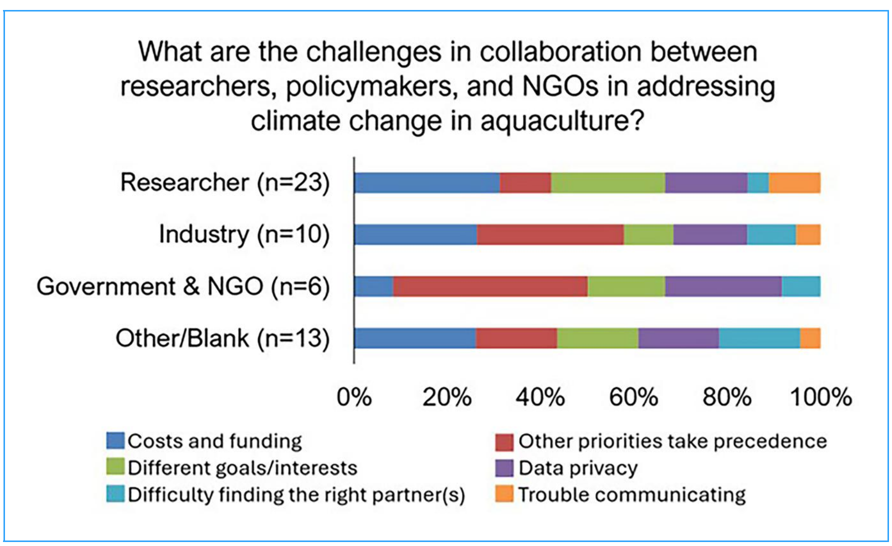

Figure 6. Proportion of each response option that was selected by 2025 workshop participants in response to a question about challenges in collaboration between stakeholders. Participants were able to select two responses to this question.

(Figures 2 and 3). When asked specifically about challenges in the "gather/use information" sub-stage, being unsure about the quality of climate change information was a primary concern (27% of all responses), and this was especially true for the 10 industry professionals who responded to the question (36% of responses from Industry group) (Figure 5A). This was followed by finding information (25% of all responses).

For the *planning* stage of adaptation, leadership was the top challenge within the developing sub-stage (31% of all responses), especially among researchers (34%) and industry (36%) (Figure 5B). The need for leadership corresponds to open-ended responses from 2024 related to the vision dimension of adaptive capacity (Table 2). Leadership was followed by knowledge gaps (20% of all responses) (Figure 5B), which was also evident in 2024 and corresponds to the knowledge dimension of adaptive capacity (Table 2). Understanding the feasibility of different options (25% of all responses) and concern about negative consequences (22% of all responses) were the leading challenges within the selecting sub-stage (Figure 5C). These responses reflect the uncertainty around climate change adaptation and the risk of maladaptation [8], which are also characteristics of wicked problems [12].

In the *managing* stage of adaptation, resources were the primary concern in the implementation sub-stage (36% of all responses) (Figure 5D) which reflects the assets dimension of adaptive capacity (Table 2). Motivational factors were also evident in the monitoring and evaluation sub-stage where interest in evaluating adaptation was the most frequently selected challenge (23% of all responses), though the availability of expertise, data, and evaluation methodology were more important among researchers (28% of responses from Researcher group) (Figure 5E).

Overall, knowledge, resources, and leadership were identified as some of the key challenges to climate change adaptation, but knowledge in particular appears to be a challenge across all three stages of adaptation. As the role of researchers is to generate knowledge, this is an area where researchers and stakeholders are naturally aligned, though the specific goals and expectations associated with that knowledge may differ (Table 1).

3.4. Collaboration for climate action in aquaculture

In 2025, we included Mentimeter questions about collaboration to understand challenges from the perspective of different stakeholders. Competing priorities were the primary barrier to collaboration on climate change and aquaculture for industry and government & NGO groups. Funding was the primary barrier for researchers (31%), followed by having different goals/interests (24%). Although having a shared goal is central to participatory and transdisciplinary research, this was less of a concern for industry (16%) and government & NGO (17%) stakeholders than the practical issues of prioritization (Industry = 32%, Government & NGO = 42%) and data privacy (Industry = 25%, Government & NGO = 25%), as well as funding for the Industry group (26%) (Figure 6).

Participants also responded to the open-ended question: "How can collaboration between industry, researchers, policymakers, and NGOs be improved?" Some of the opportunities identified included more opportunities to share knowledge and better communication, targeted funding calls, working with people with skills and attitudes that support collaboration, and structuring research programs around common goals (Table 3).

4. Discussion

The data presented here suggest that there are opportunities for collaboration on climate change adaptation in aquaculture; researchers, industry, and government & NGO representatives at two climate change workshops were largely in agreement that climate change is a problem, and that we need to be doing more to prepare for it. Of course, the perspectives captured here represent those professionals willing and able to attend a climate change workshop, and understanding, perceptions, and experience of climate change may differ across the broader salmon aquaculture community. Therefore, while the collective perspective of workshop participants suggests there is opportunity to develop shared goals around climate change research, more detailed and context-specific information about distinct knowledge gaps and priorities will be needed to shape defined projects and collaborations. This will require increased effort and engagement on the part of both researchers and industry. However, the role of broader knowledge exchange such as these workshops appears to be a welcome step toward collaboration (Table 3). As one participant expressed, "[We need more] sessions like this, to realize that we have common goals."

4.1. Choosing the right level of integration and participation to address adaptation challenges

Some of the challenges in addressing wicked problems manifested in participant responses to questions about climate change adaptation. It is apparent that climate change adaptation is complex, and that there is uncertainty around the expected impacts of climate change on aquaculture, the feasibility of adaptation options, and the consequences of implementing adaptation actions (Figure 5C). Knowledge about potential climate change stressors and impacts on aquaculture is growing, for example, an increase in sea lice and mortality events [38], jellyfish and harmful algae blooms [39,40], heatwaves [38,41], and increasing incidence and severity of storms [15,42]. Industry and technology companies across the supply chain are developing and implementing adaptation measures including monitoring and forecasting extreme events [43,44], semi-closed recirculating systems [45], and offshore systems that can withstand extreme weather [46]. Other potential adaptations include strategies such as moving farms to less impacted areas, building flood protection, changing farm practices including stocking larger fish, as well as policy and governance changes that support adaptation [17,47]. However, adaptation is an area of climate change research in need of more attention; it is worth noting that in the 2025 workshop, all groups rated their understanding of adaptation lower than their understanding of climate change, impacts and mitigation. Challenges remain and successful adaptation will require context-specific understanding of both climate change impacts and the feasibility and suitability of adaptations [15,47].

The Ocean Decade emphasizes the need for co-developed and transdisciplinary approaches to ocean challenges, and translating its call for "the science we need for the ocean we want" to the challenge of aquaculture adaptation suggests a need to address knowledge gaps while also finding ways to move forward and make decisions about adaptation where knowledge gaps and axiological uncertainty remain. Therefore, disciplinary and participatory research is needed to fill important fundamental knowledge gaps, while inter- and transdisciplinary research is needed in areas where production and ecological tradeoffs are present. Given the workshop context and people in attendance, this paper focuses on collaboration between researcher, industry, and government and NGOs; however, it is important to note that communities will also hold nonacademic knowledge that will be relevant and important to addressing many climate change adaptation challenges in aquaculture. This is especially true of questions around social, environmental, and economic impacts and tradeoffs.

4.2. Recognizing challenges, acknowledging differences, and moving ahead

These collaborative approaches present new practical and ethical challenges when working across public and private sectors that have been discussed extensively in academic literature. These include challenges such as managing intellectual property [23], cultural differences between actors or workplace restrictions on how they are able to engage in research [48], and the time, resource, and skills required of transdisciplinary and collaborative research [22,49,50]. Several of these challenges were echoed in participant responses to questions about collaboration and provide an opportunity to point to ways to move forward on collaborative research efforts.

Researchers reported costs and funding as barriers to collaborative research (Figure 6) reflecting broader misalignment between university and funder expectations and metrics, and the time and resource requirements of truly collaborative research [49]. Funding requirements for collaboration have been shown to strengthen interactions between knowledge producers and knowledge users [51], but as the findings here also show, new mechanisms that facilitate long-term transdisciplinary and inclusive partnerships need more attention. Practicing and coordinating the integrated research approaches described here also requires skills and knowledge that traditional disciplinary education does not always emphasize. Incorporating cross-disciplinarity as well as industry and community partnerships in university programs can support the development of a workforce prepared to address complex Ocean Decade challenges [52].

Returning to the idea of research, policy, and industry cultures, each collaborator in a research setting may be motivated by different values or hold different assumptions about the value of research. This might include valuing research and scholarship for researchers, while policymakers and industry may place greater value on more action (Table 1). The need to bridge these potential differences was apparent in participant responses to questions about improving collaboration between researchers, industry, and government and NGOs (Table 3); some participants noted a need for joint projects, greater alignment, and more active collaboration, while others suggested that research should be equally science- and business-oriented or more focused on industry needs. These perspectives suggest that there is groundwork to be done to identify common goals and work across the cultures of research, policy, and industry in the context of climate action research. Emphasizing reflexive practice among aquaculture transdisciplinary teams will be important for recognizing differences and understanding our place within a research collaboration as well as within broader society.

Trust and respect are central to many of the challenges associated with collaborative research. Research and commentary on these issues in transdisciplinarity often focus on the role of ethics and the need for researchers to respect and recognize multiple ways of knowing [50]; however, this advice typically assumes a power dynamic wherein researchers and/or scientific knowledge has historically taken precedence. Power dynamics will differ across aquaculture sectors and stakeholders, but in the context of a growing global salmon aquaculture industry and the escalating climate emergency, the roles and responsibilities of all participants in transdisciplinary settings will require careful consideration. Institutional rules and norms already dictate administrative matters such as intellectual property and conflicts of interest, and the rules-based procedural aspects of ethics such as data privacy and informed consent. Yet, these institutional guidelines for working with participants and collaborators are inadequate in transdisciplinary settings [50]. Greater consideration and reflection on responsible research and innovation are needed when focusing on uncertain futures and complex topics, especially with regard to providing advice, producing impact, and ensuring social good [29]. Some research funders provide guidance on how to culture positive partnerships and conduct responsible research and innovation throughout the lifecycle of a project or collaboration, e.g. UK Research and Innovation [53], Norwegian Research Council [54]. Both UKRI (through AREA – Anticipate, Reflect, Engage and Act) and the Norwegian Research Council (through AIAA – Anticipation, Inclusion, Reflection, and Responsiveness) emphasize the need to look ahead and consider the desired and undesired effects that research could have, use an inclusive approach, continual reflection to ensure aligned values and goals, and where necessary influence the research direction and trajectory to ensure responsible research and innovation. These guidelines can serve as an important tool to ensure all actors within the transdisciplinary collaboration have shared principles and transparent practices, and work collaboratively toward the common goal.

4.3. Conclusion

The need for climate action in food systems including aquaculture is clear. Knowledge exchange has an important role in climate change adaptation, but further progress toward deep collaboration and transdisciplinary research will be needed to support sustainable and resilient aquaculture under climate change. The perspectives and experiences of aquaculture researchers, industry, government, and NGOs suggest that shared goals for knowledge production and action are possible, though these groups also perceive distinct barriers across different stages of adaptation. As transdisciplinary research integrates different perspectives, expertise, and experiences, it provides a strong platform to deliver change, if conducted in a responsible manner. Hence, transdisciplinary research can be a route to addressing the lack of progress in climate adaptation worldwide. The research presented here reflects perspectives on climate change and aquaculture from within the specific context of a Norwegian and Scottish workshop focusing on salmon, but the need for inter- and transdisciplinary research as well as many of the challenges identified may be relevant in other countries and for other species, as well as other food systems, if science is to support societal goals including the continued production of farmed seafood.

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Author contributions

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Data availability statement

The data that support the findings of this study are available in DataSTORRE at http://hdl.handle.net/11667/267 & http://hdl.handle.net/11667/250

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