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Best practices for producing actionable knowledge to inform fisheries management and conservation

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Abstract In applied research, there is an expectation that knowledge generators will produce information that can be acted upon by knowledge end users (i.e., actionable knowledge); however, this is not always the case, resulting in a knowledge-action gap. Currently, there is no literature directly targeted at fisheries knowledge generators (e.g., researchers) to guide them in producing knowledge that could be readily used to inform fisheries management and conservation. To that end, this paper provides evidence-based recommendations for researchers to produce actionable knowledge. Key recommendations include the following: (1) embrace co-production; (2) prioritize capacity building; (3) include Indigenous and local knowledge systems; (4) diversify forms of knowledge exchange; (5) participate in interdisciplinary research; and (6) provide training for early-career researchers on producing actionable knowledge. We also analyze challenges to producing actionable knowledge, such as trust imbalances, costs of engaging in highly collaborative work, and difficulties related to effective knowledge exchange with fast-moving research timeframes, funding restrictions, and lack of institutional support. Using several case studies, we examine how

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knowledge generators overcome such challenges to successfully implement the key recommendations. It is our hope these recommendations will encourage and facilitate actionable research, contributing to more effective fisheries management and conservation.

Keywords Capacity building · Interdisciplinary research · Knowledge exchange · Knowledge co-production · Science communication · Stakeholder engagement

Introduction

An important goal of applied research is to inform actions by practitioners, decision-makers, and policy makers. In other words, it is to generate actionable knowledge (also variously referred to as actionable research, actionable science, and useable knowledge, among other terms; see Glossary; Wall et al. 2017; Nguyen et al. 2019; Arnott et al. 2020). However, when knowledge that is produced is difficult to access, interpret, and implement, it is often not used to inform management decisions, resulting in a knowledge-action gap (Cook et al. 2012; Cooke et al. 2021b). To narrow this gap, researchers should consider ways to improve the planning, execution, and communication of their work to enhance the accessibility of their results to potential end users, ultimately resulting in informed management decisions (Nguyen et al. 2021). Knowledge generators known to produce actionable work have identified five common challenges including (1) collaboration; (2) challenges with research management; (3) maintenance of the common vision; (4) power dynamics and biases of collaborators; and (5) institutional forces (Goolsby et al. 2023). Although there are many challenges associated with producing actionable knowledge, there are also associated benefits such as the provision of information that is able to be used readily to inform management decisions (Lemos et al. 2012). For that reason, producing actionable knowledge is a long-term standing goal for knowledge producers working on applied topics such as fisheries management and conservation. Early frameworks recognize that for science to be actionable it must be credible, salient, and legitimate (Cash et al. 2003). When science is produced that meets all three of the former criteria, it can be mobilized, used, and drawn upon by knowledge end users including practitioners, policy makers, and decision-makers (i.e., actionable knowledge). Several "How-to Guides" for creating actionable knowledge have been generated for many scientific disciplines including climate change, conservation, and resource management (Gerber et al. 2020; Kelman et al. 2022; Bamzai-Dodson et al. 2023). However, a guide for actionable knowledge targeted at fisheries professionals is absent from the literature, which could limit the production of research that can be readily actioned by fisheries practitioners and decision-makers.

Fisheries are complex socio-ecological systems composed of multiple actors with competing interests over a tangible resource (Arlinghaus et al. 2017). As such, those tasked with managing fisheries are faced with many challenges when making decisions (Howarth et al. 2023). A hallmark of fisheries management is that it is evidence-based (Organ et al. 2012; or more usually, informed by science) albeit at times science is notably absent (Artelle et al. 2018). In most developed countries with natural resource management agencies, science interfaces with resource management in several forms. For example, routine monitoring (e.g., stock assessment) is a form of science that generates knowledge that feeds directly into decision-making. This is often done by those with decision-making authority who are employed by natural resource management agencies. Research, on the other hand, is often done by individuals in academia or government research units adjacent to decision-makers (albeit, sometimes within the same agency/organization). Both monitoring and research have the potential to inform management, but they do so in different ways. For the purpose of this paper, we focus on research given that monitoring is often an institutionalized component of the management cycle (Krueger and Decker 1999; McMullin and Pert 2010). Conversely, research occurs along the fundamental-applied continuum and may or may not inform the contemporary needs of fisheries managers and decision-makers. These diverse contexts and values have historically contributed to inadequate communication, collaboration, and knowledge exchange (see Glossary) among groups, sometimes with severe cultural and socio-economic ramifications (e.g., the Cod Collapse in Canada; Cvitanovic et al. 2016). Grievances about fisheries mismanagement are in the collective memories of many, leading to distrust among knowledge user groups (e.g., decision-makers and academics; Ebel et al. 2018). How-to guides from other disciplines act as a good starting point for fisheries professionals but they fail to address the uniqueness of fisheries, which may inhibit fisheries researchers from producing actionable knowledge. Here, we identify best practices for knowledge generators to produce actionable knowledge in fisheries management and conservation informed by a broad literature scan (summarized in Table 1). We also highlight cases where each best practice has been put into action with real-world examples. Finally, we present challenges and barriers that could hinder the implementation of our suggested best practices. It is our intent that this article will be used as a toolbox, providing a list of recommended actions with a visual representation of the proposed cycle for producing actionable knowledge that can be used by knowledge generators in fisheries to help guide the successful production of actionable knowledge.

Glossary

Actionable knowledge**:** Knowledge generated (e.g., by scientists) that has the potential to inform decisions by knowledge users (e.g., policy makers, practitioners)

Capacity building**:** Providing stakeholders and rightsholders with the knowledge and tools necessary to effectively engage with scientific research and other knowledge systems

Fisheries practitioners**:** Individuals whose role is to make decisions, develop policies, or implement best practices for commercial, recreational, or subsistence fisheries or to otherwise engage in aquatic conservation and management

Knowledge-action gap: A phenomenon where knowledge produced by knowledge generators is not used by knowledge users to inform evidence-based management or policy decisions, resulting in a divide/gap

Knowledge exchange**:** The process of sharing knowledge among knowledge generators and knowledge users. There are many forms of knowledge exchange including oral, visual, and written formats that prioritize the needs and preferred method of sharing knowledge by the actors involved

Knowledge generators**:** Individuals whose job/role is to produce science that is salient, relevant, and legitimate. These can be researchers, scientists, or any relevant actor (e.g., community scientists). This may also include knowledge holders (e.g., elders) who are sharing Indigenous science and knowledge amassed across generations

Knowledge users**:** Individuals whose job/role is to use knowledge produced from science (including Indigenous science and knowledge) to inform management decisions, policy decisions, or best practices. These can be policy makers, decision-makers, practitioners, or any relevant actor

What is actionable knowledge?

Actionable knowledge is used and defined in multiple ways in the literature (Beier et al. 2017; Gerber et al. 2020). Here, we define actionable knowledge as knowledge generated that informs a decision by knowledge users—in this case, in the context of fisheries management and conservation. We draw on this definition by considering other definitions of actionable knowledge, including (1) knowledge that is embraced by knowledge users to inform management decisions (Gerber et al. 2020); (2) knowledge produced that meets the management needs and goals set by knowledge users (Gerber et al. 2020); (3) knowledge produced that continues to be used by knowledge users to inform management decisions (Gerber et al. 2020); and (4) knowledge generated that supports management decisions via the use of sound knowledge (Beier et al. 2017). It is recognized that knowledge provides information required to make informed decisions, but is only one line of evidence used by decision-makers along with political, economic, and social factors (Policansky 1998). Finally, knowledge is considered "actionable" if it is used (or has the potential to be used) to inform decision-makers, regardless of whether they choose to take action or not (recall that not taking action is an action in and of itself).

Recommended actions

1) Embrace knowledge co-production

Knowledge co-production is emerging as an approach to bridge the knowledge-action gap in many disciplines of science (Beier et al. 2017; Wamsler 2017; Djenontin and Meadow 2018; Grindell et al. 2022; Fusco et al. 2020), including fisheries (Cooke et al. 2021a). Knowledge co-production aims to incorporate a multitude of knowledge types and sources to develop transdisciplinary, system-oriented understandings of problems and potential solutions (Armitage et al. 2011; Norström et al. 2020; Mills et al. 2023). To do so, knowledge co-production calls for an inclusive, engaged, and democratic (as long as that does not impede respecting or asserting Indigenous sovereignty) relationship among

Table 1 Fourteen tips for developing a team capable of participating in interdisciplinary research to produce effective solutions in fisheries management adapted from Kelly et al. (2019), Blythe and Cvitanovic (2020), and Boulton et al. (2005)

Tips for IDR	Description	Reference(s)
1. Develop an area of expertise	Develop core knowledge in a discipline, place, field of study, method, or process so you can contribute to IDR.	Kelly et al. 2019; Blythe and Cvitanovic 2020
2. Learn new languages	Develop a shared language to assist with communication of knowledge across disciplines where it otherwise may not be understood.	Kelly et al. 2019
3. Be open minded	Appreciate diversity in the knowledge, perspectives, and contributions of other researchers to encourage innovative solutions via IDR.	Kelly et al. 2019
4. Be patient	Understand that effective IDR takes time as it requires time to be spent on trust, learning, and transaction between disciplines.	Kelly et al. 2019
5. Embrace complexity	Understand complexity to be an asset in IDR as it allows multiple disciplines to work towards a common goal	Kelly et al. 2019
6. Collaborate widley	Forage partnerships with others by exploring different disciplines, engaging in knowledge co-production, interacting with knowledge brokers, and creating trust through partnerships.	Kelly et al. 2019; Blythe and Cvitanovic 2020
7. Push your boundaries	Take advantage of the opportunity to learn from other disciplines, broadening your disciplinary perspective through IDR.	Kelly et al. 2019
8. Consider if and how to engage in IDR	Consider whether or not IDR is necessary or useful for the project considering its limitations including time and funding.	Kelly et al. 2019
9. Foster interdisciplinary culture	Institutional leaders and lead researchers should encourage collaboration and integration of knowledge through IDR.	Kelly et al. 2019
10. Recognize IDR success	Institutional leaders and lead researchers should recognize and award successful IDR to encourage others to participate in IDR.	Kelly et al. 2019
11. Support female leadership	Support female leadership to foster innovation, nurture a culture of inclusion, and mitigate hierarchical power imbalances in IDR.	Blythe and Cvitanovic 2020
12. Develop impact-based performance metrics	Develop interdisciplinary indicators to analyze the success of IDR in creating solutions for complex socio-ecological problems and demonstrate impact.	Blythe and Cvitanovic 2020
13. Seek long-term funding	Seek innovative, long-term funding to accommodate the additional time required for IDR.	Blythe and Cvitanovic 2020; Boulton et al. 2005
14. Plan accordingly	Plan to consider all members involved including researchers, funders, and partners. Propose a specific research question and contextualize it allowing each discipline to define the issue in the context of their	Boulton et al. 2005

knowledge generators and knowledge users throughout all phases of a project (Cooke et al. 2021a). The nature of these relationships, and the structure of the research itself, should be iterative and context-dependent (see co-productive agility in Chambers et al. 2022). In some cases where knowledge already exists but there is conflict or disagreement, knowledge co-assessment can be undertaken where knowledge is assessed collaboratively which is an adjacent method to co-production.

Embracing co-production in fisheries science (see Cooke et al. 2021a) has the potential to improve the salience and legitimacy of the resultant knowledge, enhancing its actionability (Cash et al. 2003; Jagannathan et al. 2020). Co-production has been embraced by the UN Ocean Decade to understand the task of developing global fisheries resilience at local and regional scales (Mills et al. 2023), by the Canadian and US governments for a binational risk assessment of invasive grass carp *Ctenopharyngodon idella* (more so co-assessment; Cudmore et al. 2017), by Indigenous Nations in the Arctic to assess fishery sustainability, stock structure, and food security (Cooke et al. 2021a), by four levels of government in Toronto, Ontario to conduct ecological restoration for freshwater fishes (Piczak et al. 2022), and by knowledge generators in Maine, US, and Finland addressing more localized fishery issues (co-assessment; Maillet et al. 2017; Saarikoski et al. 2024).

Knowledge co-production has seen relatively rapid uptake by knowledge generators and knowledge users in fisheries in recent years, and its potential contributions to the generation of actionable knowledge are manifold (Cooke et al. 2021a). Yet, attempting co-production brings risks, challenges, and costs. Knowledge co-production is a time-consuming, resource-intensive, interpersonally demanding, institutionally disincentivized process (Cvitanovic et al. 2015a, b; Oliver et al. 2019; Piczak et al. 2022). Furthermore, some voices within a working group, ill-intended or not, may dominate co-productive discussions and stall progress (Oliver et al. 2019). Knowledge co-production has generally been more successful in situations where trust and communication are already present, divided parties are not too entrenched to rule out reconciliation, there are no disagreements regarding fundamental facts, and there are clear shared priorities (Oliver et al. 2019). It may be less likely to succeed where there is difficulty establishing this common ground, and/or where existing power imbalances among parties are allowed to persist, such as in highly contested or top-down managed fisheries (Ebel et al. 2018; Oliver et al. 2019). In fact, if knowledge co-production proceeds without adequately addressing such power dynamics, existing divisions could be exacerbated (Turnhout et al. 2020). Despite challenges associated with knowledge co-production, there are many benefits and we encourage researchers to pursue co-production incrementally if necessary to build confidence with these practices.

Case study: co-assessing knowledge regarding impacts of cormorants on commercial fishers in Finland

Great cormorants (*Phalacrocorax carbo*) and commercial fishers in the Baltic Sea have a history of conflict. Commercial fishers have advocated for cormorant culls, while conservationists and managers have been hesitant to enact such measures. Commercial fishers felt cormorants were a threat to their catch, whereas conservationists cited works showing they had no significant effect. This disagreement continued for more than a decade despite multiple failed attempts at mediation. Saarikoski et al. (2024) brought together a multidisciplinary group of knowledge generators with commercial and recreational fishery representatives, regulators, conservation non-governmental organization (NGO) representatives, and a community member. A joint conclusion was reached, which agreed that both sides were largely correct and that this debate was a framing issue: Conservationists were citing top-down papers focused on the entire Baltic Sea, while commercial fishers were first-hand dealing with cormorants harassing their catch on a daily basis. The authors also found that knowledge co-assessment encouraged learning and reflection among both sides, and some interviewed fishers had increased trust in the research process; however, evidence of deep distrust among these groups remains. This is an example of an incremental success made possible by knowledge co-assessment after decades of disagreement and broken communication, while it also emphasizes the difficult, long-term, and iterative nature of the process

2) Engage relevant stakeholders[1] to build capacity and trust

The benefits of engaging diverse stakeholders in research are increasingly recognized as an effective tool for producing actionable knowledge across

[1] We acknowledge that the word "stakeholders" fails to adequately capture the fact that there are also rightsholders involved in many fisheries issues. To address that deficiency, we explicitly emphasize involving rightsholders in the next recommendation.

a range of disciplines (Klein et al. 2001; Reed 2008; Cvitanovic et al. 2015b; Reed et al. 2018; Andre et al. 2023) including fisheries management (Hartley and Robertson 2006; Seijo and Salas 2014; Christie et al. 2017; Alexander et al. 2018; Lucrezi et al. 2019; Cooke et al. 2021a). The field of fisheries management is particularly complex in this sense (Wilson et al. 1994; Cochrane 1999; Caddy and Seijo 2005) as diverse stakeholders often depend on the sufficient management of fisheries resources for income, sustenance, and/or recreation. This makes fisheries management highly subjective and political, meaning that management decisions can elicit emotional and practical reactions from stakeholders which significantly influence fisheries management outcomes (Nightingale 2013). Indeed, engaging with multiple stakeholders in research can prevent conflict, cultivate trust, and build capacity for learning among knowledge generators and knowledge users (Beierle 2002; Reed 2008; de Vente et al. 2016). We emphasize the importance of building genuine partnerships based on humility and mutual trust to avoid disempowering stakeholders (see Evans and Cvitanovic 2018; Chambers et al. 2022). To do so, knowledge generators should refine their communication, facilitation, and group-process skills in addition to their research skills (Grant et al. 2008; Addison et al. 2013; Cvitanovic et al. 2019; Bamzai-Dodson et al. 2023). High levels of stakeholder participation in fisheries management can increase transparency around decision-making processes, cultivate trust and capacity building, prevent conflict, and thus promote collective action and cooperation among these diverse stakeholders (Gilmour et al. 2011; Lopes et al. 2013; Trimble and Berkes 2013; Evans and Cvitanovic 2018; Lucrezi et al. 2019).

Altogether, the importance of engaging diverse stakeholders to build capacity and trust in fisheries management is readily recognized, yet implementation remains a challenge. Commercial and recreational fishers are commonly identified as the main (and occasionally only) users of fisheries resources, whereas other actors (including rightsholders and the broader public) remain relatively marginalized (Schwermer et al. 2020). To avoid excluding relevant stakeholders from engagement actions, we recommend that knowledge generators conduct a stakeholder analysis to identify relevant stakeholders and appropriate methods for engaging each group, both at the beginning of the process and periodically throughout. Methods of engagement may involve active methods which engage stakeholders in decision-making such as workshops and surveys, or passive methods which do not such as video presentations (for review, see Schwermer et al. 2020). Ultimately, stakeholder engagement stands as a key component to effectively produce actionable fisheries research.

Case study: South Africa's Responsible Fisheries Program
One example of effective and large-scale stakeholder engagement and capacity building is South Africa's Responsible Fisheries Program (RFP). The RFP is a training course which was designed to facilitate the implementation of an ecosystem-based approach to fisheries. To achieve this, the program integrated theory and practical exercises while deliberately drawing on knowledge from various stakeholders. Over 600 fisheries professionals completed the course within its first 3 years of implementation (2007–2010), including various fishers, conservationists, and relevant law enforcement personnel. Follow-up questionnaires indicated that the participants found the interactive exercises within the course to effectively build knowledge and appreciation of the benefits of stakeholder engagement and a participatory approach to managing fisheries. The program has been associated with improvements in compliance with fisheries regulations and capacity building within stakeholders such as fishers. Through the engagement of diverse stakeholders, the RFP program was able to effectively build capacity and trust among diverse stakeholders and facilitated the implementation of an ecosystem approach to fisheries within South Africa, exemplifying how stakeholder engagement can facilitate management action in this field (Okes et al. 2012)

3) Seek opportunities to include Indigenous and local knowledge systems to inform research and management decisions

Fisheries research and management is based largely on the western science knowledge system where the scientific method is embraced (Varghese and Crawford 2021; Dahlstrom and Scheufele 2018). However, involving Indigenous and local knowledge systems (and Indigenous peoples as rightsholders) in knowledge generation has great potential for actionable research by providing novel and pertinent hypotheses (Varghese and Crawford 2021), attenuating long-standing conflicts (Young et al. 2016), and ensuring an inclusive process and outcome of decisions (Chapman and Schott 2020; Cooke et al. 2021a). Although there is no single and comprehensive perspective within fisheries, other studies have shown that including other ways of knowing enhances the legitimacy, salience, and applicability of research (Cornell et al. 2013; Reid et al. 2021; Cooke et al. 2021a).

The formation, validation, and transfer of knowledge within each knowledge system have distinct differences, where full awareness of the intra-culturally diverse ways of knowing is essential to ensure full partnership in the realm of fisheries management (Mazzocchi 2018; Stepanova et al. 2020; Alexander et al. 2021; Reid et al. 2021; Varghese and Crawford 2021). Non-Indigenous participants need to be mindful that there is no single Indigenous model of knowing (Ataria et al. 2018; Deloria et al. 2018); however, an accepted classification of Indigenous ways of knowing can be defined by a cumulative body of knowledge, practice, and belief evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment (Dudgeon and Berkes 2003; Reid et al. 2021). A way of ensuring Indigenous and western science knowledge systems contribute equally to fisheries research and management is adopting the Two-Eyed Seeing approach framework (reviewed in Reid et al. 2021). This framework includes practices to strengthen Indigenous knowledge in fisheries management by respecting Indigenous community structures and bringing together different ways of knowing driven by the ultimate goal of leaving the world a better place (Latulippe and Klenk 2020). By adhering to Indigenous frameworks such as the former, managers and knowledge generators can ensure the full representation and inclusion of Indigenous partners on important fisheries issues thereby furthering the sustainability of fisheries for all user groups (Reid et al. 2021).

Local knowledge systems are based on observations and hands-on experience accumulated over collective lifetimes of using the fishery for recreational or livelihood purposes (Berkström et al. 2019). Fisheries research and decision-making often exclude local knowledge systems, despite local knowledge holders producing (and holding) a wealth of valid and reliable knowledge that could support western science (Mackinson and Nottestad 1998; Varghese and Crawford 2021). As a result, potentially useful knowledge that could support fisheries management is underused. Further, in fisheries with a shortage of western scientific data, the inclusion of local knowledge (which may include Indigenous science) results in valuable insights on fish populations which allows for agile management decisions (Silvano and Jorgensen 2008; Silvano and Alpina 2010). Including local knowledge holders as partners in research and decision-making can result in increased trust and user-useful outcomes (Mackinson and Nottestad 1998).

Case study: bridging science and traditional knowledge to assess cumulative impacts of stressors on ecosystem health

A Two-Eyed seeing approach was implemented in a study where the co-production of knowledge (Indigenous and western) was used to assess ecosystem health on the Slave River in the Northwest Territories, Canada. Questions about the ecosystem health of the Slave River were co-developed which included (1) is the water safe to drink, (2) are the fish and wildlife safe to eat, and (3) is the ecosystem healthy? Western science (e.g., field surveys and document reviews) and Indigenous knowledge (e.g., via interviews with elders) were woven together and this collaborative effort resulted in the discovery that the social-ecological system had degraded over time. There were disparities that arose whereby Indigenous knowledge revealed a more degraded state than western science. This mismatch outlines the possibility that western science is not as effective at detecting change over long periods of time when compared to the long-term generational knowledge passed down within Indigenous knowledge holders and/or that the Indigenous knowledge was more risk averse. Ultimately, this study provides an example of the knowledge-inclusive partnerships possible through the Two-Eyed seeing framework that can inform management strategies to ensure the sustainable management of aquatic ecosystems (Mantyka-Pringle et al. 2017)

4) Diversify forms of knowledge exchange

Investing time in knowledge exchange with stakeholders is positive because it leads to better science and more inclusive and informed decisions; however, knowledge generators tend to spend little time in this endeavor and use relatively few approaches (Nguyen et al. 2019). Therefore, knowledge generators should seek to diversify methods of knowledge exchange (see Glossary) to reach diverse knowledge users such as managers, academics, and local communities, especially Indigenous communities. Knowledge users may have unique needs and preferred ways to engage in knowledge exchange, so it is recommended knowledge generators either communicate with targeted knowledge users to discuss specific methods of knowledge exchange or seek to reach a wider audience of knowledge users by diversifying methods of knowledge exchange. Doing so contributes to a better understanding and management of resource activities on the land, leading to more relevant and actionable knowledge (Wong et al. 2020). Meaningful knowledge exchange can be interpreted differently based on the diverse needs of targeted knowledge users in fisheries (Wong et al. 2020).

Case study: Lhù'ààn Mân'—Klaune Lake Research Summit

Wong et al. (2020) provide a case study of successful alternative formats of knowledge exchange where scientists participated in a research summit (Lhù'ààn Mân'—Klaune Lake Research Summit, Yukon, Canada) that was organized by the partner community, Lhù'ààn Mân'—Klaune Lake. Knowledge generators were asked by the community to format their research in a way that the community could comprehend results which included one-page summaries and community-run conference presentations by knowledge generators to knowledge users. Knowledge generators were subsequently provided community feedback specific to the research on traditional lands which increased the level of bilateral knowledge exchange, validating the knowledge that had been created. Knowledge generators were asked to commit to one alternative method of knowledge exchange that would contribute to deepening the community's understanding of the research. Various commitments by researchers included hiring community youth as research assistants and providing one-page summaries of research without scientific jargon, all of which contributed to the research being relevant to the community (Wong et al. 2020)

5) Engage in collaborative interdisciplinary research

As the Anthropocene progresses, fisheries management continues to become a more delicate balancing act of managing exploitation (recreational and commercial fisheries; see Cooke et al. 2023) and conservation (see McMullin and Pert 2010; Blythe and Cvitanovic 2020). Therefore, fisheries management decisions should not exclusively draw from knowledge generated in natural science, but rather a complex socio-ecological system requiring knowledge from other disciplines including those based in both the physical and social sciences (McMullin and Pert 2010; Kelly et al. 2019; Hare 2020). Striving for a "good Anthropocene" requires innovative solutions to not only minimize the progression of human impact on today's fisheries but ideally to also mitigate previous damage (Alexander et al. 2018; Blythe and Cvitanovic 2020), which we contend could be facilitated through the adoption of interdisciplinary research. Interdisciplinary research allows knowledge generators from different academic disciplines to integrate knowledge, providing a more comprehensive understanding of complex research topics (Repko 2008). Social-ecological systems are fundamentally complex and it can be challenging for management decisions based on one scientific discipline to account for the diverse factors involved (McMullin and Pert 2010).

Engaging in interdisciplinary research will primarily fall upon knowledge generators and there are a number of approaches suggested to facilitate implementation (Table 1). Training experts to become interdisciplinary knowledge generators can help ensure the success of interdisciplinary research as an approach to creating actionable knowledge in the advanced socio-ecological system of fisheries management (Kelly et al. 2019). Training in this manner can mitigate several challenges that arise from interdisciplinary research such as funding difficulties, credit, and publishing (Kelly et al. 2019). It will also be critical to support female leadership to nurture inclusion and mitigate power imbalances, develop impact-based performance metrics to measure the success of interdisciplinary research, seek the long-term funding required to accommodate interdisciplinary research, and support female leadership (Blythe and Cvitanovic 2020). Finally, planning (including financially) at all levels optimizes the use of individual knowledge generator expertise mitigating project-specific issues as well as those associated with interdisciplinary research (Boulton et al. 2005).

Case study: the management of Baltic Sea wild salmon stocks: a complex fishery

An example of the implementation of interdisciplinary research in fisheries management was the work done by natural scientists, social scientists, and economists on creating a holistic decision-support model for the long-term management of Baltic salmon stocks. As a result of human impact during the twentieth century, wild salmon stocks have been lost or depleted in most of the Baltic Sea. The management of these stocks is complex due to the migrating nature of the species and competing interests of stakeholder groups in different Baltic Sea countries. With the hope of recovering the Baltic Sea wild salmon stocks, four knowledge generators of different disciplines collaborated in a three-step process, resulting in a proposed management model. The first step was the interdisciplinary modeling (i.e., by natural scientists, social scientists, and economists) of the salmon stocks and socio-economic process. During this step, knowledge generators collaboratively focused on studying the uncertainty of stock assessment and setting management objectives, justifying the socio-economic feasibility of stock restoration, and how to help local communities cooperate to save the wild salmon stocks. This step resulted in ten publications that enabled knowledge generators to move on to the second step where they evaluated management options as well as future objectives based on the biological, economic, and social impacts of the Salmon Action Plan. After this assessment, knowledge generators were finally able to integrate biological, economic, and social knowledge to create a decision-support model. The entire process took approximately 7 years and resulted in the final Bayesian belief network model to restore the Baltic Sea wild salmon stocks (Haapasaari et al. 2012). It is uncertain to what degree this model was followed in the years preceding 2010; however, as of 2023 at least 7 out of 17 analyzed wild salmon stocks have demonstrated substantial recovery, particularly in the Northern Baltic Sea

6) Implement training for early-career researchers on producing actionable knowledge

While non-academic organizations such as NGOs and regulatory agencies incentivize creating actionable knowledge through core values, it is typically not a specific priority in academic institutions (Gerber et al. 2020) or academic funding schemes (Matso and Becker 2014). The focus, rather, is placed on publications, grants, and completion of degrees, leaving little room for time-consuming endeavors such as relationship building and communication with managers and policy makers (Raynor 2019; Nyboer et al. 2023). If not supported by mentors and supervisors, the result is cohorts of early-career knowledge generators that are uninformed on the steps required to produce actionable knowledge.

Academic institutions can encourage the production of actionable knowledge by implementing organized training for ECRs. In fisheries biology especially, formal training would permit ECRs to be exposed to the complexities of fisheries management early, and it would also allow the development of skills to navigate the politics and realities that may better inform their own research goals (Nyboer et al. 2023). This knowledge is pertinent to develop, as knowledge generators that are familiar and involved with the management process have been found to experience greater uptake of their research (Nguyen et al. 2019). Learning resources should be made available in the form of seminars, discussions, and dissemination of applicable material. Sharing vicarious and lived experiences in an institutionally sanctioned way would improve the current "trial and error" format of learning about how to produce actionable knowledge. We also suggest that institutions emphasize the preference for actionable knowledge for new hires and students in fisheries, in order to frame research with those goals in mind. Scientific institutions may also incentivize the creation of purposeful actionable research for their faculty and students and outwardly recognize the importance of producing knowledge that informs decisions (Nguyen et al. 2019). We propose that institutions set clear incentives to promote engagement and relationship building, as well as incorporate the creation of actionable knowledge into hiring and promotional considerations. Relationship building is important in fisheries science and when attempting to create actionable knowledge, though it can be relatively intimidating for ECRs. The act of building trust takes time and effort, and ECRs starting from scratch can be disadvantaged by time constraints (Orlando and Gard 2014). Institutions can encourage established knowledge generators to facilitate the building of relationships with fisheries partners in order to streamline actionable knowledge. Relationship building for undergraduate and graduate students could be strengthened with co-op programs similar to well-established and proven programs (e.g., nursing, engineering; MacKenzie

2015). Institutions and research supervisors may promote and create co-op programs for ECRS which will allow them to form early relationships as well as be exposed to the intricacies of fisheries work.

Case study: our experience with actionable research as ECRs

Though creating actionable knowledge is at the core of most conservation and fisheries research, it is often a non-academic product, and thus not prioritized institutionally. As a group of ECRs from various academic institutions, we reflected on our experience and knowledge of actionable research before the undertaking of this paper. For many of us, there was no exposure to formal training or education on actionable knowledge or how to produce it. We felt that although co-production and creating usable knowledge was seen as a clear positive, there was no guidance on the steps that were needed to be taken to achieve it. In writing this paper, we realized the need for formalized training and discussions, and how we may have been able to produce more actionable knowledge in previous work. We hope that future cohorts have access to more training and resources than we did and believe it will lead to earlier and stronger relationships with managers, highly relevant knowledge, and well-rounded knowledge generators—without sacrificing the necessary outputs of degrees and institutional goals

Actionable research: challenges

Although the actions we provide are intended to aid knowledge generators in overcoming barriers surrounding the production of actionable knowledge, they come with their own unique challenges (Table 2; also see those outlined in Goolsby et al. 2023). A common theme throughout our recommendations was building trust, which is an integral part of producing actionable knowledge, particularly where collaborative research (e.g., co-production, participatory research) is involved (Oliver et al. 2019). It should be noted however that too much or too little trust (i.e., either side of the optimal trust threshold) can yield undesirable outcomes and reduce the benefits of collaborative work (Lacey et al. 2018).

Cultural differences between knowledge generators and knowledge users can undercut efforts to improve knowledge exchange (Briggs 2006; Roux et al. 2006; Cvitanovic et al. 2015b). Knowledge generators gather data to support theories and test hypotheses, but the science makes up only a portion (along with political, social, and economic considerations) of what goes into the decision-making process (Policansky 1998; Cook et al. 2012; Cvitanovic et al. 2015a). This can cause friction and frustration between knowledge generators and knowledge users (Roux et al. 2006; Cvitanovic et al. 2015a). A recent review shows new science can take years to be published, meaning there is a serious lag between new, relevant knowledge and accessibility by management (Cvitanovic et al. 2015b). Several institutional barriers also act to mutually inhibit knowledge exchange between knowledge generators and knowledge users including lack of time, funding, and support for engagement activities (Cvitanovic et al. 2015a, b). The inaccessibility of science continues to be a key barrier to effective knowledge exchange between these two groups due to time lags between data collection and publishing or paywalls making primary literature inaccessible to decision-makers (Linklater 2003; Fazey et al. 2005; Cvitanovic et al. 2014, 2015b; Piczak et al. 2022). Finally, unidirectional transfer of information from knowledge generators to their audience limits its usefulness in the decision-making process as it fails to integrate the diverse social contexts of the end users (Cvitanovic et al. 2015b).

Collaborative research presents its own unique challenges. Working with research teams that possess more than one epistemology can be a challenge (Moon et al. 2021). Tokenistic engagement, whereby high-level participation is advertised but not practiced, can potentially compromise outcomes and provide false validity to end results (Cvitanovic et al. 2019). Administrative, financial, and personal (e.g., reputation, stress) costs of co-producing knowledge should be considered, as is discussed in detail in Oliver et al. (2019). Finally, conflicting agendas within a working group or the empowerment of certain agendas over others can spark friction among collaborators and undermine positive outcomes (Cvitanovic et al. 2015b; Chambers et al. 2022).

Unfortunately, there can be a perception from knowledge generators that collaborative research is a "less scientific" approach to data collection and therefore poses reputational risks to the undertakers (Cvitanovic et al. 2019). Knowledge generators that decide to engage in interdisciplinary research despite the potential reputational costs also risk the ability to receive sufficient funding and ability to publish their work in high-profile journals. There are fewer funding sources that support interdisciplinary research.

Table 2 Summary of challenges when implementing the actions to generate actionable knowledge in support of fisheries

Challenge	Implications/relevance	Relevant action	References
Trust	Too much or too little trust can undermine positive outcomes	1, 2	Lacey et al. 2018; Lacey et al. 2015; Cvitanovic et al. 2019
Cultural differences	Cultural differences between knowledge generators and knowledge users can cause friction	5	Cvitanovic 2015b; Cook et al. 2012; Policansky 1998; Roux et al. 2006; Briggs 2006
Lack of time, funding, and support	Institutions may be unable to provide employees with the necessary resources for engagement activities	5	Cvitanovic et al. 2015a, b
Inaccessibility of science	Paywalls and time lags continue to inhibit effective knowledge exchange	4	Fazey et al. 2005; Cvitanovic et al. 2014; Linklater 2003; Cvitanovic 2015b
Unidirectional knowledge transfer	Can limit usefulness in the decision-making process by failing to consider the diverse social contexts of end users	1, 4	Cvitanovic et al. 2015b
Different epistemologies	Different epistemologies can exist within working groups, important that collaborators understand their respective legitimacy	3, 5	Moon et al. 2021
Tokenistic engagement	Unequal participation can provide false validity research outcomes	3, 5	Cvitanovic et al. 2019
Administrative and financial costs	Costs and administrative burdens can impede successful collaborative research	5	Oliver et al. 2019
Conflicting agendas	Empowerment of certain agendas over others can spark friction among collaborators	2, 5	Cvitanovic et al. 2015b; Chambers et al. 2022
Outside perceptions	Perception that collaborative research is "less scientific," posing reputational risks	5	Cvitanovic et al. 2019
Decreased funding success	Lower funding success for interdisciplinary research	5	Bromham et al. 2016
Publication destinations	Lower likelihood of publishing interdisciplinary research in high-profile journals	5	Rafols et al. 2012

Moreover, there is lower funding success for interdisciplinary research (Bromham et al. 2016) and a lower likelihood of publishing interdisciplinary research in high-profile journals (Rafols et al. 2012) although there is some evidence that change is afoot.

Integration of principles into actionable knowledge

Although many guides and recommendations are available to knowledge generators on how to produce actionable knowledge (Gerber et al. 2020; Kelman et al. 2022; Bamzai-Dodson et al. 2023), there has been no guide created specifically for challenges associated with fisheries, and here we aimed to address that gap. With a thorough understanding of these challenges, it becomes clear that actionable knowledge in fisheries management needs its own set of recommendations: (1) embrace co-production; (2) prioritize capacity building; (3) include Indigenous and local knowledge systems; (4) seek alternative modes of knowledge exchange; (5) participate in interdisciplinary research; and (6) provide training for early career researchers that will aid in the production of actionable fisheries science. We acknowledge recommendations 1 through 4 are all important aspects of co-production which is intentional given the

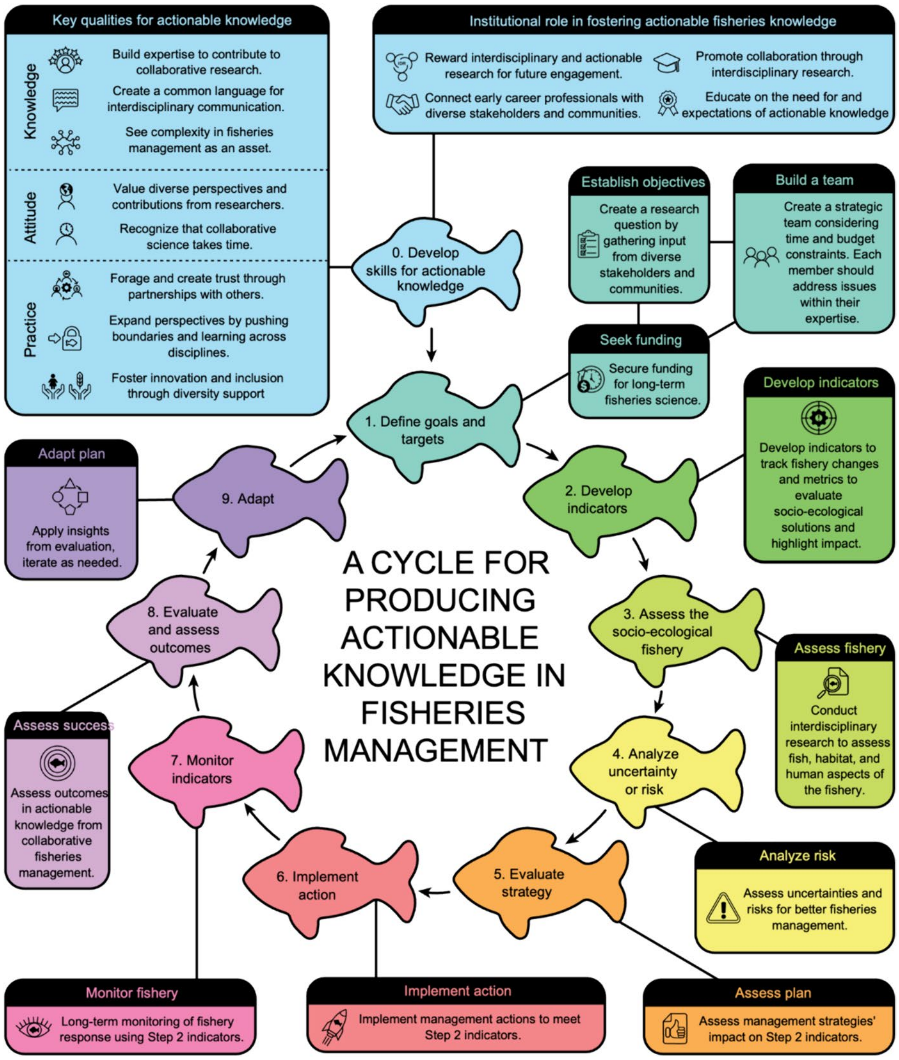

Fig. 1 A cycle for producing actionable knowledge in fisheries management modified from the National Oceanic and Atmospheric Administration (NOAA) as an ecosystem-based management process cycle (Alexander et al. 2018). Even before the cycle is initiated, it will be essential to implement the principles identified here: Step 0. Therefore, before entering the cycle, we encourage researchers to first work on their knowledge, attitude, and practices to become proficient in IDR. We also recognize the institutional responsibility to cultivate researchers capable of producing actionable knowledge (see Table 1). Once a researcher has become capable of producing actionable knowledge in fisheries, they may now utilize the provided cycle as a guide. First, we recommend defining goals and targets, which includes utilizing stakeholders to assist in establishing objectives based on a specific need, building a diverse team of researchers, and seeking long-term funding (Step 1). Then, develop indicators or metrics to evaluate solutions and highlight the impact on the fishery (Step 2). Next, researchers should conduct interdisciplinary research to assess the fish, habitat, and human dimensions of the fishery (Step 3). For effective fisheries management strategies, researchers should follow up their assessment by analyzing the risks associated with the socio-ecological aspects of the fishery (Step 4). Next, evaluation of the effectiveness of potential management strategies and their effect on the indicators developed in Step 2 should be assessed (Step 5). After previous careful consideration, the implementation of fisheries management strategies should proceed with the aim of achieving the goals established in Step 1 (Step 6). Next, researchers should continue to monitor the fishery long-term and its response to the implemented actions, utilizing the indicators established in Step 2 (Step 7). After monitoring, researchers should evaluate and assess whether the outcomes achieved success in generating actionable knowledge through collaborative efforts (Step 8). Finally, we highly encourage researchers to apply insights gained from the evaluation and assessment of outcomes and adapt their fisheries management strategies as needed, thus repeating the cycle (Step 9)

overwhelming evidence that co-production is critical for generating actionable knowledge. Applying our recommendations developed within the framework of fisheries management, we generated a cycle inspired by NOAA's revised ecosystem-based management process cycle by Alexander et al. (2018). The aim of this cycle is to aid knowledge generators in generating actionable scientific outcomes in the field of fisheries management (Fig. 1). We recognize that these recommendations all present challenges when trying to work within institutional structures, but it is necessary for knowledge generators to begin to take these steps in their work. It is our hope that knowledge generators in fisheries will implement these recommendations into their work to create knowledge that more directly informs fisheries management and conservation decisions and actions.

Positionality

This project was envisioned by several of the established researchers who are co-authors (including Cooke, Cvitanovic, Young, Nyboer, Nguyen, and Hinderer) but the project evolved under the leadership of trainees enrolled in a graduate course in applied ecology at Carleton University. Working collaboratively, the trainees further scoped the paper, conducted literature scans, and engaged in team brainstorming to shape the paper. Carleton University is located on the traditional and unceded territory of the Algonquin Nation which is where the majority of our learning, thinking, and writing took place. We acknowledge that all of the team members are based in North America aside from Cvitanovic in Australia such that our perspective is inherently biased due to our rather privileged lived experiences and context. The team includes one individual of Indigenous ancestry as well as allies although the lens used to craft this paper is largely influenced by our western science training. We call for more efforts to consider what actionable knowledge means through an Indigenous lens.

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Data availability There were no data collected or used as part of this synthesis.

Declarations

Ethics approval This study did not involve the use of live animals nor human subjects. As such, no ethical approvals were required. We certify that the paper was generated consistent with the academic integrity policies of our institutions and that no artificial intelligence tools were used.

Conflict of interest Cooke is on the editorial board of Environmental Biology of Fishes and Piczak is a guest editor for this special issue but neither was involved in handling the peer review of the paper.

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