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Co-creating knowledge with fishers: Challenges and lessons for integrating fishers' knowledge contributions into marine science in well-developed scientific advisory systems

Edited by
Nathalie A. Steins, Matthew R. Baker, Kate Brooks, Steven Mackinson and Robert Stephenson

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Co-creating knowledge with fishers: Challenges and lessons for integrating fishers' knowledge contributions into marine science in well-developed scientific advisory systems

Topic editors
Nathalie A. Steins — Wageningen University and Research, Netherlands
Matthew R. Baker — North Pacific Research Board, United States
Kate Brooks — Deakin University, Australia
Steven Mackinson — Scottish Pelagic Fishermen's Association, United Kingdom
Robert Stephenson — Fisheries and Oceans Canada (DFO), Canada

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EDITED AND REVIEWED BY
Stephen J. Newman,
Western Australian Fisheries and Marine Research Laboratories, Australia

*CORRESPONDENCE
Nathalie A. Steins
nathalie.steins@wur.nl

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Editorial: Co-creating knowledge with fishers: challenges and lessons for integrating fishers' knowledge contributions into marine science in well-developed scientific advisory systems

Nathalie A. Steins[1*], Matthew R. Baker[2], Kate Brooks[3], Steven Mackinson[4] and Robert L. Stephenson[5,6]

[1]Wageningen Marine Research, Wageningen University & Research, IJmuiden, Netherlands, [2]North Pacific Research Board, Anchorage, AK, United States, [3]KAL Analysis, Elsternwick, VIC, Australia, [4]Scottish Pelagic Fishermen's Association, Fraserburgh, United Kingdom, [5]Department of Fisheries and Oceans Canada, St. Andrews Biological Station, St. Andrews, NB, Canada, [6]Department of Biological Sciences, University of New Brunswick, Saint John, NB, Canada

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Editorial on the Research Topic
Co-creating knowledge with fishers: challenges and lessons for integrating fishers' knowledge contributions into marine science in well-developed scientific advisory systems

This Research Topic on '*Co-creating knowledge with fishers – integrating fishers' knowledge contributions into marine science*' brings together 16 papers from researchers and fishers who have been leading science-industry research collaboration (SIRC) across regions with well-developed scientific advisory systems. In such systems, marine science is heavily dependent on both fisheries-independent and fisheries-dependent data from statutory obligations (e.g., catch and effort data). Knowledge gaps could be addressed more fully by gathering, accessing and integrating fishers' observational and experiential knowledge. Whilst efforts to this end are gaining momentum, there are few documented examples where SIRC projects are shown to be effective in scientific assessments and to inform advisory processes. Challenges associated with integrating fishers' knowledge contributions relate to both the mechanics of the scientific advisory system and opinions on governing its integrity. Deliberate contributions from industry to science, for example through SIRC, are frequently met with questions around conflict of interest, trustworthiness and reliability, hindering their integration into/with science in support of management. This is problematic in a science-policy context where use of best available (scientific) information is prescribed or binding, but where budget declines and increasing demands for data and information to service ecosystem-based management effectively result in delegation of responsibilities (and costs) of sampling from government to industry. Our Research Topic explores and comments on the question of how to integrate knowledge contributions into well-developed scientific advisory systems. In particular, we detail studies that deal with three themes outlined in Table 1, and in the following sections, summarize their main findings. We conclude by interpreting what these findings mean for the future of marine science that has the use of best available information as its foundation.

Dilemmas in using fishers' knowledge contributions

Four papers in this Research Topic particularly speak to our first theme (Table 1). Steins et al. identify three issues that seem to be inhibiting systematic integration of voluntary industry contributions to science: (i) concerns about data quality, (ii) beliefs about limitations in usability of unique fishers' knowledge, and (iii) perceptions about the impact of industry contributions on the integrity of science. Following a review of published evidence, they conclude that, while these issues are real, they can be overcome. Moving forward requires a deliberate move towards alternative modes of knowledge production that includes the facilitation of transdisciplinary approaches to systematically collecting and analysing experiential knowledge as well as establishing clear procedures for data collection and verification. These findings are echoed in the Policy and Practice Review by Baker et al., presenting insights from a networking session of scientists and industry representatives at the International Council for the Exploration of the Sea (ICES). A key insight is that the form of collaboration and framework (mandated, voluntary, compensated or contracted) matters and influences data types and outputs. Necessary conditions for respectful and sustainable collaborative research include data quality controls. These include ensuring that data or final reports follow regulatory standards and are peer-reviewed before their use in science and management, as well as integrating fishers' knowledge in interpretation, validation, transparency, and accountability. Here, the paper by Wilson et al. offers valuable insights from practice. It examines stakeholder engagement in management procedure development in RFMOs for Atlantic bluefin tuna *(Thunnus thynnus)*, Greenland halibut *(Reinhardtius hippoglossoides)*, Atlantic mackerel *(Scomber scombrus)* and Pacific saury *(Cololabis saira)*. The four case studies differed in the amount and type of stakeholder engagement. The authors propose that the presence of formalised structures and processes are essential elements for inclusive and open engagement. Recommendations include the establishment of science-management dialogue groups, where there are key roles for stakeholder inputs and feedback during crucial stages of the process. Another example of how dilemmas in integrating fishers' knowledge play out in practice is demonstrated in the Policy and Practice Review on tackling bycatch of marine mammals and birds in the Bay of Biscay by Cazé et al. Here, complex socio-political dimensions that affect trust and lead to tensions amongst fishers, researchers, government and NGOs hinder the co-creation of knowledge to better understand fisher-species interactions for developing regulations that are adapted to local specificities. The authors use an examination of conflicts and collaboration as a tool to uncover dilemmas in bycatch mitigation policies and learn how best to overcome them. Conflicts, they argue, may serve in preparing the system for change. Disagreements can generate positive friction and become catalysts for social change, if negotiating processes are in place to allow for discussion among different narratives on sustainability and for collective learning.

TABLE 1 Themes of interest to Research Topic.

1. Dilemmas in using fishers' knowledge contributions and what it means for how the future of fisheries science is best conducted in the emerging frameworks for responsible research and innovation.
2. Experiences of how fishers' experiential knowledge from operating in a dynamic socio-ecological system has been incorporated into scientific research in support of fisheries or ecosystem management.
3. Studies that have overcome, or have been thwarted despite efforts to overcome perceived or real challenges associated with integrating fishers' knowledge contribution into current scientific advisory processes, including research integrity concerns.

Experiences of incorporating fishers' knowledge

Our second theme (Table 1) attracted eight papers. Two of these involved fishing industry-based Research Fleets, where fishers collect observational data to advance scientific understanding on fish stocks and ecosystem dynamics. Both papers show how Research Fleets can consistently collect copious amounts of data and significantly improve knowledge used to inform management, as well as strengthening partnerships between science, industry and management. Authors Heimann et al. present the example of the Black Sea Bass Research Fleet in New England to collect detailed catch data, using sampling protocols jointly developed by scientists, managers, and industry members, and streamlined to make data collection as efficient and minimally intrusive as possible. Data collected will be included in the black sea bass *(Centropristis striata)* fishery stock assessment. This collaboration is a success due to integration of stakeholder input throughout the project as well as the commitment to transparency of data collection and use among fishing industry, management, and scientific stakeholders. Similar experiences are reported in Olsen et al. where the Northeast US Shelf Research fleet has been trained and equipped with oceanographic sensors. Researchers have used the data to better understand oceanographic phenomena including marine heatwaves, shelf-break exchange processes, warm core rings, and salinity maximum intrusions onto the continental shelf. Fishers' experiential knowledge enhanced the research capacity of this project by offering a human dimension absent from uncrewed ocean observation tools. This SIRC also brought additional benefits to the fishers as they are able to use the results in real-time to help inform and guide their fishing operations.

Other ways of incorporating fishers' experiential knowledge in science are by using qualitative information from interviews, questionnaires and group discussions as an added layer to 'regular' scientific data collection and assessment or development of best practices in management. Five papers provide examples. The paper by Bliss et al. in SIRC on capelin *(Mallotus villosus)* in Newfoundland shows how interviews with fishers aided addressing key stock assessment knowledge gaps on putative deep-water spawning sites as a first step in determining the contribution of deep-water spawning to capelin recruitment. Boat-based surveys that followed resulted in knowledge on seven previously undocumented deep-water spawning sites. Researchers now use these results to build a time series for monitoring capelin spawning. As applies to other cases reported in this Research Topic, this capelin SIRC strengthened fisher-science advisor relationships. Another example where interviews played a key role is reported by Damiano et al. The paper describes the cases of Management Strategy Evaluations (MSE) of Atlantic cobia *(Rachycentron canadum)* and black seabass *(Centropristis striata)* fisheries in the Southeast US. In both cases it was not possible to conduct a "full" MSE with direct participation of fishers in the MSE process, a situation that often occurs in MSE processes and usually results in a 'desk-based' MSE. The authors explored whether semi-structured interviews with commercial and recreational fishers could elicit similar kinds of information that fishers provide during direct participation in MSE. They demonstrate this is indeed the case. Integrating information from semi-structured interviews with MSE offers a cost-effective alternative intermediate approach to fisher participation in MSE when direct participation is not possible. Authors Kelly et al. report on the on-going development of the decision-support tool FishGuider in Norway. FishGuider supports knowledge creation for research and advisory processes and also provides information to fishers to assist everyday fishing operations. Researchers used questionnaires to find out about fishers' needs in terms of information they would like to see in the tool to help inform strategic and tactical decision-making. The development process revealed important tradeoffs between comprehensiveness of the information included in the tool and user-friendliness. Also, continuous dialogue and soliciting of feedback from fishers is central to qualifying the true importance of information for decision making.

Examples of facilitating and integrating fishers' experiential knowledge using group discussions are provided in three papers. Authors Mercer et al. detail the contribution of a two-day "Northern Shortfin Squid Population Ecology and Fishery Summit" hosted by the fishing industry, towards improving stock assessment and management. Research data sets and knowledge from fishers and processors were brought together to better describe the fishery dynamics, distribution, life history, and oceanographic drivers of *Illex illecebrosus*. Post-summit collaborative work focused on jointly developing custom standardized catch per unit of effort indices to provide indicators of population trends, now used in the stock assessment. The authors suggest that large-group summits are effective for developing initial relationships and trust between science and industry collaborators and identifying research priorities, while semi-structured conversations with individual industry members facilitate understanding of specific factors that influence fishery dynamics and identification of potential covariates for catch rate standardizations. Such conversations are also effective for reviewing research results and identifying future work areas. The paper by Murua et al. reports similar benefits of knowledge exchange workshops and co-developed research activities with fishers from the principal tropical tuna purse seine fleets of 23 countries. Fishers' experiential knowledge was sought to reduce ecological impacts associated with the use of fish aggregating devices (FADs), by empowering and equipping skippers and crew with the means to address bycatch in their fisheries. The programme had a strong communication focus and resulted in innovative, co-constructed solutions, better stewardship and increased trust of scientists. It has stimulated unprecedented large-scale science-industry research projects across oceans, such as multi-fleet biodegradable FAD trials, widespread use of non-entangling FADs, and adoption of best practices for the safe handling and release of vulnerable bycatch. The Policy Brief by Baker et al. outlines opportunities and implications for improving marine science and fisheries management through SIRC, leveraging insights of more than a hundred researchers, managers, industry representatives and fishers participating in the Lowell Wakefield Fisheries Symposium on cooperative research and strategies for integrating industry perspectives and insights in fisheries science. To be effective, these types of collaborations require understanding the strengths, perspectives, interests, structures, and sensitivities of participating groups, as well as identifying methodologies and study designs necessary to ensure robust scientific results. Key insights were that initial success is often achieved through finding common ground and staying simple, while long-term success is often achieved by maintaining momentum, carefully examining processes, and repeating what works. Continued collaboration means constantly refreshing and revisiting aims and objectives, and constantly refining the approach and addressing challenges and limitations to collaboration. Best practices for SIRC include collaborative, robust, relevant, cost-effective and timely initiatives that involve dedicated and engaged partners.

Overcoming challenges in using fishers' knowledge

Our third theme (Table 1) is central to four papers. Two papers are about dealing with challenges in setting up research fleets for improving stock assessment quality. Jones et al. discuss the lessons learned from the Northeast US Study Fleet programme, where groundfish fishers collect high-resolution catch, effort, and environmental data to address shortfalls in fisheries-dependent data collection. Like other authors in this Research Topic, they experienced that interactions with industry emerging from the collection and application of these data contribute to increasing mutual understanding and trust. Sustaining the interest on both sides of the collaboration needed for consistent time-series is, however, a challenge. This is also true for addressing equity issues and potential bias associated with working with a select group of fishers. Also there are challenges in dealing with data for science and data for regulatory purposes. The authors stress the importance of ongoing communication with captains and involving boundary spanners. They recommend developing detailed roadmaps for each data collection to keep participants engaged as collaborators, targeting specific fisheries to keep resources from being stretched too thin, and partnering with data end-users early in the process. The paper by Mackinson et al. reports on the processes and challenges associated with the development of the Scottish Pelagic Industry-Science Data Collection Programme into a routine and consistent voluntary sampling regime of sufficient quality, which is now the main source of biological data on pelagic fish catches in Scotland. One challenge identified was the perceived reluctance from the national administration, driven by concerns over data quality, data continuity and reputational concerns. These were overcome by setting up a collaborative process from the beginning and starting with a pilot process that enabled a step-wise approach, followed by the development of a Memorandum of Understanding to ensure data collection flows from the industry. Transparency, documentation, and communication were key in dealing with the issue of reputational concerns. A second challenge was balancing the pace of progress with expectation: too slow for the industry, too fast for the national administration. Monthly meetings and setting realistic time scales for individual tasks were key to managing this. This paper also identifies core design principles of SIRC that are also transferable to other sectors. These include the importance of quality assurance and a good communication structure.

The two other papers on overcoming challenges are examples of where management or political related concerns, legacy and trust issues entangle with scientific co-creation processes. The paper by Schram et al. is about concerns raised by small-scale fishers and NGOs over the possible adverse effects on marine organisms caused by the electrical stimulation of flatfish pulse trawling in the North Sea. These fishers were involved in the design and implementation of a fishing experiment to investigate their concerns. This, as well as engaging them in discussion of the results was important in increasing the saliency and credibility of the results. It also revealed the intricate relation between perceived scientific knowledge gaps and political or management related concerns. Authors Calderwood et al. take a narrative approach to collaboration with Irish fishers to co-create knowledge. Drawing on case studies, they reflect how data from industry can best be used and integrated into scientific processes. Key barriers include misunderstandings regarding the roles of scientists and the scientific process, a lack of transparency, a lack of trust, legacy issues from previous management approaches and research with poor stakeholder engagement, and impacts of Brexit. Remaining aware of these issues and the pressures they have created is critical to effectively co-create knowledge and common understanding. Equally important are building trust and active communication. The authors emphasize that efforts to build social capital for co-managing, co-creating, and collaborating with fishers includes an inherent request for their time, whilst research often does not even cover the costs of participating. This issue should be addressed. They also acknowledge that there is no one-size-fits- all solution for building social capital with fishers. Time is needed to understand individual fisheries and fishers, their interest in contributing their knowledge, and time available to do so.

Conclusion

Our Research Topic brought together a wealth of information on dilemmas, experiences, challenges and opportunities associated with integrating fishers' knowledge contributions into marine science. We deliberately focused on regions with well-developed scientific advisory systems as this is where issues about stakeholder engagement and knowledge co-creation are matters of debate rather than necessity. Responsible research and innovation frameworks demand use of 'best available information', and in relation to fisheries, some information can only come from fishers.

The collection of papers in this Research Topic substantiates that use of 'best available information' is confronted with legitimate concerns regarding perceived risks to the credibility of scientific advice, particularly when science evidence is applied to management. Such concerns can be overcome by developing transparent quality assurance systems in a collective effort between scientists, fishing industry, managers and other relevant stakeholders. Also, objective evaluation of the performance of the information for its intended purpose is required. This calls for adaptations to current fisheries governance frameworks and a new culture of cooperation.

A common thread in all papers is the important contribution SIRC provides to establishing a relationship of mutual trust, which is essential to establishing salient, credible and legitimate science for advice.

From the collective experience documented, we extract ten commonly applicable guiding principles for integrating contributions from SIRC into conventional marine sciences: (1) identify where there is both opportunity and utility in information that fulfils a need expressed by industry or science; (2) take fishers' concerns seriously even if they do not seem at first to make 'scientific sense'; (3) always be open and honest with others and address 'elephants in the room', including equity issues; (4) be aware that fishers' participation is linked to their sense of ownership; (5) recognize that fishers' time for participation is (usually) not paid for, unlike that of scientists, and discuss ways of acknowledging or rewarding them even if it cannot be financially; (6) create effective and regular feedback mechanisms between scientists and the skippers and crew involved; (7) involve end-users of the data from the outset; (8) in case of data collection by fishers, (jointly) establish transparent quality assurance processes; (9) involve social scientists when using qualitative collaborative research methods; and (10) constructively engage, challenge and support necessary developments in national and international institutional processes that determine whether data from industry programmes or other fishers' knowledge contributions have the chance to be applied in stock assessments or other science for advice.

Author contributions

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Learning From the Study Fleet: Maintenance of a Large-Scale Reference Fleet for Northeast U.S. Fisheries

Andrew W. Jones[1], Katie A. Burchard[1], Anna M. Mercer[1], John J. Hoey[1], Michael D. Morin[1], Giovanni L. Gianesin[2], Jacob A. Wilson[1], Calvin R. Alexander[1], Brooke A. Lowman[1], Debra G. Duarte[2], David Goethel[3], James Ford[4], James Ruhle[5], Rodman Sykes[6] and Troy Sawyer[7]*

[1] Northeast Fisheries Science Center, National Marine Fisheries Service, Narragansett, RI, United States, [2] Northeast Fisheries Science Center, National Marine Fisheries Service, Woods Hole, MA, United States, [3] Fishing Vessel Ellen Diane, Hampton, NH, United States, [4] Fishing Vessel Lisa Ann III, Newburyport, MA, United States, [5] Fishing Vessel Darana R, Wanchese NC, United States, [6] Fishing Vessel Virginia Marise, Narragansett, RI, United States, [7] Fishing Vessel Debbie Sue, Narragansett, RI, United States

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Edited by:
Nathalie A. Steins,
Wageningen Marine Research IJmuiden, Netherlands

Reviewed by:
Teresa Johnson,
University of Maine, United States
Floor Quirijns,
Wageningen Marine Research IJmuiden, Netherlands

****Correspondence:***
Andrew W. Jones
andrew.jones@noaa.gov

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Logbook data from commercial fisheries are a vital component in the machinery of management, including tracking the volume of catches and allocating catch spatially. At the same time, logbooks can provide a unique window into the ecological and sociological conditions in marine fisheries, where fishermen interact with marine species and environments frequently and broadly. Traditional logbooks, however, often are not sufficiently standardized (when personal logs), or lack the detail (when regulatory documents) required to adequately understand fisheries ecosystems. The Study Fleet program, operated by the Northeast Fisheries Science Center's Cooperative Research Branch, was developed to address these shortfalls by engaging members of the fishing industry in collecting high-resolution catch, effort, and environmental data using electronic logbooks. Since its inception, the Study Fleet has expanded from a small project focused on collecting detailed catch information from the New England multispecies groundfish fishery to a program with a wider scope encompassing a variety of fisheries, gears, and environmental parameters from North Carolina to Maine U.S. Over the years, a number of lessons have been learned about recruiting and supporting industry partners, managing the data, evolving technical specifications, and the challenges associated with analyzing and applying self-reported fisheries data. Here we describe the current state of the program and provide summaries of the Study Fleet program operations and outcomes from 2007-2020, with an eye towards successes, challenges, and applicability of the approach in other regions. We suggest other reference fleet programs, as well as other developing fishery dependent data collections (e.g., electronic monitoring programs), develop detailed roadmaps for each data collection to keep participants engaged as collaborators, target specific fisheries to keep resources from being stretched too thin, and partner with data users early. Additionally, we suggest programs invest in the long-term participation of individual fishermen, carefully weigh the pros and cons of involvement in regulatory reporting, and plan data products and applications well in advance to ensure that the sampling scheme and granularity of the data meet the needs of stock assessment, ecosystem, and oceanographic scientists.

Keywords: logbook, CPUE, fishery dependent data, Northeast United States, self-reported data, cooperative research, reference fleet

INTRODUCTION

Around the world, fishermen use logbooks to record information about where, when, and how they fish and what they catch. Logbooks can take many forms, from paper notebooks in the wheelhouse to advanced electronic systems. In many fisheries, fishermen are required to submit trip summaries of logbooks to fishery managers, detailing what species and quantities were caught. These data are used to track catch quotas and estimate fishery removals, among other applications. Logbooks have been identified as a valuable source of contemporary and historical information (Fox and Starr, 1996; Pederson and Hall-Arber, 1999; Johnson, 2007; Hoare et al., 2011; Kraan et al., 2013; Mion et al., 2015; DeCelles et al., 2017; Steins et al., 2020). For example, in the southeast United States (U.S.) logbooks have been used to better understand changing size at maturity in red snapper (*Lutjanus campechanus*) and other southeastern species (Bonney et al., 2021). On the West Coast of the U.S., recent work paired long-term logbook data with sophisticated Bayesian analyses to explore potential drivers of change in community composition (Essington et al., 2021). In many cases, however, the utility of logbook data for fisheries science is limited by the coarse spatial and temporal resolution of the typical trip summary reports (summed effort and catch) by reporting grids.

Fishery dependent data (logbooks, seafood dealers' records, and data from regional observer programs) provide a unique window into marine systems. Collections of fishermen's information span regions and seasons not often sampled by scientific surveys, are a type of information inherently trusted by stakeholders, and provide observations of biological information at a scale that dwarfs regional scientific surveys (Cadrin et al., 2020a; Steins et al., 2020). Because much of this information is required to guide management, and does not require additional costs, leveraging these data sets for science can be an economical form of data collection (Johnson and van Densen, 2007; Pennington and Helle, 2011; Bell et al., 2017). Conversely, because the samples lack a statistical design, data track the behavior of fishermen as they seek to maximize their profits and adhere to management requirements, making trends more challenging to interpret (Maunder and Punt, 2004). Despite this, there is a growing interest in the applications of fisheries dependent data, especially data that is self-reported by fishermen or collected with advanced technology such as electronic monitoring (van Helmond et al., 2020; Bell et al., 2021; ICES, 2021). This is in part because of expanding monitoring requirements and the rapid advancement of the technology used to record catches. Finally, the recent development of sophisticated statistical methods that avoid the common pitfalls of earlier methods (Forrestal et al., 2019; Clegg et al., 2021), facilitates the potential application of the data sets.

Logbooks are often recorded by individual fishermen or small businesses but can also be a component of reference fleet programs (Rountree et al., 2004; Nedreaas et al., 2006; Roman et al., 2011; Mercer et al., 2018; Clegg et al., 2021). These programs provide more structured and often higher resolution data collection and more robust quality assurance and quality control (QA/QC), with the intention of using the logbook data as a scientific product (Bjørkan, 2011; Pennington and Helle, 2011; Bastille, 2019). Reference fleets can also provide the methodological structure needed for fishermen to effectively contribute scientific data, such as oceanographic conditions (Manning and Pelletier, 2009; Gawarkiewicz et al., 2019; Gawarkiewicz and Mercer, 2019; Van Vranken et al., 2020).

In addition to the direct scientific value of data collected by stakeholders, there is growing appreciation for the broader value of engaging stakeholders and industry members in research endeavors (Neis et al., 1999; Johnson and van Densen, 2007, Feeney et al., 2010, Stephenson et al., 2016; Thompson et al., 2019). There are myriad indirect benefits of this type of science-industry research collaboration (*reviewed in* Steins et al., 2020), including improved communication of results, the sharing of insights only available to those actively involved in the fishery, increased capacity of stakeholders to actively participate in fisheries science, and perhaps most importantly trust in the scientific process. Despite the clear direct and indirect value of these programs, collaborations of this nature are difficult to maintain, and can fall short of their initial goals. Regardless, it is important to report the progress and findings of these programs, highlighting the lessons learned from specific collaborative efforts.

One of the largest and longest-running scientific logbook programs in the U.S. is the Study Fleet (Palmer et al., 2007; Bell et al., 2017), a program developed and operated by the Northeast Fisheries Science Center's (NEFSC) Cooperative Research Branch (hereafter CRB) that engages fishermen in collecting high-resolution catch, effort, and environmental data. This program traces its origins to recommendations by members of the fishing community during regional strategic planning workshops in 1999 and 2000 (Hartley and Robertson, 2006). The primary objective of the Study Fleet at its time of initiation was to recruit a fleet of commercial New England groundfish vessels to provide high-resolution (temporal and spatial) self-reported data during routine fishing activities. Additionally, the region's fishing community articulated a need for enhanced logbook reporting to complement and leverage haul-based data collected by independent fishery observers (Palmer et al., 2016; Bell et al., 2017). The ultimate goal of collecting this high-resolution data was and still is to improve the accuracy and precision of stock and ecosystem assessments to inform fisheries management. The Study Fleet also seeks to enhance opportunities to incorporate fishermen's local ecological knowledge into assessments through collaboration with NEFSC scientists, thereby enhancing trust and support for scientific management advice (**Figure 1**).

A secondary objective of the Study Fleet has been to evaluate hardware and software options for electronic logbook (hereafter ELB) reporting technology that would improve the accuracy and timeliness of mandatory Vessel Trip Reports (VTR). The ELB allows fishermen to automate data entry to make it easier to collect data during their already labor-intensive fishing trips. Specifically, the ELB enables fishermen to easily collect data on gear characteristics, fishing location, time, and catch by species and disposition (kept or discarded) for each fishing effort. This increases the spatial and temporal resolution of self-reported fishery-dependent data dramatically, from estimates of fishing effort and catch summed across multiple hauls and days within large statistical areas (10s of km^2) to haul records with precise time and location parameters collected electronically.

Here we outline the current Study Fleet program operations, summarize the scope of data collected to date, and highlight high-level successes and challenges. We detail the current state of the data set generated by this program with an eye towards making it available for regional stock assessments or qualitative comparisons to other regions. Building on these data summaries we develop specific recommendations for other study or reference fleet programs.

PROGRAM DESCRIPTION

Vessels are selected to participate in the Study Fleet through a structured competitive bid process. Selection considers multiple factors including: vessel size, fishing location, species targeted, frequency of fishing, and for vessels that have participated previously, the quality of prior data submissions. Contracts run for a period of five years, with approximately five to ten vessel slots being selected at a time, and a number of participants continuing with the program through multiple cycles. Participating captains are provided with a small stipend, as the program requires substantial time and attention to record the additional data. The monetary compensation, however, is one of many motivators for captains to participate (e.g. desire to contribute to fisheries science). Study Fleet target species have shifted over time (**Appendix A**), with the composition of the participating vessels reflecting priorities related to stock assessments, industry interests, and management actions. Additionally, the total number of contracts has been limited by the program budget, which has varied over the course of the program. Participants in the program have provided written consent to have data utilized for applicable scientific purposes. Data collection dovetails with regional regulatory reporting requirements and the use of these data complies with the ethical standards of the National Marine Fisheries Service (NMFS).

Data collection by Study Fleet vessels at sea mirror information collected by the northeast region's observer program (NEFSC, 2019). Specifically, trip information (e.g., information about the date a trip sailed), haul information (e.g., the latitude and longitude where a given fishing effort occurred), as well as haul-specific (haul-level) catch and discard information are reported. A detailed track

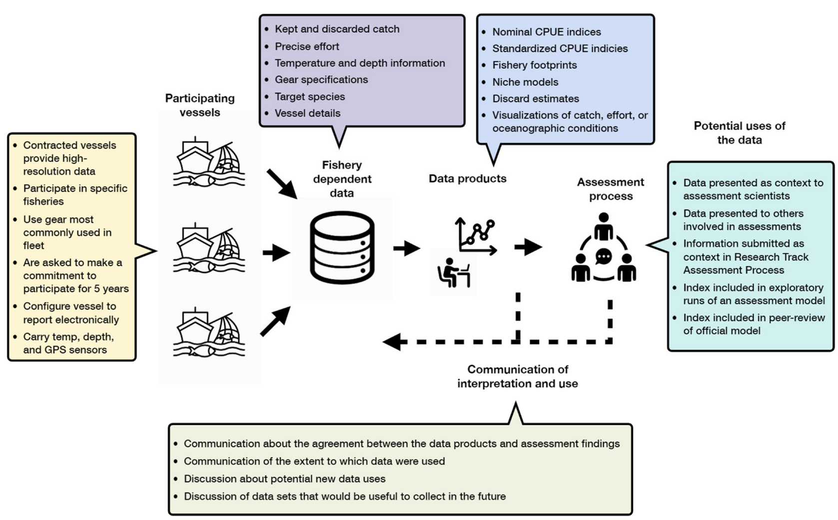

FIGURE 1 | A conceptual diagram of the data flow and purpose of the Study Fleet program. Starting with the reporting vessels and fishermen (yellow) information flows to the Science Center (purple and blue) where it is curated and developed into analytical products for science and management. These products are presented as part of the assessment process (darker green) and then communicated back to participating captains (light green). This cycle is simplified in many ways as iterative loops are likely to improve the products and assessments.

of GPS fishing locations can be recorded by the logbook software and differentiates the Study Fleet haul duration and location information from that collected by the observer program. Catch and discard weights can be generated in a variety of ways. For kept catch, basket or tote counts are often extrapolated using a known conversion factor. Captains typically use visual estimates and extrapolations for discarded catch, as more intensive methods (e.g., basket counts) frequently used by observers and field staff can be considered possession when observers are not onboard and could potentially lead to regulatory fines. Kept catch estimates by captains and observers at the end of the trip can be verified against dealer weight receipts, and discarded catch estimates can be compared to estimates by observers on co-sampled trips.

In addition to collecting detailed catch and effort information, Study Fleet vessels also record bottom water temperatures using temperature sensors attached to their fishing gear. Bottom water temperatures are collected during every gear haul and are matched with the catch and effort records. Probes from different manufacturers have been deployed over the history of the program including instruments from Aquatec (https://www.aquatecgroup.com), Star-Oddi (https://www.star-oddi.com), and Lowell Instruments (https://lowellinstruments.com). Advances in the probes and integration with the laptop eventually allowed Captains to see recorded temperatures during a tow within minutes of hauling that net.

Data are submitted at the end of the trip as an electronic file which is loaded into databases at the NEFSC. The high-resolution haul data are then summarized and formatted to the lower-resolution required by management and submitted to the regional management offices. Ultimately, kept catch that is sold to dealers is weighed and reported, and this components of the catch can be verified, as discrepancies between dealer and vessel records can prompt an inquiry into the nature of the difference. Information on discards are not regularly compared, but studies which have paired the discard estimates from captains to observer records have found reasonable similarities between their magnitudes (Bell et al., 2017). Specifically, the majority (>65%) of comparisons of the trend and scale of discard estimates were similar between Study Fleet and the observer program. Additionally, significant differences that were discovered where related to the large number of samples rather than substantial effects.

The sampling scheme inherent to the Study Fleet is somewhat distinct from other regional fishery dependent data sets (i.e., regulatory trip reporting and regional observer programs). Specifically, the vessels participating in the program report continuously, documenting all of their fishing activity with minor exceptions (e.g., when participating in other research). This produces a time series across seasons and years of trip, effort, and catch information that is similar to regulatory vessel trips reports where all landings must be reported by permitted vessels, but at a higher spatial resolution. In practice this means that captains record the catch, effort (e.g., active fishing time), and location of each fishing event or haul rather than aggregating the catch for an entire trip, providing a single location at the center of the region sampled, and a mean estimate of the active fishing time across hauls. While the resolution of sampling mirrors the observer program, the sampling scheme is distinct. The observer program attempts to select a random stratified sample by fishery-area and month (Palmer et al., 2016), and the Study Fleet data represents more of a longitudinal sample of the participating vessels. Because of this sampling scheme, the Study Fleet may not be as unbiased a representation of a given fishery (e.g., geographically or temporally), and for applications of the data, methods such as random subsampling of the Study Fleet time series (Clegg et al., 2021), provide a means to ensure the representativeness of the data set. Further, combining and comparing the time series of regional fishery dependent data program programs (observer, Study Fleet, and regulatory VTR reporting) is likely the best way to evaluate data quality and representativeness.

PROGRAM DATA SUMMARIES

Since 2007, the number of hauls and trips reported by the Study Fleet program have increased dramatically (**Table 1**). In recent years, Study Fleet structure and funding has stabilized, and as a result the Study Fleet has collected high-resolution catch and effort data from around 3,500 trips per year (**Figure 2**). Limited funding and eligible and interested fishing vessels are the major constraints on the program's size and the volume of data generated. Specifically, the programmatic need for high-resolution accurate reporting by captains has limited the pool of those interested in participating. As the number of participating vessels increased, the number of records reported using the ELB system at a coarser resolution (one or a couple records per trip) increased. This pattern reflected an interest from captains in the use of electronic reporting, but less interest in reporting at a level higher than that required by managers. In the past five years the number of trips with trip records has greatly increased to approximately 4,000 per year (**Figure 2**). This trip-level data, however, is less useful for understanding fishery and ecosystem dynamics, as the spatial and temporal resolution is analytically limiting.

The number of fishing vessels participating in the Study Fleet has increased over time, however, only a limited number of vessels have a continuous record of data collection (**Table 1** and **Appendix B**). The general trend in Study Fleet participation is of rapid increase, however the voluntary records do not begin until 2011. These vessels, trips, and hauls are currently spread across a range of fisheries in the northeast (**Figure 3**) with the largest number of hauls targeting groundfish, summer flounder (*Paralichthys dentatus*), scup (*Stenotomus chrysops*), longfin squid (*Doryteuthis pealii*), shortfin squid (*Illex illecebrosus*), and sea scallops (*Placopecten magellanicus*). The vast majority of these data come from vessels fishing mobile gear, with 'fish' otter trawl gear being the most common (**Table 2**). Generally, otter trawl gear has been the dominant category of gear used by vessels in the program. Other gears have become more common in recent years suggesting that the ELB is capable of supporting these fleets.

TABLE 1 | Metrics of study fleet participation.

Metrics of Study Fleet Participation From 2007 - 2020														
SOURCE	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Number of Vessels														
STFLT	12	23	23	28	27	33	29	38	37	42	43	42	38	38
NCRP	0	0	0	0	1	1	16	49	30	33	28	35	40	36
Number of Trips														
STFLT	343	613	1261	1413	1650	1638	2041	1903	1887	1989	2481	2238	2169	2139
NCRP	0	0	0	0	3	1	99	981	1072	1299	990	1467	1480	1476
Number of Hauls														
STFLT	1955	5429	8989	9511	10048	9432	12355	11492	13300	16694	18231	15415	14831	13083
NCRP	0	0	0	0	52	33	1024	10242	8663	7001	4125	5683	6348	6046

Number of vessels, trips, and hauls by year and reporting type (contracted study Fleet 'STFLT' or other voluntary haul-level reporting Northeast Cooperative Research Program 'NCRP'). Vessels reporting at the haul-level that are not part of the contracted Study Fleet but were participating in another NEFSC program that mandated haul-level reporting (such as pilot electronic monitoring programs) are grouped under the NCRP category.

Comparing the number of Study Fleet records to the other major fishery dependent sampling programs from the region (Northeast Fisheries Observer Program and At-Sea-Monitoring Program), we can see that the number of trips and hauls is similar in size to the number recorded from trawl gear vessels (**Figure 4**). The increased coverage in the observer data set reflects the shift to catch share management and the associated enhanced reporting requirements around 2010. As is evident in the time series (**Figure 4**), the Study Fleet effectively provided fishery dependent data during the COVID-19 pandemic, while observers were restricted from deploying. Thus, when answering research questions using fishery dependent data, combining these two distinct data sets will provide the most information.

The spatial coverage for Study Fleet and observer trawl haul data are shown in **Figure 5**. The two data sets overlap primarily in the Southern New England region. The Study Fleet data set has more representation in the Mid-Atlantic region while the observer data set has a center of mass in the Gulf of Maine and Georges Bank. Again, subtle spatial differences in sampling between these program suggest that combining information may be beneficial for specific projects and questions. Additionally, **Figure 5** shows the potential differences in spatial patterns that might be produced if different metrics of fishing activity are used (e.g., number of trips, number of hauls, or the pounds of catch). These generally suggest similar areas are represented regardless of the level at which the data is aggregated.

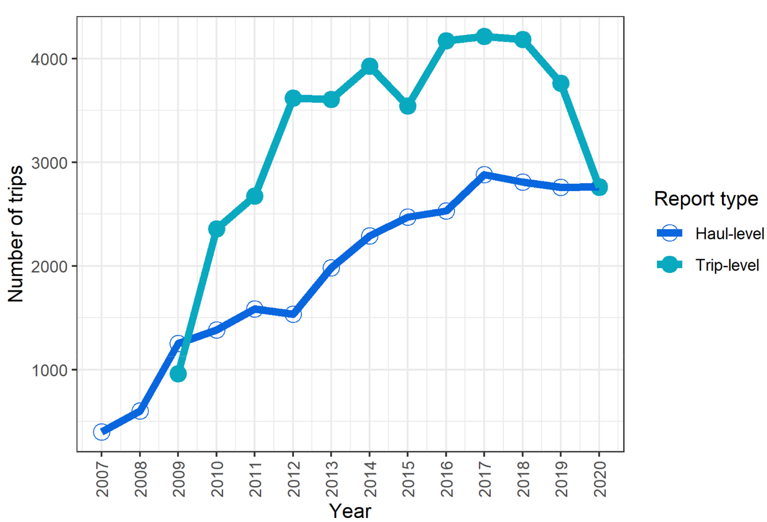

FIGURE 2 | The number of trips that were collected by the ELB system. Haul-by-haul reporting (high-resolution) trips are shown in dark blue (open circles), and trip reporting (lower resolution) in light blue (closed circles).

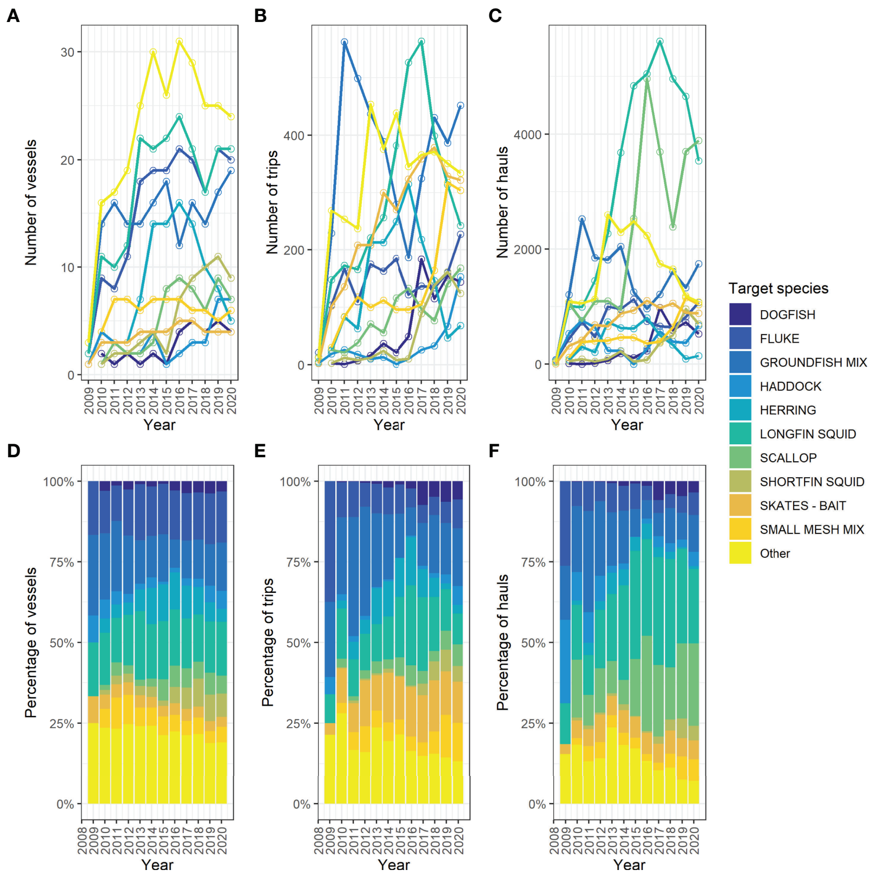

FIGURE 3 | The breakdown of Study Fleet number of vessels, trips, and hauls by target species through time. The trends through time for each level of the data are shown in panels **(A–C)**. The annual proportions of vessels, trips, and hauls are shown in panels **(D–F)**. The category 'Other' includes twenty additional target species designations each of which comprised less than three percent of the total trips records.

The landings reported by the Study Fleet program as a proportion of total landings have increased for a number of regionally important stocks (**Figure 6**). This is especially true for the two squid species (longfin and shortfin) which have had a large and increasing number of participating vessels. However, as in the case of Atlantic cod (*Gadus morhua*) this is partially driven by a decreasing trend in total catch. Metrics of coverage which are a key element used to assess the representativeness of the program show similar patterns in the number of vessels included and trips from which data are reported (**Appendix C**). These levels of participation are crucial to providing assurance that the effort and catch information is representative of the larger fishery that is being sampled (see **Primary Lessons Learned**).

The oceanographic data set associated with the catch and effort data reported by Study Fleet participants (**Figure 7**) follows a similar pattern to those we see in the programs trip and haul summaries (i.e., increasing rapidly in the early 2010s). These oceanographic records are collected coincidentally with catch and effort data from a number of fisheries, and the composition of target species associated with these records has fluctuated through time. Some Study Fleet vessels also participate in other industry-based oceanographic monitoring programs, such as the

TABLE 2 | Study fleet participation by gear type.

Study Fleet Participation by Gear Type From 2007 - 2020														
Gear type	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Otter trawl fish	311	460	1056	1184	1439	1371	1649	2055	1930	2097	2275	2348	2492	2616
Other	31	154	214	264	207	272	469	792	995	1165	1226	1361	1177	1046

The number of trips by program participants summarized by gear type and year. Other gear types include demersal longline, gillnet, scallop dredge, pair trawl, mid-water trawl, scallop otter trawl, and hand line which all occur at relatively low frequencies (less than five percent).

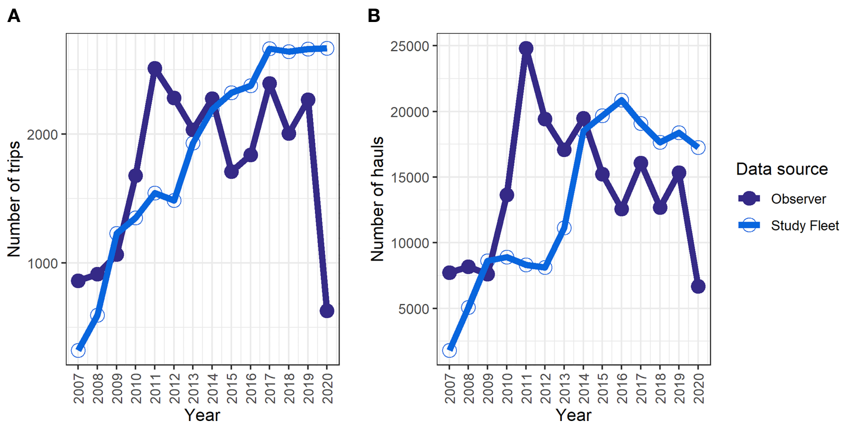

FIGURE 4 | Trends in annual trips **(A)** and hauls **(B)** for the Study Fleet program are shown in blue (open circles). For comparison, the annual number of trips and hauls from trawl vessels is shown in purple (closed circles) from another large monitoring program in the region, the fishery observer programs. The goals and sampling schemes of these programs are quite different, but together they represent a large amount of fishery dependent data from the region. Of note is the dip in total trips in the observer program in 2020, a result of a pause in operations for the COVID-19 pandemic.

environmental monitors on lobster traps and large trawlers program (eMOLT, Manning and Pelletier, 2009). Coordinating among research programs is essential to effective processing and application of data.

Examples of Data Applications

Indices of Abundance

Data collected by the Study Fleet program has been used to improve our understanding self-reported catch and effort information (e.g., Palmer et al., 2009). More recently these have been turned into catch per unit effort (CPUE) indices for summer flounder (Gervelis, 2018), scup (NEFSC, 2015), shortfin squid (Jones et al., 2020; Lowman et al., 2022), as well as the Gulf of Maine haddock stock (Cadrin et al., 2020b). These CPUE indices derived from Study Fleet data inform the stock assessments in a qualitative manner and provide valuable perspective on the survey-based indices of abundance (Blackburn, 2017; NEFSC, 2022a; NEFSC, 2022b). Through time, CPUE analyses have become more sophisticated, transforming from purely nominal indices to more technical indices that are standardized using generalized linear or generalized additive models (*sensu* Maunder and Punt, 2004). In the future, the goal is to develop Study Fleet CPUE indices into products that are regularly included in regional stock assessments. Within the range of assessments from the region, these CPUEs could serve a variety of roles from providing context, to being included in model runs and potentially even in final models (there are a number of ways these indices can potentially be included as valuable additions to the assessment process; see **Figure 1**).

Fishery Footprints

Fishery footprints describe the spatial distribution of catch and effort (e.g., Amoroso et al., 2018). The fine-scale location data collected by the Study Fleet (vessel position in latitude and longitude collected once per minute) have been used in a number of contexts to develop estimates of fishery footprints. Recently a fishery footprint that included specific comparisons to the planned footprints of offshore wind projects was initiated. This work is likely to expand in scope and parallel efforts in other regions (e.g., Methratta et al., 2020; Schupp et al., 2021) to understand operational conflicts between marine renewable energy developments and fishing operations. Data sets similar to the Study Fleet data collected from onboard EM camera systems have recently been used to understand the impact of spatial management measures on fishing operations (Bell et al., 2021), and there is a high likelihood that Study Fleet data will be used for similar means in the near future.

Habitat Modeling

Combining catch information with other sources of data (geographic and oceanographic data) has facilitated the development of species distribution models. Previously this work was conducted to identify areas where river herring (*Alosa* spp.) bycatch might be lowest for vessels targeting Atlantic herring *(Clupea harengus*, Turner et al., 2017). More recently, Lowman et al. (2021) constructed a species distribution model for northern shortfin squid (*Illex illecebrosus*) to better understand the distribution of this squid and the proportion of its distribution that is overlapped by the fishery. Additionally, catch and effort information from Study Fleet vessels has been used to describe species distributions in space and time, and potentially association with temperature. Species distribution models as well as other explorations can be used to both improve our understanding of their availability to the region's standardized surveys (e.g., Manderson et al., 2015), as well as the potential impacts of climate change (e.g., McHenry et al., 2019).

Discard Estimation

Bell et al. (2017) compared the use of self-reported kept and discarded catch data against observer data to derive area-specific

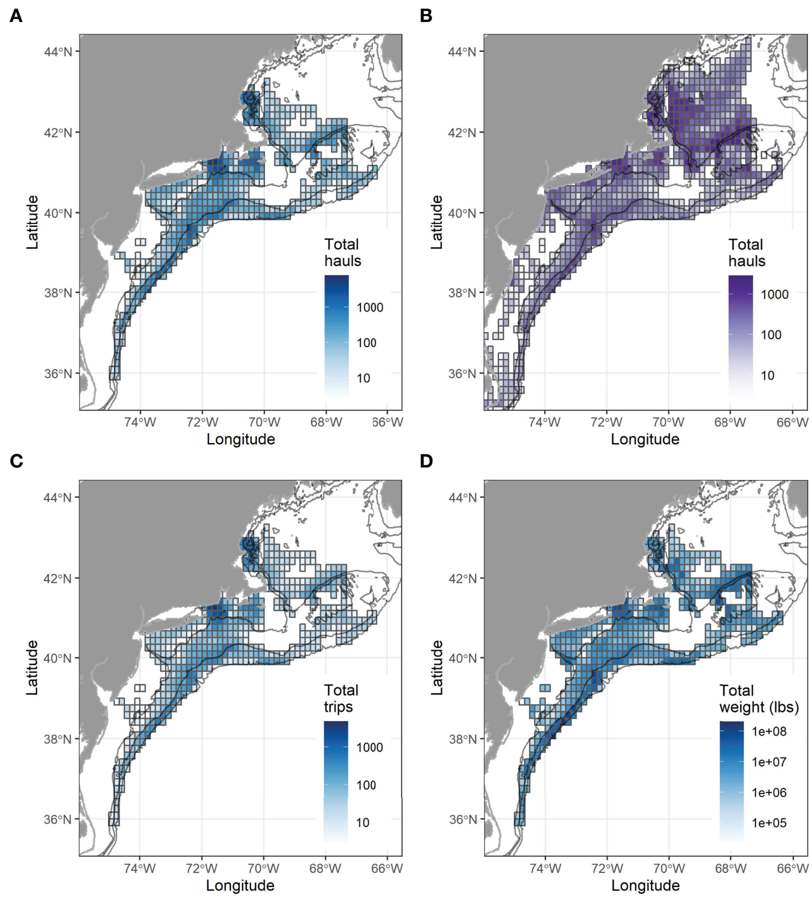

FIGURE 5 | Maps showing the spatial distribution of high-resolution fishery dependent trawl records for 2007 - 2020 gridded into 5-minute squares. In panel **(A)**, the total number of Study Fleet hauls are shown. For comparison the distribution of observer records for otter trawl gear are shown in panels **(B, C)** shows the total number of trips by Study Fleet vessels. Panel **(D)** shows the total catch by Study Fleet vessels (lbs). In all panels cells with fewer than three unique permits (records from fewer than three vessels) have been omitted. In panels **(A–D)** 258 (55%) cells were omitted and in panel **(B)** 182 were omitted (19%).

discard estimates similar to the Standard Bycatch Reporting Methodology (SBRM). In the northeast U.S., the SBRM (Wigley et al., 2007) is a legally required, peer reviewed, analytical approach for estimating discards to be used in stock assessments and management actions including setting quotas and monitoring compliance. This comparison suggested that self-reported logbook data could be a cost effective means to estimate the bycatch of specific stocks that were examined (of the twenty comparisons thirteen were similar in size and trends were similar through time, four had only similar trends through time and three were not similar). More recently, discard data has been utilized to help develop monitoring standards for a logbook audit program for the region's pre-implementation electronic monitoring programs (Jones et al., 2018). These research applications follow along from work by Roman et al. (2011) and suggest self-reported catch and effort data as a cost-effective mechanism for estimating discards.

Improving Biological Parameter Estimates

Study Fleet has shown success in implementation of an industry-based biological sampling program. While length and weight measurements are not taken by all participants, opportunistic collections have been a key success of this program. Collaboratively working with industry provides an opportunity to access species across space and time that are unavailable to seasonal surveys. These biological samples can improve the data available for studies on age, growth, reproductive dynamics, and bioenergetics. For example, yellowtail flounder samples from three stocks were obtained from Study Fleet vessels across three years to estimate potential annual fecundity (McElroy et al., 2016). Additionally, yellowtail flounder, winter flounder, and summer flounder samples were obtained to support a bioenergetics study on flatfish (Wuenschel et al., 2018).

DISCUSSION

Haul specific logbook data, and reference fleets like the NEFSC Study Fleet provide a unique perspective on marine ecosystems, as they record consistent observations over long periods of time and incorporate the tacit knowledge of fishermen (Johnson, 2007; Hulme, 2014). As with other forms of passive cooperative

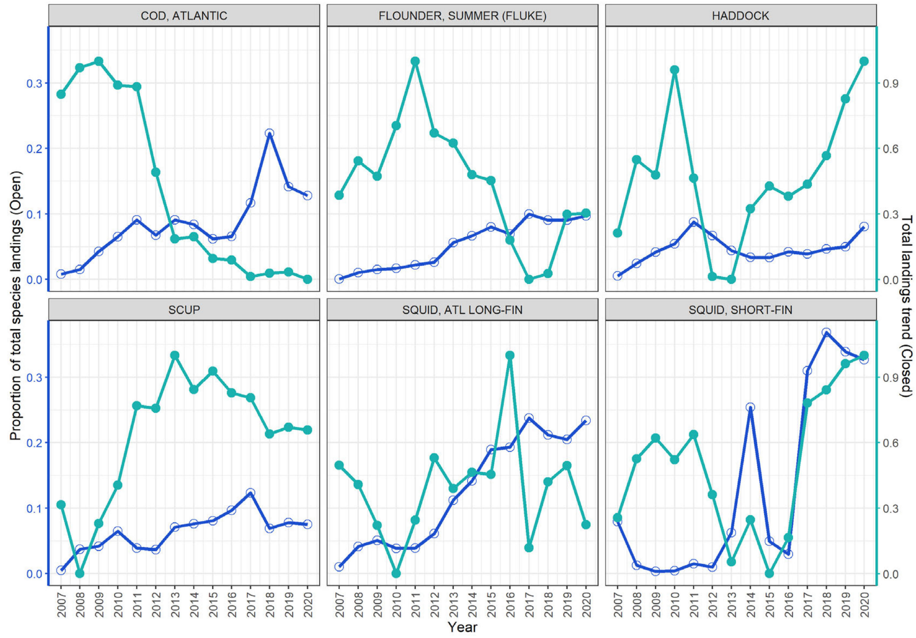

FIGURE 6 | The proportion of six species' regional commercial landings reported through Study Fleet (dark blue open circles), relative to the trend in total commercial landings of the species (light blue closed circles).

research, the curation of logbook data by fisheries scientists provides the most straightforward path to having the data used for scientific purposes (Mangi et al., 2018; Bonney et al., 2021). Additionally, the interactions with industry that emerge from the collection and application of these data are likely to increase understanding and trust (Thompson et al., 2019; Holm et al., 2020). A number of these benefits have been realized by the Study Fleet program, with products from the collaborative efforts being incorporated into stock assessments, however it is clear that the program has yet to meet its full potential. A number of lessons were learned during the first 15 years of the Study Fleet that will inform the future of this program and may be of use to developing programs in other regions. Many of these lessons have been seen in other research ventures that engages stakeholders in research partnerships (Mackinson et al., 2011; Gawarkiewicz and Mercer, 2019; Steins et al., 2020; Van Vranken et al., 2020). Having these same lessons

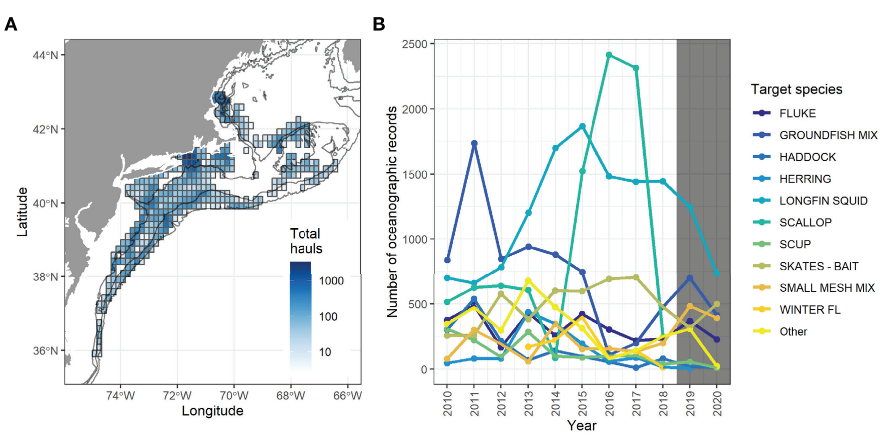

FIGURE 7 | The trend in oceanographic records across space and through time. Panel **(A)** shows the density of sampling across space for all years sampled (2010-2019). Cells with fewer than three unique permits (records from fewer than three vessels) have been omitted. Panel **(B)** shows the number of hauls with registered oceanographic data from 2010 to 2020. Data from 2019 and 2020 (shaded gray) are still being processed and sums represent incomplete totals. In panel **(A)** 223 (40%) cells were omitted.

emerge repeatedly from independent programs suggests that they are likely to be encountered by other programs attempting to pursue substantive industry collaborations.

Primary Lessons Learned

Sustaining Participation is Hard

As with a number or science-industry research collaborations (e.g., Mangi et al., 2018), a key takeaway from over a decade of working with the fishing industry is that participation and engagement are not guaranteed on either side of the collaboration. Participation and interest in providing data to scientists and managers, and their interest in receiving it, is often linked to specific topics and pending management action. This ebb and flow of interest is part of most research endeavors (Mackinson, 2022), but presents a challenge to creating a consistent time series. This is a barrier to maintaining participation in a broader range of longer-term collaborative research addressing dynamic and evolving questions and capacity building. Building a Study Fleet that is diverse in participation, but stable over time would provide the maximum scientific benefit (data which is the most representative), but without tangible products and impacts over time, participation is difficult to sustain. A unique aspect of the Study Fleet program is that its extended period of operation means that there is currently a need to plan for key participants leaving fisheries. Partnering with regional training programs could provide a means to sustain interest, but it is likely that some time series from specific vessels may have a maximum length.

Find Fishermen Who Really Want to Contribute to Science

For many reasons successes in cooperative research can be challenging to find. Previous research has suggested that finding 'boundary spanners', that is individuals who can recognize the value of tacit knowledge while also contributing to scientific objects (Johnson, 2007), is essential. For this project, identifying and onboarding these individuals was a key early success. Evidence of the commitment of these fishermen to the program can be seen in a number of ways. For example, while direct compensation (quarterly stipend) maybe a motivating factor for some fishermen to participate in the Study Fleet, many fishermen who are part of the program have been willing to accept reductions in compensation between 2005 and 2016 (due to budget constraints). This commitment to continuing to collect data, regardless of reduced compensation, reflects their support for the mission of the program. Many fishermen care deeply about the science that informs the management of the fisheries on which their livelihoods rely, and take pride in their contributions of data and knowledge through the Study Fleet. Finding and partnering with these key industry collaborators has been essential to developing and sustaining a research program of this nature. At the same time, it is important to consider those fishermen who may be left out of the program and potential biases that may be introduced by focusing on a subset of a given fishery (Steins et al., 2020). Recent efforts to apply Study Fleet data in novel and impactful ways have re-invigorated Study Fleet participants and sparked additional interest in participation from other fishermen. For example, the catch data have been used to develop CPUE standardizations for a number of stock assessments (e.g., Cadrin et al., 2020b), and data have been made available to regional academic partners for research purposes in the hopes of spurring additional analytical products. Within the region, fishermen often inherently distrust fisheries science and scientific advice because they are often excluded from the process (Johnson, 2007). In a manner similar to other cooperative programs, the Study Fleet provides a venue for fishermen to directly contribute to the scientific process, turning anecdotes into data points.

Fishing Operations Are Diverse and One Piece of Software Does Not Work for All

There are dozens of different gear types used for commercial fisheries, all of which have unique operational sequences and metrics. Developing a data collection system (software and hardware) for all gear types has proven to be extremely difficult, and has limited participation by fixed gear vessels in the Study Fleet. In recent years, operational constraints on software systems were identified for fixed gears and extensive user comments guided enhancements in the layout and sequencing of logbook data entry screens. The challenges of collecting effort-level data for fixed gear types where multiple strings can be deployed at the same time and with some gear left fishing while the boat returns to port, are not fully resolved and require further technical development. A clear lesson from this work is that programs should make an effort to engage and consult with the full breadth of potential users from diverse fishing operations early during the software development phase. Engaging diverse users early in the program can help to anticipate the potential diversity of uses and the flexibility that might be needed.

A Multi-Purpose Logbook Is Useful, But Can Detract From the Scientific Impact

After the demonstrated success of the ELB for the Study Fleet, other groups pushed for its use as a regulatory reporting tool. This utilization of the technology for regulatory reporting rather than science has the potential to provide increased participation and better relationships (because NMFS is providing software and a service) between scientists and fishermen, but comes at a cost of time and resources. This is especially true when resources and field support are limited and are spread across a range of fisheries and the reporting technology is continuously being developed. In this program, there was a hope that the use of the ELB for mandated reporting would lead to more interest in reporting for scientific purposes, but our evaluation of trends in participation suggests that this transition only occurred on one or two occasions. Generally, fishermen preferred to report at a lower-resolution, unless a higher level of participation was required of them (e.g., vessels who opted into pilot electronic monitoring programs). Planning and programmatic mechanisms that enhance scientific partnerships/collaborations to maintain and expand overall activity in a fishery or region are needed given constrained research budgets.

Straddling the Regulatory Divide Can Be a Challenge

The Study Fleet program participants collect using software that is also approved for northeast U.S. federal vessel trip reporting. Therefore, components of the data collected to address scientific questions are passed onto regional regulators and used to maintain regulatory compliance. To perform both of these functions simultaneously, it is essential that boundaries are maintained between regulatory and scientific applications and that fishermen understand how their data are being used. Additionally, there is a need to communicate how data submitted by fishermen are handled and processed to align with specific management programs. Often the QA/QC modifications that are made to data following submission are poorly documented or understood by fishermen, sector managers, or NMFS staff, and this is the core driver of fishery dependent data modernization efforts throughout the Northeast and other regions nationally. Documenting these processes and communicating them back to the fleet will help to avoid issues experienced in this region.

Data Management and QA/QC Need to Be Planned For

At its heart, the Study Fleet seeks to engage the fishing community in collecting high-resolution data sets of catch, effort, and environmental conditions. Each of these elements require high level QA/QC to ensure consistency and applicability. Competition among programs within the region hampered early development and continued evolution of a robust QA/QC system for the Study Fleet. Fully funding these programs would have expedited the availability and enhanced the utility of the data for stock assessments and ecosystem research. Documentation and dedicated staff to operationalize the delivery of standard data products to end users are key to reference fleets realizing their full scientific value. Additionally, end users need to understand the protocols that govern QA/QC and data collection by fishermen.

Data management has become more challenging as the Study Fleet program has developed from a small fleet of vessels in a single fishery to a large number that are spread geographically and across fisheries and gear types. To ensure that data sets are curated and available to analysts and collaborators, sufficient time and resources must be dedicated to data management and data flow. Developing standardized and regular data reports for collaborating participants and for program managers is an important next step for the Study Fleet. These reports could be used to help analyze patterns of omissions or other data quality metrics. Additionally, they could be used to synthesize across multiple types of fisheries dependent data.

Involve Assessment Scientists Early and Connect Often

Moving data from vessels into science and management is a large challenge for research collaborations (Steins et al., 2020). As with many other science-industry collaborations, this program exists in a data rich region where almost all stock assessments are supported by long-term scientific surveys. Because of the length of these time series, assessment scientists are cautious about bringing in fishery dependent data which has many complexities and caveats. While stock assessment scientists assert that there are benefits to these data sets (e.g., the large number of samples collected, and that they are sampled throughout the year), there is hesitation to include the information unless there are significant data gaps to fill.

A number of groups organized by the New England Fishery Management Council, such as the recent Fishery Dependent Data for Stock Assessments Working Group, have advocated for the wider use of fishery dependent data like that collected by the Study Fleet (Cadrin et al., 2020a). These studies highlight the potential utility of Study Fleet data, however regular use in annual operational stock assessments is not possible until the data are integrated in research track stock assessments that occur at 3- to 5-year intervals.

In discussions with collaborating participants, a common concern is that these data are not utilized to its full potential. Ensuring the data meets its potential, informing both qualitative (e.g., providing context to assessments) and quantitative aspects (e.g., improving discard estimates, being incorporated in assessment models as standardized CPUEs) of the fisheries science and management process is a multifaceted challenge. As mentioned previously, the Study Fleet data reflect a somewhat narrow and non-random selection of vessels, and the trip records themselves are continuous rather than random. Additionally, the number of vessels needed to provide a representative picture of trends in catch for any given fishery have not been well established. Communicating these potential pitfalls, and working with assessment scientists to ensure analyses consider these features of the data is an area of active development for this program.

Recently, a number of collaborative efforts have been initiated with assessment scientists, and familiarity and trust in the data are growing. Study Fleet derived CPUE trends have been presented at and incorporated in recent stock assessments. These efforts have highlighted the need to better understand topics that relate to the representativeness of Study Fleet data for different fisheries, as well as the efficiency of commercial gear and how that might affect trends in CPUE. The analytical possibilities are expanding and recent collaborative planning workshops appear to be building analytical capacity for upcoming assessments. Increasing engagement from specific fleets and specific fisheries for longer time periods will enhance the likelihood of success.

Providing Information Back to Captains Is Essential

Finally, there is an ongoing need to develop and expand data reports that are provided back to fishermen. Currently the flow of data is mostly unidirectional, with participants submitting data but relatively few products reporting this information back to the data collectors. Captains find great value in having access to their data, as it allows for a number of comparisons between sources (dealers, observers, port samplers, etc.), and for them to build insight from their fishing activities. Some basic applications to provide this access have been developed and piloted (**Appendix D**), but there is considerable room for growth in this area. Developing these tools with fishermen, fleet managers, and scientists to prioritize what is most useful would continue to build on the clear success of this program. These types of tools are likely to be valuable for creating an awareness of the importance of accurate reporting. Additionally, being able to see and use collected data, as well as receive information about how their data are being integrated into scientific processes, is vital to sustain participation in this type of scientific endeavor (Holm et al., 2020).

Key Recommendations

Based on these lessons learned, we developed a set of recommendations for data collections similar to the Cooperative Research Study Fleet program in the northeast US. This includes data sets leveraging cameras or other technology to create high resolution fishery dependent data, especially those hoping to apply the data to scientific aspects of fisheries management (e.g., ecosystem and stock assessments). These recommendation echo elements of those suggested by other science-industry research collaborations (Steins et al., 2020), and emphasize that for logbook oriented collaborative projects similar lessons apply.

1. *Develop detailed roadmaps for each data collection to keep participants engaged as collaborators.* These road maps would explain to participants when and how their data are expected to be used, how likely it is to be used, and set clear expectations and milestones.

2. *Target specific fisheries to keep resources from being stretched too thin.* Focusing on a limited set of fisheries and on the data sets most likely to be used will help to ensure the program 'succeeds'.

3. *Partner with data users early.* End users of the data from science-industry collaborations require continuous and representative time series to perform their analyses. This means that data products and summaries need to be planned well in advance, and planning should incorporate a spectrum of people including assessment scientists, scientists with a deep knowledge of fishery dependent data sources, and ideally, fishermen most familiar with the data.

AUTHOR CONTRIBUTIONS

AM, AJ, KB, MM, JH, DG, JF, JR, RS, and TS conceived of the study. KB, MM, GG, JW, CA, DG, JF, JR, RS, and TS collected and curated the data. AJ, DD, BL, and AM participated in the formal analysis. AJ, AM, KB, and JH contributed the original draft. All authors contributed to the editing. MM provided software development. Resources were contributed by JH, DG, JF, JR, RS, and TS. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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A Transdisciplinary Approach Towards Studying Direct Mortality Among Demersal Fish and Benthic Invertebrates in the Wake of Pulse Trawling

Edward Schram[1]*, *Pieke Molenaar*[1], *Susan de Koning*[1,2] *and Adriaan D. Rijnsdorp*[1]

[1] Wageningen Marine Research, Wageningen University and Research, IJmuiden, Netherlands, [2] Geography, Planning and Environment, Institute for Management Research, Radboud University, Nijmegen, Netherlands

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Steven Mackinson,
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Office for National Statistics,
United Kingdom

***Correspondence:**
Edward Schram
edward.schram@wur.nl

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Between 2009 and 2020, beam trawlers in the North Sea switched to electrical stimulation to target sole (*Solea solea)*. The transition to pulse trawling raised widespread concern about possible adverse effects of electrical stimulation on marine organisms. Environmental NGO's and small scale fishers claimed that it would electrocute marine life and create a 'graveyard' in the wake of pulse trawlers. This paper uses realistic field experiments to investigate the 'graveyard' hypothesis. In cooperation with fishers, a field experiment was designed where we simultaneously sampled marine organisms in the wake of pulse trawlers and in untrawled control areas. The impact was quantified by estimating the direct mortality among three dominant fish species and four dominant invertebrate species. In total, nine experimental tows were conducted in two years. Direct mortality among fish and invertebrates was low (0-10%) and did not differ between the pulse trawl track and the untrawled controls. Equally, no impact of the pulse trawl was found on external damages and vitality scores. The limited effects observed are likely due to the mechanical impact of the pulse and the sampling gear. The results of experiment do not support the claim that pulse trawling results in mass mortality among marine organisms in the trawl track. Throughout the research period, the concerns of small-scale fishers on pulse fishing shifted from being focused on biological effects to political and managerial issues. This can partly be attributed to the engagement in and the results of our research and has increased its credibility and salience. By integrating fishers' knowledge and examining their perceptions through transdisciplinary research, we were able to show the importance of untangling the intricate relation between perceived knowledge gaps and political or management related concerns.

Keywords: fisheries, impact, bottom trawling effects, mortality, Fisher's knowledge, Electrotrawling

INTRODUCTION

The Dutch beam trawl fishery in the North Sea is a mixed fishery that targets Dover sole (*Solea solea*) and plaice (*Pleuronectes* platessa) with other species as valuable bycatches (Gillis et al., 2008). The beam trawls are equipped with tickler chains to mechanically chase flatfish from the seabed into the net. In the North Eastern Atlantic, the beam trawl fishery is considered to be among the fishing gears with the largest ecological impact on the benthic ecosystem because the tickler chains penetrate the sediment and disturb the top layer of the sea bed (Hiddink et al., 2017; Rijnsdorp et al., 2020b). The relatively small codend mesh size required to retain the slender sole results in large bycatches of undersized plaice (*Pleuronectes platessa*) and other fish species (Uhlmann et al., 2014; Rijnsdorp et al., 2020a *submitted*). The relatively high towing speed results in a high fuel consumption (Poos et al., 2013).

Between 2009 and 2021, part of beam trawl fleet targeting sole was temporarily allowed to switch to electrical stimulation with pulse trawls to explore the possible reduction of the adverse impact of conventional beam trawls on the ecosystem (Van Marlen et al., 2014; Haasnoot et al., 2016). Vessels used a pulsed bipolar current (PBC) that causes a cramp response that immobilises the fish and facilitates their catch (Van Stralen, 2005; Soetaert et al., 2015a; Soetaert et al., 2019; Rijnsdorp et al., 2020a, *submitted*). Beam trawl fishers were eager to switch to pulse trawling, as the pulse trawls proved to be robust and reliable, and because the gear was more efficient to catch sole at a lower speed and lower fuel consumption (Poos et al., 2020; Turenhout et al., 2016; Soetaert et al., 2015a). The Dutch government supported the transition by funding research projects and by negotiating the extension of the number of pulse licenses from 22 in 2009 to 84 in 2014 (Haasnoot et al., 2016).

The increase in pulse licenses was heavily criticized (Haasnoot et al., 2016; Le Manach et al., 2019; Kraan et al., 2020) and fueled the already existing concerns about the adverse effects on marine life and the consequences of the more efficient gear for other fishers (Stokstad, 2018; Quirijns et al., 2018). Pulse trawling was thought to electrocute marine life (Bloom, 2018). Recreational and small-scale fisherman from England, Belgium, France and Netherlands for instance claimed that such exposure causes direct mass mortality among fish and benthic invertebrates, resulting in a 'graveyard' in the wakes of pulse trawlers (Bloom, 2018). The available scientific knowledge did not support these claims. In particular, laboratory experiments did not find an increased mortality rate among marine organisms exposed to the electric pulse used in the fishery for sole (Smaal and Brummelhuis, 2005; Soetaert et al., 2015b; Soetaert et al., 2016a; Soetaert et al., 2016b; Soetaert et al., 2018; de Haan et al., 2009; de Haan et al., 2015), whilst field studies showed that over 90% of undersized plaice, common sole, turbot, brill and thornback ray caught in a commercial pulse trawl is alive when landed on deck (Schram and Molenaar, 2018, *submitted*). The only adverse effect of electrical stimulation shown by laboratory and field studies is the occurrence of spinal-injuries in cod (Van Marlen et al., 2014; De Haan et al., 2016; Soetaert et al., 2016a; Soetaert et al., 2016b). However, direct mortality in the wake of pulse trawlers was never studied under realistic field conditions.

Following the growth of the number of pulse licenses, the Dutch government funded additional research projects to fill knowledge gaps on the effects of electrical stimulation on marine organisms and organized a series of International Pulse Dialogue Meetings (Steins et al., 2017; Kraan and Schadeberg, 2018). In these meetings, aimed to discuss the results of the ongoing scientific research and the concerns with stakeholders and other interest groups, small-scale fishers reiterated the need to study the 'graveyard' question and expressed their interest to become involved in the research (Quirijns et al., 2018).

In this paper we report on a study of the direct mortality among demersal fish and benthic organisms in the wake of a pulse trawler operated under realistic field conditions and describe the role of stakeholder involvement in the planning of the research and the evaluation of the results.

MATERIALS AND METHODS

Field Experiments

General Set Up

Two field experiments were conducted on the 18th to the 19th of June 2019 and on the 15th of September 2020, hereafter referred to as Experiment 1 and Experiment 2. Each field experiment involved a commercial pulse trawler to create trawl tracks where organisms were exposed to the commercial pulse stimulus, and a commercial shrimp trawler to sample the pulse trawl track. Both pulse trawlers were double rigged with a trawl on either side of the vessel. Trawl tracks were created with 11m (Experiment 1) or 12m (Experiment 2) wide pulse trawls during experimental tows of 35 - 45 minutes. Within 15 - 30 minutes after pulse trawling, the shrimp trawler sampled the tow tracks for 10 min with a 9 m wide small-meshed shrimp beam trawl and at the same time took a control sample outside the pulse trawl track (**Figure 1**). Experimental conditions are presented in **Table 1**.

This design resulted in paired samples of treatments and controls for all tows. Experiment 1 consisted of two different pulse trawl treatments: pulse trawl tracks created by a complete pulse trawl (PULSE_CMPLT) and a pulse trawl with its netting and ground rope removed, resulting in only the seawing and pulse electrodes being towed over the seabed (PULSE_NO_NET). Experiment 1 was designed in cooperation with small-scale fishers and representatives of small-scale fisheries organizations (see below). Experiment 2 included only pulse treatment PULSE_CMPLT paired with its controls because in Experiment 1 no significant difference between the two pulse trawl riggings was found (**Supplementary Material SM1**). In total four tows were done in Experiment 1 with two tows per pulse trawl treatment. In Experiment 2 five tows were done, yielding five paired samples for PULSE_CMPLT and Control.

Trawl Specifications and Modifications

The trawl dimensions and specifications of the pulse and sampling trawls are presented in **Supplementary Material SM2**. To maximize the number of organisms that the sampling trawls could pick up from the seafloor, the conventional shrimp bobbin ground ropes of sampling trawls were replaced by heavy closed ground ropes consisting of rubber discs supplemented with 97 additional lead discs (0.9kg).

Pulse trawls had additional chains (10 m, Ø18 mm) attached to each end of the wings to create clearly visible slits on the seafloor that marked the boundaries of the pulse trawl tracks. The electrodes of the pulse trawl without ground rope and net were fixed in parallel position by one Dyneema® rope that connected

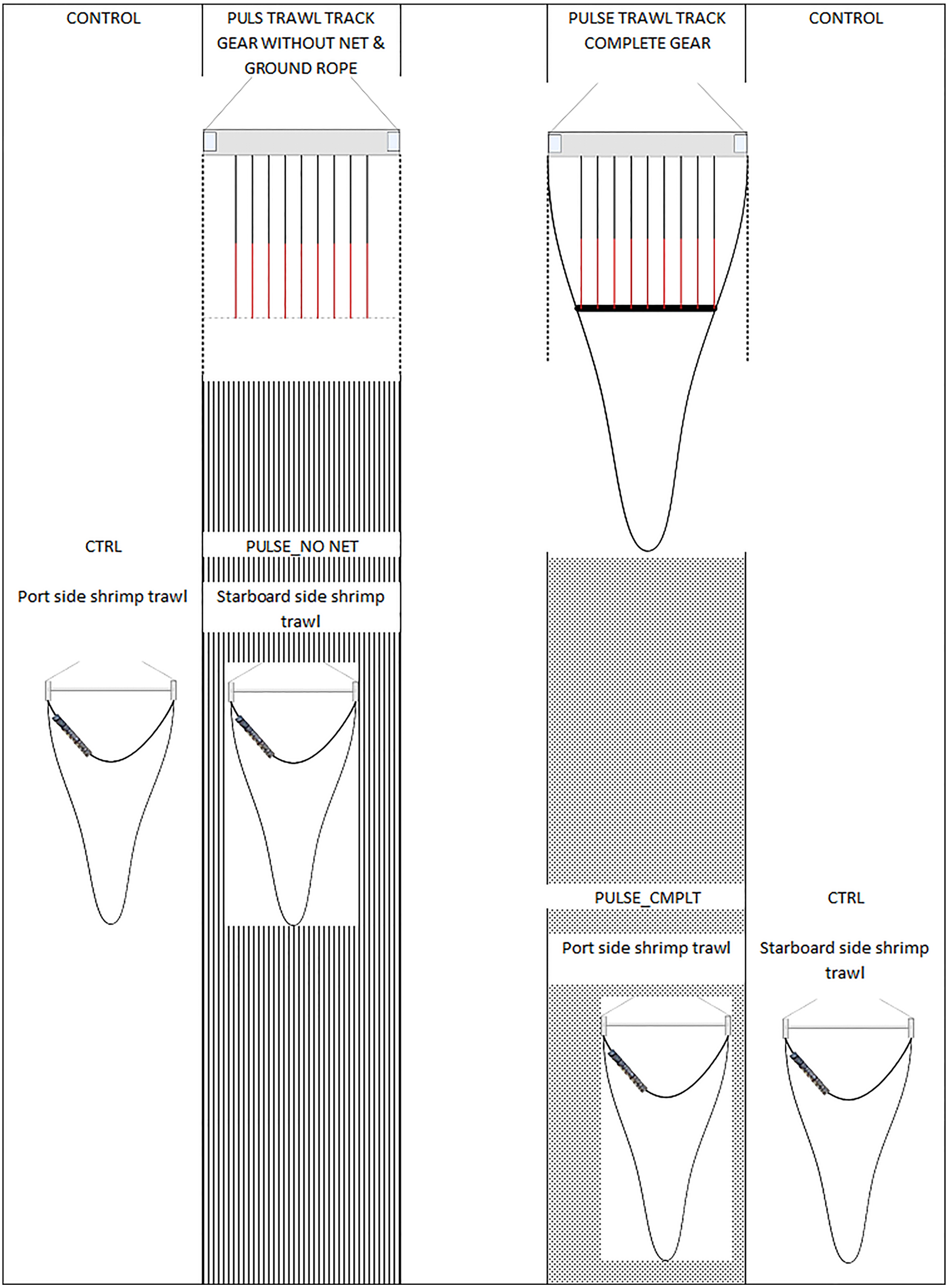

FIGURE 1 | Schematic presentation of the experimental design. Paired samples for PULS_NO NET and CTRL (Experiment 1 only) and for PULSE_CMPLT and CTRL (Experiment 1 and 2) were collected by deploying the shrimp trawls in and next to the respective pulse trawl tracks

TABLE 1 | Experimental conditions. Parameters were recorded per sampled tow. Presented are the minimum and maximum values recorded (range).

Parameter	Unit	Experiment 1	Experiment 2
Wave height[1]	m	–	0.3
Wind direction[1]		E-W-SW	S-N-NW
Wind speed[1]	Bft	0-2	2
Seafloor type[2]		Sandy/hard	Sandy/hard
Speed over water[3]	kts	4.7-5.0	–
Speed over seafloor[3]	kts	4.0 – 4.5	4.6
Sailing direction[3]	°	20 -200	16 - 200
Water depth[4]	m	21-23 [4]	22 – 25 [4]
Current direction[3]		NE	S - N
Current speed[3]	kts	0.8-2.2	0.1-1.1
Water temperature[5]	°C	11 – 13.2 [5]	–

[1]*Skipper's estimate.*
[2]*Skipper's knowledge & echo sounder equipment.*
[3]*Vessel's navigation equipment.*
[4]*Sea gauge pulse trawler.*
[5]*Sensor on pulse trawl.*

the aft ends of adjacent electrodes to prevent that electrodes could touch each other.

Deployment of Sampling Gear in Pulse Trawl Tracks

To deploy the sampling gear as precisely as possible in the trawl track, the shrimp trawler (with its trawls at the surface) followed the pulse trawler just outside its wake at a distance of approximately 120 m. A buoy on a 100 m rope, attached to the end of one of the booms of the pulse trawler, aided to maintain the shrimp trawler in proper position. Whilst navigating behind the pulse trawler, the shrimp trawler localized the pulse trawl on the seafloor and logged its track using a WASSP F3 multibeam sonar (WASSP Ltd, Auckland, New Zealand). When a clear trawl track had been observed, long enough for a 10 min sampling tow, the shrimp trawler returned to the starting position and deployed one of its trawls in a pulse trawl track and the other outside of the pulse trawl track (**Figure 1**). Towing time for sampling was limited to 10 minutes to minimize the impact of retention in the cod-ends on the sampled specimens. Towing speed over the seafloor of the sampling trawl ranged from 2.5 – 4.0 kts. All pulse trawl tracks and sampling tows were made against the tidal current to prevent benthic organisms to be washed out of the pulse trawl track by water currents. The pulse trawler refrained from discarding by-catches in the study area to prevent their inclusion in samples.

Underwater Video Recording

For each sampling tow, video recordings were made to be able to confirm the sampling from the pulse trawl tracks and to estimate the proportions of sampling inside the pulse trawl track. To record underwater videos the head rope of the sampling trawl was equipped with two forward looking cameras (GOPRO Hero 4) inside the right and left sides of the sampling trawl towed inside the pulse trawl track. Diving lights (Deep Blue 3500 lux) were installed next to each camera to increase visibility. To enable visual trawl path detection on the underwater video recordings a hard sandy sea bottom was chosen west of the Dutch coast (**Figure 2**). This sediment type is prevalent among the Dutch coast and provides reasonable visibility as the sand settles on the seabed after trawl passage.

Collection and Processing of Samples

The total catch weight of the sampling tows ranged between 4.6 and 21.5 kg. The samples collected in the port side and starboard side cod ends of the sampling trawls were discharged separately into 50L plastic baskets, each placed inside a plastic tub filled with surface seawater. Each tub was aerated to supply oxygen to the biota in the samples during their short storage prior to sample processing. Sub-samples of benthic organisms and fish were taken from these catches as follows. The content of each basket was homogenized by manual mixed before a sub-sample of approximately 2L was netted from the basket. To collect sub-samples from the entire water column, the net was dipped to the bottom of the basket and then filled up an upwards motion towards the surface. The sub-sample was placed in a 30L rectangular plastic tub filled with aerated seawater. Specimens of interest were manually picked from the tub and placed in water filled, aerated containers. If needed, a second or third sub-sample was taken from the basket holding the total catch to obtain at least 20 specimens per species. Sub-sampling of benthic organisms and fish was completed for both catches before we proceeded to assess the condition of the collected specimens. The order of sub-sampling and condition assessment for the port and starboard side catches was alternated between tows. To keep the time required to process all sub-samples within practical limits, sub-sampling was limited to six species in Experiment 1 and five species in Experiment 2 based on their abundance in the first samples (**Supplementary Material SM3**). The following species

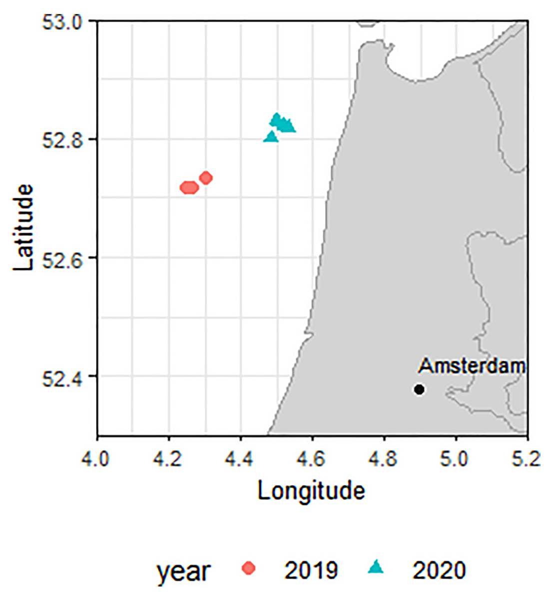

FIGURE 2 | Locations of the Experiment 1 (2019, red dots) and Experiment 2 (2020, blue triangles) tows.

were sampled: plaice (*Pleuronectus platessa*), dab (*Limanda limanda*), solenette (*Buglossidium luteum*, Exp. 1 only), flying crab (*Liocarcinus holsatus*), hermit crab (*Paguroidea* spp., Exp. 1 only), brittle star (*Ophiuroidea* spp.) and brown shrimp (*Crangon crangon*, Exp. 2 only).

Assessment of the Condition of Fish and Invertebrates

For all sub-sampled specimens (n = 20 per species) we established whether individuals were dead or alive. Specimens that displayed any kind of movement were considered to be alive. Specimens that displayed no movement or were crushed were considered to be dead. For 10 out of the 20 sub-sampled specimens per species treatment effects on condition were assessed in more detail by determining a range of damage scores (**Table 2**). Fish condition was assessed according to Van der Reijden et al. (2017), including damages to fins, skin and mucus layer and the presence of haemorrhages and summarized in a vitality class. Damage in invertebrates was assessed according to Bergman and Van Santbrink, (2000), including loss of limbs and crushing of carapax or disc. For brown shrimp we developed the 'jump reflex test' (**Table 2**). The abdominal muscle of brown shrimp is specialized in powerful contractions that enable the shrimp to jump backwards. This muscle has been shown to fatigue quickly (Hagerman & Szaniawska, 1986) making the 'jump reflex test' a suitable measure for condition and ability to display behaviour potentially essential for its survival.

Reconstruction of the Path of the Sampling Trawl

Observations by underwater videos of the shoes of the sampling trawling passing the slits drawn in the seafloor by the chains attached to each end of the pulse trawls and the electrodes of pulse trawl (PULSE_NO_NET only) allowed for the positioning of the sampling trawl relative to the pulse trawl track at multiple time points. The obtained set of positions were used to reconstruct the pathways of the sampling trawl for each haul and to estimate the area swept inside the pulse trawl track by the sampling trawl. **Figure 3** presents an example of a reconstructed trawl path of the sampling trawl relative to the pulse trawl tracks. A full set is presented in **Supplementary Material SM4**. The area sampled by the sampling trawl inside the pulse trawl track was expressed as percentage of the total area sampled for each tow **(Table 3)**.

Data Analysis

Differences in direct mortality between PULSE_NO_NET and PULSE_CMPLT were tested per species by Fisher's exact test using the raw counts of life and dead specimens in both treatments. As for none of the species tested a significant effect

TABLE 2 | Description of condition scoring.

Condition – All fish species	
Vitality class	**Description**
A	Fish lively, no visible signs of loss of scale or mucus layer.
B	Fish less lively, minor lesions and some scales missing, mucus layer affected up to 20% of skin surface area, some point haemorrhaging on the blind side.
C	Fish lethargic, intermediate lesions and some patches without scales, mucus layer affected up to 50% of skin surface area, several point haemorrhaging on the blind side.
D	Fish lethargic or dead, clear head haemorrhaging, major lesions and patches without scales, mucus layer affected for more than 50% of the skin surface area, significant point haemorrhaging on the blind side.
Damage scores – All fish species	
Damage	Description (1 = present; 0 = absent)
Fins	Fins are damaged or split (including tail fin).
>50%	Damage to skin surface, scale or mucus layer at more than 50% of the dorsal body surface.
Head hemorrhages	Presence of a hemorrhage in the head of the fish
Hypodermic hemorrhages	Presence of a hypodermic hemorrhage
Intestines	Intestines are protruding or are visible through damaged body tissue of the fish.
Wound	Presence of a wound such that flesh is visible.
Damage scores – Invertebrates	
Damage	Description (1 = present; 0 = absent)
Limbs	Crabs & starfish: one or more limbs or arms (partly) lost.
Crushed	Carapace (crab, shrimp) or disc (starfish) damaged or crushed
Out of shell – undamaged	Hermit crabs: shell lost but animal undamaged
Out of shell - damaged	Hermit crabs: shell lost and animal damaged
Reflex – Brown shrimp	
Reflex	Description (1 = present; 0 = absent)
Jump	Shrimp placed in a tank jump backwards in response to a gentle touch of the head region with the observer's index finger

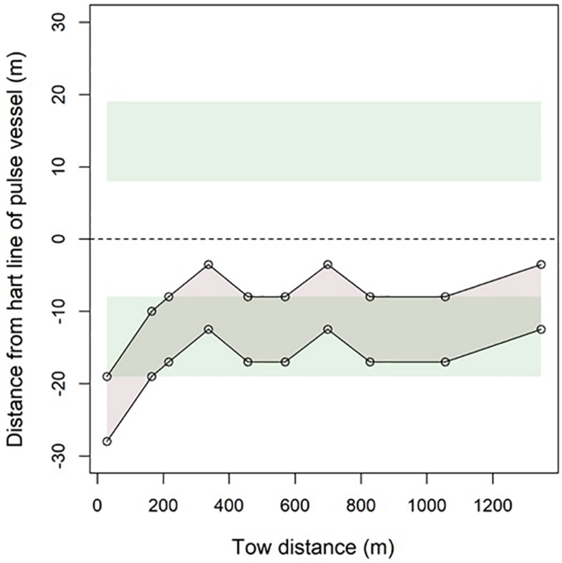

FIGURE 3 | Tracks of the starboard and port size pulse trawl (green) and reconstructed sampling track (grey) from the observed positions (o) of the shrimp trawl (o) of tow 1. The centerline of the pulse trawlers is positioned at 0 m on the y-axis.

was detected (SM 1), all observations for pulse trawl treatments PULSE_NO_NET and PULSE_CMPLT were merged into a single pulse trawl treatment (PULSE) for further analyses.

The direct mortality estimates may be affected by the proportion of the surface area sampled in the pulse trawl tracks (**Table 3**). The possible influence was tested using a binomial GLM model: $Y_i \sim \beta_1+\beta_{2Xi}+\varepsilon$ where response variable $Y_i=n_i/N_i$, n_i is the number of dead animals and N_i is the total number of animals sampled in tow i, and the explanatory variable X_i being either the treatment (PULSE, Control: model m1) or the proportion of the trawl track of the pulse trawlers sampled (model m2) and ε is the bionomial error. In model 2, the proportion of the pulse trawl track sampled ranged between 0.43 and 0.94 in the treatment observations and were set at 0 for the control samples.

For direct mortality and individual reflex and damage scores 2x2 contingency tables were constructed per species for the raw counts of life and dead specimens (two levels) and treatment (Pulse vs Control) combination. For fish condition, expressed by vitality class A, B, C or D, 4x2 contingency tables were constructed per species for the counts per vitality class (four levels) and treatment (Pulse vs Control) combination. The contingency tables employed all observations of experiment 1 and 2. Fisher's Exact test was used to analyze the frequency distributions in these tables for significant treatment effects. Treatment effects were considered significant when p ≤0.05.

TABLE 3 | Estimates for the areas swept inside the pulse trawl track by the sampling trawl.

Experiment	Sampling tow	Area sampled inside pulse trawl track (% of total sampled area)
2019	1	80
	2	45
	3	49
	4	43
2020	5	89
	6	81
	7	61
	8	94

Swept areas are expressed as percentage of the total area swept by the sampling trawl during a sampling tow.

Interviews and Workshops

We held two workshops (2019 and 2020) and a series of interviews (2020) with small-scale fishers and representatives of small-scale fisheries organizations. We defined small-scale fishers for the purpose of this research as fishers engaged in gillnet fisheries, handling fisheries and shrimp fisheries. The objectives of the first workshop were to inform participants on the research objectives and to discuss experimental design options. Outcomes of this discussion were implemented in the design of Experiment 1. After reporting results of the Experiment 1 (Schram & Molenaar, 2019), we conducted ten interviews with fishers (8) and fisheries representatives (2). The interviews were performed in a semi-structured manner, using a predefined topic guide. Interviews were recorded with informed consent of the respondents and analyzed in a qualitative and quantitative manner using iterative coding in Atlas.ti 8.4.22.

The results of the interviews were validated in a second workshop in July 2020. Next to the validation of the results of the interviews, the workshop functioned as a way of informing small-scale fishers on results of Experiment 1, the design of Experiment 2 and providing space for additional input in the location and species to be examined in Experiment 2. The workshop was publicly announced and open for all Dutch small-scale fishers and representatives. Respondents of the interviews were personally invited to participate in the workshop. Seven fishers and representatives registered as participants. Three fishers/representatives actually joined the workshop. Reasons for the low number of participants could be a last minute emergency meeting of one of the fisheries organizations, or the good conditions for fishing that day.

RESULTS

Field Experiments

Direct Mortality Among Fish and Invertebrates

Overall, the large majority of sampled animals was alive upon sampling, resulting in survival (the reciprocal of mortality) ranging from 90-100% among treatments for the fish and the invertebrates. For all sampled species direct mortality did not differ between specimens collected inside the pulse trawl tracks (PULSE) and those collected in the control areas (Control) (Fisher's exact test p > 0.05, **Table 4**). These treatment effects could be tested for significance without taking the areas swept inside the pulse trawl tracks during the sampling tows into account (**Supplementary Material SM5**).

TABLE 4 | Acute mortality (% of total number of observations, N) of specimens sampled from the pulse trawl tracks (Pulse) and from the unfished control areas (Control).

Species	Pulse		Control		Fisher's Exact test
	%dead	N	%dead	N	p-value
Dab	5.9	170	10.1	179	0.17
Solenette	5.4	93	3.4	88	0.72
Plaice	0.0	115	0.8	127	1.00
Brittle stars	6.7	178	9.4	149	0.42
Hermit crabs	0.0	72	0.0	78	1.00
Flying crab	9.8	133	9.2	131	1.00
Brown shrimp	4.9	183	3.5	171	0.60

For none of the species a significant difference between Pulse and Control was detected (Fisher's exact test, p-value > 0.05).

Condition of Fish

For the three fish species sampled, most of the sampled fish were undamaged. The proportion of vitality class A ranged between 73% and 95% (**Table 5**). No difference in frequency distributions over the vitality classes A, B, C and D was detected between fish sampled from pulse trawl tracks (PULSE) or control areas (Control) (Fisher's Exact test p-values > 0.05, **Table 5**). Testing the separate damage types showed no significant difference between the fish sampled from the pulse trawl track or the unfished control area (Fisher's Exact test p-values > 0.05, **Table 6**).

Damages in Invertebrates

Damages observed in invertebrates are presented in **Table 7**. All hermit crabs we assessed were undamaged. Among flying crabs we observed missing limbs in 16-18% of the specimens where the majority of the brittle stars (58-63%) had lost at least part of one limb irrespective of the treatment. Differences in the occurrence of damages from either the pulse trawl track or the unfished control areas were not detected (Fisher's Exact test p-values > 0.05, **Table 7**).

Interviews and Workshops

In the first workshop, fishers expressed their concerns on pulse fisheries, which focused mainly on impacts on non-caught individuals, suspected use of higher than legally allowed voltages, (local) overfishing and the indirect impact of pulses on behaviour of round fish. Fishers experience a huge difference between fishing after a bottom trawl has passed, or fishing after a pulse trawl has passed. In the first case fishers have increased catches, while in the second they catch less or even nothing. Fishers suggested to do the experiments close to the 12-mile zone and include a PULSE_NO_NET treatment in the experiment to investigate mechanical versus electrical impacts. Fishers also suggested to use an extra heavy ground rope, to be able to catch everything that has been in contact with the pulse trawl. All these suggestions were included in the research design of the first experiment.

The interviews, which were performed after the results of the first experiment were published, showed mixed feelings among small-scale fishers with regard to pulse fisheries. They understand the urgency of innovation in the beam trawl sector, for which pulse could be a more efficient alternative. Some respondents therefore regard pulse fisheries as a good development, if it is not used to raise catches, but to decrease effort and expenses. The respondents state that by increasing catches, pulse fishers have flood the market, which led to decreased fish prices and has harmed the whole fisheries sector. Next to that, respondents argue that the introduction of pulse fisheries led to increased fishing pressure in certain areas and displacement of other types of fisheries. Within the small-scale fisheries sector, many fishers suspect that pulse fishers did not adhere to maximum peak voltage as established in the pulse exemptions. If pulse fishers would adhere to the regulations and would limit the amount of catches, respondents feel that pulse fisheries would not have had the impact on fish stocks and other fisheries as experienced today by small-scale fisheries. Besides the alleged misuse of pulse trawling, respondents also oppose to pulse trawling because of the exemption policy (only part of the fishers received an exemption), which lead to unfair competition among fishers.

When asked after the results of the first experiment, respondents declared that the results did not address their concerns. The experiment focused on benthic organisms, and although they understand the importance of benthic organisms for the North Sea ecosystem, they are more worried about the direct effects of pulse fishing on fish and shrimp. For shrimp, respondents worried that when they are pulsed, their reflexes make them jump, after which they can be hit by the ground rope and will end up dead on the seafloor instead of being caught or having escaped. Therefore, some fishers criticized the use of different gear combinations such as using the pulse trawl without using ground ropes, as this

TABLE 5 | Frequencies of vitality classes A-D (% of total number of observation, N) for plaice, dab and solenette sampled from pulse trawl tracks (Pulse) and unfished control areas (Control).

Species	Treatment	Total N	A (%)	B (%)	C (%)	D (%)	Fisher's Exact test p-value
Dab	Control	90	76.7	14.4	1.1	7.8	0.842
	Pulse	90	73.3	17.8	0.0	8.9	
Solenette	Control	40	95.0	2.5	0.0	2.5	0.177
	Pulse	40	80.0	12.5	0.0	7.5	
Plaice	Control	84	91.7	6.0	2.4	0.0	0.445
	Pulse	76	86.8	11.8	1.3	0.0	

For none of the species a significant difference between Pulse and Control was detected (Fisher's exact test, p-value > 0.05)

TABLE 6 | Presence of damages (response = 1, % of total number of observations, N) in dab, solenette and plaice sampled from pulse trawl tracks (Pulse) and unfished control areas (Control).

Species	Treatment	Total N	Fins split	> 50% scale loss	Head hemorrhages	Hypodermic hemorrhages	Intestines	Wounds
			(%)	(%)	(%)	(%)	(%)	(%)
Dab	Control	90	37	5	2	12	0	8
	Pulse	90	29	2	2	9	0	8
	p-value		0.91	0.94	0.69	0.83	1	1
Solenette	Control	40	0	0	0	0	0	0
	Pulse	40	0	5	0	5	0	0
	p-value		1	0.25	1	0.25	1	1
Plaice	Control	84	31	5	5	12	0	0
	Pulse	76	37	1	4	5	0	0
	p-value		0.27	0.96	0.74	0.96	1	1

Within species, no difference between Pulse and Control in the presence of damages was detected (Fisher's exact test, p-value > 0.05).

TABLE 7 | Presence of damages (response = 1, % of total number of observations, N) in brown shrimp, flying crab, hermit crab and brittle star sampled from pulse trawl tracks (Pulse) and unfished control areas (Control).

Species	Response	Pulse		Control		Fisher exact test
		Response=1 (%)	N	Response=1 (%)	N	p-value
Brittle stars	Missing limbs	63.3	98	58.2	91	0.55
	Crushed disk	0.0	98	0.0	91	1.00
Hermit crabs	Out of shell – undamaged	0.0	41	0.0	40	1.00
	Out of shell – damaged	0.0	41	0.0	40	1.00
Flying crab	Missing limbs	17.7	96	16.0	94	0.85
	Crushed carapace	4.8	96	3.2	94	0.72
Brown shrimp	Absence of jump reflex	53.6	110	55.0	111	0.89
	Crushed carapace	0.0	110	0.0	111	1.00

Within species, no difference between Pulse and Control in the presence of damages was detected (Fisher's exact test, p-value > 0.05).

does not represent real life pulse fishing practices. The fishers suggested to use "normal" gear and conduct the experiment within the 12-miles zone, for instance near Scheveningen or IJmuiden.

Except for the concerns which relate to the biological/ecological impact of pulse fisheries, the respondents were mostly concerned about the political developments in the fisheries sector. Small-scale fishers feel non-represented by the larger fisheries organizations and feel that their stakes are not represented in decision-making processes. They suspect that the North Sea fleet of bottom and pulse trawlers is regarded as a priority by the Dutch government, and that therefore the negative impact of pulse on other types of fisheries and marine nature is not studied extensively. Furthermore, some small-scale fishers feel that researchers are under pressure to deliver good results for the pulse gear. They stress that they trust the individual researchers, but not the politics behind the research.

In the second workshop we discussed the results of the interviews, to validate our findings. Fishers agreed with the abovementioned concerns raised by the respondents and with the suggestions for adapting the second experiment. Researchers discussed the suggestions together with the fishers, for instance with regard to the species which would be examined in the second experiment. Fishing within the 12-miles zone was suggested, to be able to look at mortality among shrimp and to study the area in which the small-scale fishers actually fish. As explained to the participants, conducting the experiment in the 12-miles zone would make the field work more challenging, as a special permit that allows the use of pulse trawlers of the large segment (11-12 m wide beams) has to be arranged and the water near the coast is much more murky, making it difficult to use cameras to ensure fishing in the wake of the pulse. However, the participants of the workshop emphasized that the closer to the coast the experiment would take place, the more relevant the results would be for small-scale fishers. Based on the results of the interviews and the discussion at the workshop, we decided that for the second experiment, the pulse trawler would have the same complete pulse gear on both sides and that a permit for conducting the experiment within the 12-miles zone would be requested.

DISCUSSION

This study was conducted because of concerns that pulse trawling causes direct mass mortality among benthic biota in its trawl track. These concerns are relevant in the assessment of impacts of pulse trawl fisheries and were not previously investigated *in situ*. To address the concerns properly, we engaged small-scale fishers in research design and studied their concerns through interviews and workshops.

We sampled three fish species and four invertebrate species from pulse trawl tracks on the seafloor shortly after pulse trawlers had passed as well as from unfished control areas. Sampled specimens were generally in good condition, especially the fish species, and direct mortality was low for all species. We found no evidence for higher direct mortality and poorer condition for any of the species sampled from the pulse trawl tracks compared to the unfished control areas. Although this study refutes the claim that pulse trawling causes a 'graveyard' by electrocution of marine life, we cannot rule out the possibility that intensive pulse trawling on a fishing ground could result in an aggregation of dead organisms on the sea floor, just like any other fishery that produces discards would do.

No difference in direct mortality among fish and invertebrates was detected for the complete pulse trawl and pulse trawl without net and ground rope. These treatments were designed to distinguish mechanical and electrical impacts of pulse trawling. It is reasonable to assume that in the case where a passing pulse trawl causes direct mortality, this effect would be larger for the complete pulse trawl because it combines mechanical and electrical impacts. However, direct mortality among biota collected from the pulse trawl track made by the complete pulse trawl was already low and did not differ between the trawled and the control area. Given the low direct mortality inflicted by pulse trawling a much larger number of sampling tows is required to test the effect between electrical impact and the mechanical impact from ground rope and net.

The direct mortality among the three fish species tested (plaice, dab and solenette) was low (between 0 to 10.1%) and did not differ significantly between the pulse trawl track and control treatments. Direct survival, the reciprocal of direct mortality, observed in the current study is comparable to the direct survival of plaice, sole, turbot, brill and thornback ray sampled from two hour tows by commercial pulse trawlers (Schram and Molenaar, 2018; Schram et al., *submitted*).

Exposure to electrical pulses may inflict internal injuries, such as spinal injuries and hemorrhages, which could result in a delayed mortality (De Haan et al., 2016; Soetaert et al., 2016a). Because the recorded injury rate in pulse trawl catches was low (<2.5%) in 14 dominant North Sea fish species sampled (Boute, 2022; Boute et al., 2022) it is highly unlikely that pulse-induced internal injuries will result in mass mortality. This conclusion also holds for the two species (cod, sandeel) for which higher injury rates were observed, because cod is only a small fraction of a beam trawl's catch (ICES, 2020), and because none of the sandeel exposed to a commercial pulse stimulus in a tank experiment developed internal injuries (Schram et al., 2022).

Delayed mortality may also occur due to the damage imposed by trawling and handling of the catch (Van der Reijden et al., 2017; Veldhuizen et al., 2018; Cook et al., 2019). A strong relationship was observed between fish condition directly after landing on deck and the long-term chances of survival of individual fish (Schram and Molenaar, 2018; Schram et al., *submitted*). In the current study we used the same method as in Schram and Molenaar (2018) to determine the condition of individual fish and found that the large majority of fish were in excellent condition (vitality class A) and did not show any sign of damage. This is in stark contrast to the condition recorded in commercial catch of pulse trawlers. Jointly taken, we consider it unlikely that fish exposed to pulse trawls shown high delayed mortality. Dedicated survival studies in which sampled fish are kept in captivity to monitor their long-term survival are needed to corroborate this.

For dab we observed 'wounds' in all treatments with an incidence of 7% in the sampled fish. Without exception these wounds were skin ulcerations which are prevalent in wild common dab (Vercauteren et al., 2018) which we consider to be unrelated to the current experimental treatments.

Similar to our observations on fish, direct mortality among the tested invertebrate species was low and ranged from 0% to 10% across treatments. Our observations correspond with the findings of Bergman et al. (1992) who studied direct mortality among benthic invertebrates escaping through 90 mm meshes of tickler chain beam trawls. Bergman et al. (1992) collected specimens in narrow meshed cover nets and found direct survival of brittle star and swimming crabs to be nearly 100%. In our study, direct mortality did not differ between the pulse trawl track and control treatments. To what extent this low direct mortality is indicative for the long-term survival is unknown because unlike the fish in this study, we have no information on the long-term survival in relation to the condition of individual invertebrates. Dedicated survival studies similar to those described for fish are required to establish long-term survival.

Condition of flying crabs and brittle stars was assessed by checking individuals for crushed carapaces (crabs) or discs (brittle stars) and for (partly) missing limbs. None of the assessed brittle stars and only a few flying crabs were found to be crushed, which indicates that the mechanical impacts of the passing pulse trawl and capture by the sampling trawl are probably limited. Missing limbs were observed across treatments in both invertebrate species but no difference between the pulse trawl track and control treatments were detected. Since we did not determine whether the loss of a limb was recent, we cannot attribute loss of limbs to impacts of the pulse or sampling trawl nor exclude such impacts. With an incidence of 65% to 90% across treatments the majority of the brittle stars showed some degree of damage. This may be a reflection of the sensitivity of this invertebrate to the mechanical impacts of a trawl. Although long-term effects of loss of limbs is unknown, it is clear that the impact of a pulse trawl does not cause additional mortality due to loss of limbs compared to other trawls with comparable mechanical impact.

The abdominal muscle in brown shrimp is specialized in powerful contractions enabling shrimp to jump backwards and has been shown to fatigue quickly (Hagerman & Szaniawska, 1986). Our observation that irrespective of the treatment, the jump reflex was absent in almost half of the tested brown shrimp, may indicate fatigue of the abdominal muscle and thus a compromised escape mechanism in these specimens. This is an important result, as it directly addresses one of the concerns raised by small-scale fishers, who are afraid that the combination of the pulse trawl and a ground rope would harm shrimp instead of catching shrimp. However, absence of the jump-reflex cannot be attributed to exposure to electrical stimulation because no treatment effect was detected; it occurred in equally high numbers among shrimp sampled from the pulse trawl track as the unfished control areas. It seems therefore more likely that it is an effect of exhaustion due to the catch process by the sampling trawl.

Condition of hermit crabs was assessed by checking individuals for non-specified, visually detectable damage while being in or out of its shell. All assessed hermits crabs were found to be undamaged. This either suggests that hermit crabs are very resilient to the impacts inflicted by the passing pulse trawl and catching by the sampling trawl, or that our condition assessment criteria lack sensitivity to detect impacts by the pulse and sampling trawl.

Critical to the credibility of this study is the assurance that specimens were actually sampled from the pulse trawl tracks. Our underwater video observations revealed that during sampling tows the sampling trawl moved in and out of the pulse trawl track, confirming that part of the specimens were indeed sampled inside the pulse trawl tracks. Based on the analyses of the underwater video observations the area sampled inside the pulse trawl tracks was estimated to range from 43% to 94% of the total swept area among the nine sampling tows. Our binomial GLM modelling approach revealed that direct mortality estimates were not affected by the proportion of the pulse trawl track sampled. Treatment effects could consequently be tested for significance without taking into account that the area swept inside the pulse trawl track. The catches of marketable sole (>24 cm) of the pulse trawlers whilst making the pulse trawl tracks as recorded by the skippers were within the range of catch rates of other pulse trawlers fishing in the same area and the same week (**Supplementary Material, SM6**). This corroborates that the pulse stimulus was switched on during the experimental tows. It is well known that by switching off the pulse stimulus, the catch rate of sole drops by about 80% (Rijnsdorp et al., 2021).

The sampling trawl in this experiment was equipped with a modified ground rope to collect as much specimens from the seafloor as possible. It should be noted however that we probably sampled exclusively from the seafloor as is reflected by the species we sampled. Any biota residing in the seafloor did not appear in our samples and we therefore have no data on the effect of a pulse trawl on the infauna. The absence of infauna in our samples shows that pulse field exposure does not stimulate infauna to immediately emerge to the surface of the sediment.

The results of the field work in 2019 were shared with fishers through a report and article in the Dutch newspaper for the fisheries sector. After publication of the results, we saw a shift in the topics raised by small-scale fishers in the interviews and the second workshop. Instead of focusing on the scientific uncertainty surrounding the pulse trawl, fishers focused on management and political issues, such as the role of the Dutch government in stimulating pulse fisheries and alleged misuse of pulse techniques by Dutch fishers. The shift from knowledge related towards management and political concerns could be explained in several ways. First, the results of the first experiment showed no direct mortality of benthic organisms after a pulse trawler has passed. These first results, which were known to most fishers who participated in the interviews and second workshop, could already have influenced their perceptions of pulse fisheries. Second, the worries concerning direct mortality were mostly raised by English and French fishers, and might not have been the biggest concern of Dutch small-scale fishers from the start. However, in our research we put the focus on this topic, which might explain the interest of small-scale fishers in the direct mortality in the wake of the pulse during the first workshop. To understand the direct impact of the results of this study on perceptions of this particular topic, English and French fishers should be included in the study. Third, the engagement of fishers in research design and the interest in the concerns of fishers in general, for which there was space in the interviews and workshops, might have led to increased trust between fishers and researchers. By engaging stakeholders in research, trust in science and scientific advice can increase (Röckmann et al., 2015). Fishers value face-to-face contact (Gray et al., 2005) and trust between fishers and researchers is built through long-term relationships, regardless of the specific research topic (Ebel et al., 2018). Furthermore, collaborative learning processes and including lay expertise can advance the scientific understanding of the problem at hand (Röckmann et al., 2015). The shift from discussions on the credibility of the knowledge produced in pulse research towards more management related discussions might therefore be an indication that through engagement of fishers the credibility of the current study has increased. Coming back to the third explanation, the change in perceptions witnessed in this study might be less related to the absence of increased direct mortality of fish and benthic organisms in the wake of the pulse than to the participative approach taken by the researchers. As research in the environmental domain and especially in nature resource management fields such as fisheries often aim to address concerns raised by one or more stakeholder groups, we would advise to include these stakeholders in an earliest stage as possible in delineating the research question and developing the research design. Moreover, we recommend to keep them engaged throughout the research process, to enable research to be both relevant and credible to the people it matters to. Next to the interviews and workshops, stakeholder engagement in this study also included indispensable contributions of the three commercial fishing vessels to successfully conducting the field experiments. These demanded skill, dedication and commitment of skippers and crews. Especially positioning and keeping the sampling trawl inside the pulse trawl track was a major challenge for the skipper, to which he was committed to accomplish or he felt his reputation as a skipper would be tarnished. Clearly the high level of commitment of these stakeholders was indispensable to the success of the field experiments.

In conclusion, our study refutes the claim that pulse trawling would result in mass mortality among fish and invertebrate species. For all species tested, our field experiment did not find any support for direct mortality from the exposure to a pulse stimulus, consistent with the results of laboratory exposure experiments (review in ICES, 2020). Additionally, our study showed the importance of stakeholder engagement in problem-framing and research design, especially in the case of applied and politically sensitive research domains. By engaging stakeholders the credibility of our research improved, and we were able to identify other and underlying preoccupations regarding our research topic.

DATA AVAILABILITY STATEMENT

The data underlying this article will be shared on reasonable request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because although the study involves the sampling and handling of vertebrates, the study is not considered an animal experiment under the Dutch animal experimentation act.

AUTHOR CONTRIBUTIONS

Conceptualization: ES, PM, and SK; design and methodology: ES, PM, and SK; performing field experiments: ES and PM; Interviews and workshops: SK and PM. Collection of data: ES and PM; data analysis: ES and AR; writing original draft: ES, PM, SK, and AR; Writing – review and editing: ES, PB, SK, and AR. All authors contributed to the article and approved the submitted version.

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The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.907192/full#supplementary-material

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Deakin University, Australia

REVIEWED BY
Hannah Murphy,
Fisheries and Oceans Canada (DFO), Canada
Ming Sun,
Stony Brook University, United States

*CORRESPONDENCE
Matthew Damiano
mddamian@ncsu.edu

†These authors have contributed equally to this work

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Integrating information from semi-structured interviews into management strategy evaluation: A case study for Southeast United States marine fisheries

Matthew Damiano[1*], Bethany Wager[1†], Alex Rocco[1†], Kyle W. Shertzer[2†], Grant D. Murray[3†] and Jie Cao[1]

[1]Department of Applied Ecology, Center for Marine Sciences and Technology, North Carolina State University, Morehead City, NC, United States, [2]National Oceanic and Atmospheric Administration (NOAA) Beaufort Laboratory, Southeast Fisheries Science Center, Beaufort, NC, United States, [3]Duke University Marine Lab, Nicholas School of the Environment, Beaufort, NC, United States

Management strategy evaluation (MSE) has become a more common tool for engaging stakeholders in fisheries management, and stakeholder participation in MSE is increasingly recognized as a vital component of the process. The participation of stakeholders, specifically fishers, in MSE is of particular importance because they often possess intimate knowledge of the socio-ecological management system that MSE seeks to model. When the resources to conduct a "full" MSE with direct fisher involvement are unavailable, MSEs are sometimes conducted by desk-based analysts with no fisher engagement. We propose an intermediate framework in which information collected from semi-structured interviews is used to inform a "desk-based" MSE. We demonstrate that semi-structured interviews with commercial and recreational fishers can elicit some of the same kinds of information that fishers provide during direct participation in MSE. We conducted 30 semi-structured interviews with commercial and recreational fishers from the Southeast United States participating in either Atlantic cobia (*Rachycentron canadum*) or black sea bass (*Centropristis striata*) fisheries. We collected primarily qualitative and some quantitative information about preferred conceptual objectives and management measures, and how their fishing behavior has changed in response to past management action. Commercial fishers generally preferred conceptual objectives and management measures that align with traditional MSY-based fisheries management, while recreational fishers' responses were substantially more heterogeneous, indicating a more diverse range of desired objectives and preferred management measures. We synthesized this information to develop a suite of management procedures that employ a range of fishing mortality-based constant-catch harvest control rules and size-based management measures for simulation testing against preferred objectives by sector. We demonstrate that integrating information from semi-structured interviews with MSE in this way offers a cost-effective alternative intermediate approach to fisher participation in MSE when direct participation is not possible.

KEYWORDS

marine resource management, fishers' knowledge, management strategy evaluation, experiential knowledge, ecosystem approach management

Introduction

Management strategy evaluation (MSE) is an increasingly common tool for engaging stakeholders in fisheries management (Deith et al., 2021). MSE is a closed-loop simulation framework that seeks to model entire management scenarios. MSE typically includes an operating model (OM) to simulate population and fishery dynamics, an estimation model to determine stock status, i.e., an assessment or some simplification of the process, and an implementation model in which a management procedure is applied. Then the effects are projected forward in time (Punt et al., 2016; Ono et al., 2017). The primary goal of MSE is to identify management procedures that will achieve objectives in the long-term and are robust to uncertainty (Butterworth and Punt, 1999; Butterworth, 2007).

One of the key advantages of MSE is the ability to directly involve stakeholders in the development of management scenarios (Bunnefeld et al., 2011). Stakeholder participation in MSE is widely recognized as a vital component of the process (Bunnefeld et al., 2011; Feeney et al., 2019; Goethel et al., 2019; Deith et al., 2021). The degree of stakeholder participation is dependent on the timetable for completing the MSE and the format. MSEs can be conducted over multiple years as an iterative process in which stakeholders participate as part of a dedicated MSE group. Over several years, the group identifies conceptual objectives and uncertainties in the management system, works with scientists to operationalize those objectives, selects candidate management procedures for simulating testing, and engages in participatory modeling exercises to identify risks and tradeoffs by evaluating management procedures against objectives and over a range of uncertainties (Punt et al., 2016; Feeney et al., 2019; Goethel et al., 2019). We refer to these as "full MSEs" with "full" stakeholder participation. Examples include the OysterFutures workgroup who met nine times over two years for a Maryland eastern oyster (*Crassostrea virginica*) MSE (Goethel et al., 2019; Goelz et al., 2020), and the Management Strategy Advisory Board of the International Pacific Halibut commission who met twice a year during 2013-2020 to participate in MSE for pacific halibut (*Hippoglossus stenolepis*) (Branch, 2020). Full MSEs can also be conducted under truncated timetables in which stakeholder involvement in the MSE can be facilitated through a series of workshops designed to expedite the process, e.g., the Atlantic herring (*Clupea harengus*) MSE, which was conducted in just one year (Deroba et al., 2019). Stakeholder participation is a central aspect of what makes MSE effective (Dickey-Collas, 2014; Goethel et al., 2019). The participation of fishers is of particular importance because they often possess intimate knowledge related to uncertainties in the socio-ecological management system that MSE attempts to model, e.g., fishery operations, social and political dynamics, biology, ecology, and fine-scale spatial and seasonal processes (Neis et al., 1999; Crona, 2006; Wilson, 2006; Murray et al., 2006; Paterson, 2010).

However, MSE is a time and resource-intensive process, therefore many MSE tools or simulation frameworks for assessing tradeoffs are developed by analysts without fishers' involvement. These are colloquially referred to as "desk-based" MSEs. Semi-structured interviews are a common tool for eliciting qualitative and quantitative fishers' knowledge (Hind, 2015), and information obtained from semi-structured interviews has been used to inform, complement, improve, or directly integrate fishers' knowledge with stock assessment (Neis, 1992; Carruthers and Neis, 2011; Tesfamichael et al., 2014; Duplisea, 2017). This study began with the idea that there could be a 'middle ground' between full and desk-based MSEs in which semi-structured interviews are conducted during a desk-based MSE with stakeholders, specifically fishers, to address knowledge gaps related to conceptual management objectives, candidate management measures, fishing behavior, and other observations related to the management system when resource limitations preclude direct stakeholder participation.

In this paper, we present a case study in which we applied this intermediate MSE approach to two marine fisheries in the Southeast United States: the Southeast black sea bass (*Centropristis striata*) and Atlantic cobia (*Rachycentron canadum*) fisheries. Although commercial fishing remains the dominant source of global removals, regionally, recreational fishing can rival or exceed commercial removals (Coleman et al., 2004; Arlinghaus et al., 2019). In the Southeast United States (SE US), recreational fishing is the dominant source of fishing mortality (Shertzer et al., 2019). We chose these two fisheries for our case study to compare interview results and integration with MSE across fisheries with different degrees of recreational use. The overarching goal of the article is to describe how information obtained from semi-structured interviews conducted with commercial and recreational fishers was used to inform a MSE tool designed to evaluate tradeoffs between potentially competing commercial and recreational fishing objectives. We present results from interviews with commercial fishermen and recreational anglers in each fishery and discuss how information obtained from interviews was used to set up management scenarios for future testing of the MSE tool.

Methods

Case study background

Currently, both fisheries' recreational component is made up of private recreational anglers and the for-hire recreational fleet, i.e., private charter vessels and headboats, and there exists at least one commercial fishery (SEDAR, 2018; SEDAR, 2020). The management procedure used to set total allowable catch (TAC) for both black sea bass and cobia fisheries is a constant catch harvest control rule (HCR) based on a fishing mortality (F) reference point and is regulated using management tools such as minimum size limits, vessel/trip limits, bag limits and seasonal closures (SEDAR, 2018; SEDAR, 2020). Southeast black sea bass fisheries are managed using an 11-inch size limit and vessel limits in the commercial sector, and a 13-inch size limit and combination of bag limits and vessel trip limits for the recreational sector, respectively (SEDAR, 2018). The TAC for black sea bass is allocated nearly equally (50-50) between commercial and recreational sectors, but in recent years, commercial fisheries have not attained their allocation, recreational fishing, primarily from private angling, has become the dominant source of mortality and the magnitude of dead discarded fish from the recreational sectors has greatly increased (Rudershausen et al., 2014; SEDAR, 2018). The Southeast Atlantic cobia commercial fishery, an incidental bycatch fishery, is managed using a 36-inch size limit and vessel limits, while the recreational fishery is also managed using a 36-inch size limit and bag limit (SEDAR, 2020). As of the 2019 stock assessment, the commercial fleet is allocated less than 10% of the TAC, and the recreational fleets over 90% (SEDAR, 2020). During the past 10 years however, the recreational fleets have landed more than 95% of the cobia TAC (SEDAR, 2020).

Research design

We conducted interviews with commercial and recreational fishers from the Southeast US to learn what they valued about the fishery they participated in, their desired fishery objectives, preference for future management actions, and how past management actions had affected their fishing behavior. Interviews were conducted using a semi-structured interview instrument (Appendix I), meaning that interviewees could introduce other topics, including suggesting alternative goals and management actions not included in the instrument (Patton, 1990; Murray et al., 2010; Carruthers and Neis, 2011). The goal of the interviews was to obtain information related to the values driving broad-scale conceptual fishery objectives (Andrews et al., 2021), learn fishers' preferred management measures, and collect information on fisher behavior that could inform the development of the MSE tool. We designed the interview instrument to include questions salient to the history of management in each fishery and described in the case study background.

We conducted a total of 30 interviews between May and August of 2020 in two phases due to a difference in sampling methods. During the first phase, 14 interviews were conducted during May with five commercial fishers who fished for black sea bass in the commercial pot fishery, one commercial fisher who caught cobia in seasonal commercial bycatch fisheries, six recreational fishers for black sea bass, of whom five identified as private anglers and one as a private charter, two recreational fishers for cobia, of whom one identified as a private angler and the other a private charter and headboat captain (Table 1). We selected initial interview participants based on the number of years of participation in each fishery with preference for those who had fished for 10 or more years, and additional participants were identified using snowball sampling by asking interviewees to recommend other commercial fishermen or recreational

TABLE 1 Interview participation by sector (recreational or commercial) and species (black sea bass or cobia) by phase (1 or 2).

Phase I Participants	Number of Phase I participants	Phase II Participants	Number of Phase II participants
Recreational black sea bass	6	Recreational black sea bass	10
Recreational cobia	2	Recreational cobia	6
Commercial black sea bass	5	Commercial black sea bass	
Commercial cobia	1	Commercial cobia	

anglers (Murray et al., 2006). The second phase occurred during June-August, in which an additional 16 interviews were conducted with 16 recreational fishers, all of whom identified as private anglers: ten who fished for black sea bass and six who fished for cobia (Table 1). Participants during the second phase were selected from the National Oceanic and Atmospheric Administration's (NOAA) Marine Recreational Information Program (MRIP) database using a combination of stratified random sampling (by state within the Southeast US) and systematic random sampling of license holders who had renewed their license for 10 or more years.

Interviews

Our study occurred during the height of the COVID-19 pandemic, therefore all participants were contacted and interviewed *via* telephone. Once contacted, fishers were read a script that described the purpose of the study and how information collected during interviews would be used (Appendix II). For those who declined to participate, we thanked them for their time and ended the call. For those who chose to participate, we assigned them a code referring to the species they fished for, i.e., "BSB" for black sea bass or "COB" for cobia, the sector they fished in, i.e., "CO" for commercial and "RE" for recreational (includes private and for-hire sectors), and their number in the order of interviews conducted. Detailed notes, including participant quotes, were made during each call. We attempted to call from university-owned computers using Cisco Jabber to call from a North Carolina State University (NCSU) number and record calls. However, calls were flagged as spam on cell phones, therefore all calls were made using personal phones and were not recorded. As such, we made transcriptions whenever possible during calls, and kept detailed notes. Interviews ranged from approximately 20 minutes to 1.5 hours. All participants were anonymously referred to in terms of their target species and sector in our results. All data collection and analyses involving human subjects were conducted in compliance with NCSU's Human Subjects Independent Review Board.

Integration with MSE

We synthesized the information obtained from the semi-structured interviews to be integrated with an MSE tool. The MSE tool consists of an OM connected with an assessment model, and an implementation/projection model. The OM was conditioned to reflect the estimates of population and fishery dynamics from the most recent black sea bass and cobia stock assessments (SEDAR, 2018; SEDAR, 2020), and written in R statistical software (R Core Team, 2022). The assessment model is an integrated statistical catch-at-length model developed by Cao et al. (2017) for the Gulf of Maine Northern Shrimp (*Pandalus borealis*) population in AD Model Builder (Fournier et al., 2012); it is a forward-projecting assessment that applies a growth transition matrix to the fish (or shellfish) population dynamics to model the probability of fish transitioning from one length bin to the next (Chen et al., 2003). The implementation/projection model is an extension of the OM that simulates the population forward in time three years, then a stock assessment is conducted to model the real-world assessment process, then implementation/projection model applies reference points estimated from the assessment to the population to simulate the implementation of management procedures, and the process is repeated. This forms the complete MSE simulation loop that models the entire management scenario. We chose a size-structured framework because most marine stocks in the Southeast US are managed using regulations that are size-based and avoids the need for age-length conversion which introduces additional uncertainty into assessment model estimates (Quinn and Deriso, 1999; Cao et al., 2017).

We emphasize that the purpose of this study is not to present the MSE model in full or its results, but rather to demonstrate the ways that semi-structured interviews can be integrated with the framework itself. Integration with the framework described above was accomplished by synthesizing the interview results to determine the conceptual objectives of commercial and recreational fishers in black sea bass and cobia fisheries against which management procedures are evaluated and determine the management procedures for simulation testing. We used interview responses related to changes in fishing behavior to determine what kind of HCR was necessary to capture the functional response of the commercial and recreational fleets to changes in the population dynamics within the implementation/projection model. We determined management procedures for implementation and simulation testing by reconciling the HCR with preferred management measures, i.e., finer-scale tools such as sector allocation and minimum size limits. We also used responses to determine performance metrics: the measurements that are required to determine whether objectives were met by the management procedure (Plagányi et al., 2014; Grüss et al., 2016).

Results

Responses to interview questions

Results are organized in the following order: summaries of responses from general recreational fishers (if applicable), followed by summaries specific to recreational black sea bass and cobia fishers, followed by general commercial fishers (if applicable), followed by summaries specific to commercial black sea bass and cobia fishers.

In response to Question 1, which asked what was most important to participants about the fishery, most recreational fishers voiced that sustainability/conservation and the ability to keep fishing seasons open were of utmost importance to them (Table 2). Some recreational fishers discussed their concerns: those who fished for cobia specifically cited a reduction in the availability of legal-sized fish and importance of larger fish to the fishery (Table 2). Recreational black sea bass fishers also identified catching larger fish as being of great importance (Table 2), and identified maintaining clean water, fishery sustainability, availability, and equitable harvest between recreational and commercial sectors as features important to them (Table 2). Commercial both black sea bass and cobia fishers described fishing as a business and necessity for their livelihood. In this sense, they summarized what they valued about the fishery in terms of how it fit into their business portfolio. However, some commercial black sea bass fishers expressed enthusiasm for eating black sea bass, and the sustainability of the fishery (Table 2).

Question 2 asked participants to choose three conceptual objectives from a list of six that we provided: A) "Catching the greatest number of pounds," B) "Catching the greatest number of fish," C) "Catching the largest size fish," D) "Maximizing the length of the season," E) "Conservation of the resource," and E) "Increased access or opportunity within the fishery," and rank each as their first, second and third most-preferred. All participants were encouraged to provide any other objectives they thought were missing and rank them if desired. Responses to Question 2 provided quantitative summaries of objective prioritization for commercial and recreational fisheries by species (Figure 1). We note that not all participants chose to rank objectives, providing qualitative answers instead. Recreational black sea bass fishers ranked "catching the largest fish," and "maximizing the length of the season" second and most frequently, each with n = 4, and "conservation of the resource" and "increased access or opportunity [within the fishery]" third, each with n = 4; another also suggested reducing recreational black sea bass discards as an objective but did not rank it. The recreational black sea bass fisher who identified as a charter captain explicitly suggested the sustainability and optimization of yield as their top-ranked objective. Recreational cobia fishers ranked "maximizing the length of the season" first with n = 5, and also second with n = 4, and "catching the greatest number of fish" third and most frequently with n = 6; the fisher who identified as a charter and headboat captain suggested "consistency of success" as an equally top-ranked objective to "maximize length of the season," referring to a combination of having enough days to fish and enough fish available to be caught. Commercial black sea bass fishers consistently ranked "catching the greatest number of pounds" first (n = 3), followed by "catching the greatest number of fish" and "increased access or opportunity [within the fishery]" (n = 2), and nearly all options excluding "catching the largest fish" were ranked third by at least one participant (n = 1). One commercial black sea bass fisher suggested that one objective should be reducing mortality from recreational discarding of black sea bass. The commercial cobia fisher ranked "increased access or opportunity [within the fishery]" first, "maximizing the length of the season" second, and "catching the greatest number of pounds" third. At least one recreational black sea bass fisher ranked each objective first, but "catching the greatest number of pounds" received the highest rank (n = 3).

Question 3 asked participants to choose three management measures from a list of six that we provided: A) "Changing the vessel/trip or bag limits," B) "Changing the size limits," C) "Changing the size limits to a slot limit," D) "Seasonal closures," E) "In-season adjustments to vessel/trip or bag limits," and E) "Changing catch limit allocation among sectors," and rank them as their first, second, and third most-preferred. Interviewers encouraged participants to list any additional management measures they preferred and rank them as desired. Question 3 provided quantitative summaries of management measures preference for commercial and recreational fisheries by species (Figure 2). Recreational black sea bass fishers ranked "change size limits" first and most frequently (n = 6), "change size limit to a slot

TABLE 2 Responses to interview Question 1 by sector (recreational or commercial) and species (black sea bass or cobia).

Recreational Black Sea Bass	Recreational Cobia	Commercial Black Sea Bass	Commercial Cobia
Enjoyment/being able to get outdoors/ Food	Having year-round availability of legal fish	Sustainability/keeping it open	Important seasonal bycatch, supplement to other fisheries
Availability during cooler months	Uniqueness of the fish and availability	Important winter fishery	
Regularly catch fish/large individuals	Maintaining healthy stock of larger fish	Added source of income/family business	
Maintain clear water		Enjoy eating them	
Sustainability/legitimate season (keep it open)			
Equitable harvest			

Question 1 asks fishers to tell the interviewer what they value most about the fishery.

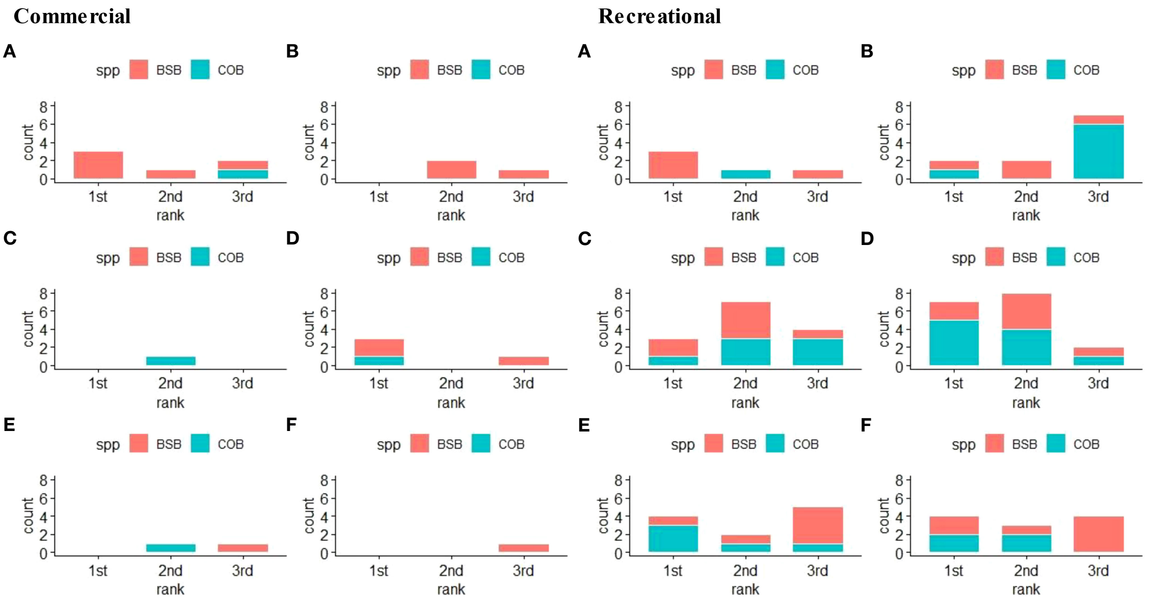

FIGURE 1
Tallied responses to Interview Question 2 which asks fishers to identify their top three conceptual objectives from a list provided by the interviewer. Conceptual objectives were ranked 1st, 2nd, or 3rd by commercial fishers (left) and recreational fishers (right) for black sea bass (red) and cobia (blue). Options for ranking were **(A)** "Catching the greatest number of pounds," **(B)** "Catching the greatest number of fish," **(C)** "Catching the largest size fish," **(D)** "Maximizing the length of the season," **(E)** "Conservation of the resource," and **(F)** "Increased access or opportunity within the fishery.".

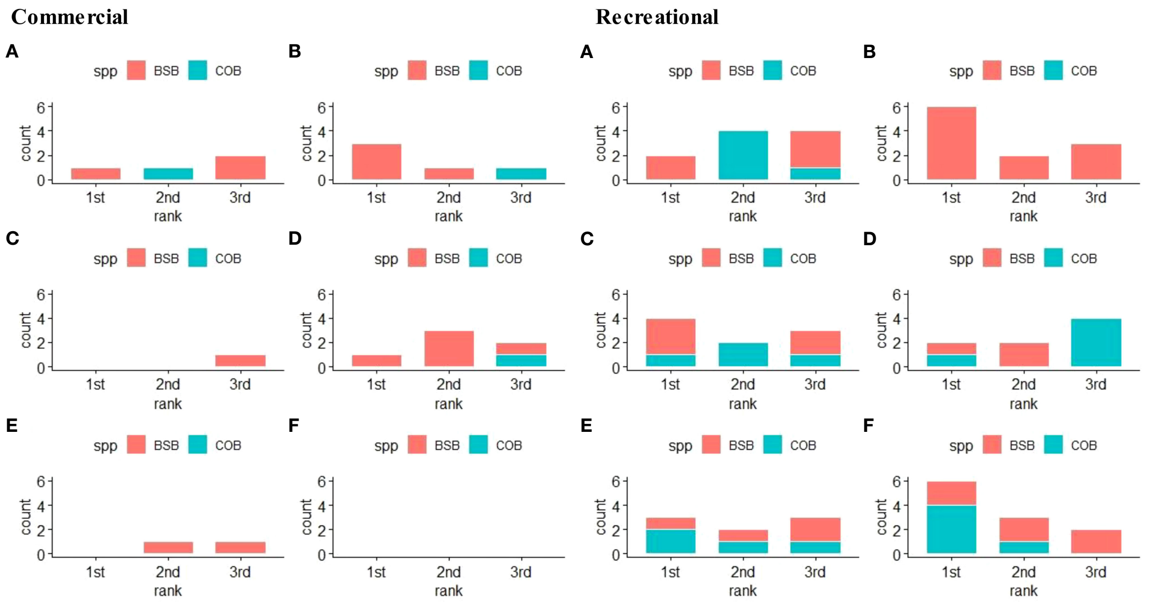

FIGURE 2
Tallied responses to Interview Question 3 which asks fishers to identify their top three management measures from a list provided by the interviewer. Management measures were ranked 1st, 2nd, or 3rd by commercial fishers (left) and recreational fishers (right) for black sea bass (red) and cobia (blue). Options for ranking were **(A)** "Changing the vessel/trip or bag limits," **(B)** "Changing the size limits," **(C)** "Changing the size limits to a slot limit," **(D)** "Seasonal closures," **(E)** "In-season adjustments to vessel/trip or bag limits," and **(F)** "Changing catch limit allocation among sectors.".

limit" second (n = 5), and "change vessel/trip/bag limits," "change size limits," and "seasonal closures" third, each with n = 3. Recreational cobia fishers generally ranked "change allocation among sectors" first (n = 4), "change vessel/trip/bag limits" second (n = 4), "change vessel/trip/bag limits," "change size limit to a slot limit," and "in-season adjustments to limits" third, each with n = 1. Commercial fishers consistently ranked "changing the size limits" first (n = 3), "seasonal closures" second (n = 3), and "changing vessel/trip/bag limits" third (n = 2). The commercial cobia fisher did not choose to rank any of the six measures first, ranked "changing vessel/trip/bag limits" second, and both "changing size limits" and "seasonal closures" third. No additional management measures were proposed.

Question 4 asked participants to describe any changes in their fishing behavior in response to past vessel or trip limits, depending on whether they were a commercial or recreational fisher. Some recreational fishers expressed hesitation when answering this question. They often answered that they followed the regulations, threw small fish back, or did not fish during a closure. Other recreational fishers reported that they fished less, targeted other species, or promoted more catch and release when trip limits were reduced. Some also expressed that this caused them to fish less offshore. A recreational cobia fisher reported that, "I will not run offshore and justify the fishing if I can't come home with enough fish." Most recreational fishers however stated that it caused no change to their behavior, that they followed the regulations, and kept fewer fish. Commercial fishers generally cited switching up gear, fishing new areas, or targeting different species when past changes to vessel limits were implemented. Commercial black sea bass and cobia fishers reported having to change some aspect of their business operations when vessel limits were reduced; for example, the commercial cobia fisher described changing the business model to focus on fewer catches of higher quality meat, stating that "you need to be able to make it on less and be smart about how to go about it, " and one commercial black sea bass fisher shared that they, "had to work to maximize profits. Used to have two guys working on the boat, now we have only one. I've cut corners on everything I can. Learned to maximize bait and groceries. Pay less a percent to the crew that I used to. Been taking off things off expenses, taking tackle out of expenses." Another commercial black sea bass fisher commented on their frustration with past changes to trip limits, "We've gone through changes and every year we go through a different change. The problem with trip limits is they're not very enforceable. Can tell you from the commercial aspect, if commercial boats were required to carry VMS (vessel monitoring system), if they were required to have that, then it would be more enforceable … all they can do is look at your fish box, might catch a red snapper violation, but can only gauge trip limit when catch is offloaded."

Question 5 asked participants to describe any changes in their fishing behavior in response to past changes to size limits in their respective sector. Recreational fisher responses varied. Some expressed that the greater size limits caused them to fish more to catch their limit, and others stated that they, "just didn't focus on black sea bass as much. But if I'm catching 9/10 under size, I could be going after something else, I know I can catch." Some recreational fishers expressed concern about handling more fish and increased discard mortality. One cobia angler stated that they "gotta handle more fish, so there's more opportunity for injury to fish and angler." A recreational cobia fisher said that the changes in size limits were confusing, especially near state lines, or that they were disappointed and did not understand the rationale behind differing size limits among sectors. Slot limits, which were suggested as a potential management measure in Question 3, came up in discussions with both commercial and recreational fishers in response to this question. Most commercial fishers were against a slot limit because it would forgo yield. Recreational fishers were generally more receptive to slot limits. Some stated that they thought it would enable them to focus on retaining larger fish (within the legal range), with one angler stating that "if the science supports, I support it". Others took the opportunity to say, "no slot limits." Commercial fishers generally reported that they let more fish go, changed gear to accommodate the new size limits, or had no change. One commercial black sea bass fisher had repeatedly expressed that more restrictions would have negative effects for commercial fishermen; they said, "fight them [size limit changes] when they come up and they're proposed. Fight them and try to stop them. No size limit when I started."

Question 6 asked participants to describe any changes in their fishing behavior in response to past seasonal closures. Recreational and commercial fishers for both black sea bass and cobia cited fishing less, targeting other species, or not fishing at all. Some recreational fishers stated that they were disappointed when closures occurred but noted that their livelihood was not at stake; others responded by saying they simply followed the regulations. However, one recreational cobia fisher reported that, "If I catch a cobia and it's out of season, he goes in the box." One commercial black sea bass fisher described how they switched fisheries entirely in response to closures: "I gill netted instead of black sea bass fishing. Now I can black sea bass fish all year. I luckily can fish here in the wintertime for black sea bass now though since closures have not happened in a while." Commercial black sea bass fishers also expressed strong opposition to seasonal closures, stating that they wanted to avoid them at all costs.

Synthesis of interview results for integration with MSE

Several responses to Question 1 overlapped with ranked conceptual objectives listed in Question 2, therefore we synthesized responses to Questions 1 and 2 to identify a preliminary set of conceptual objectives and performance metrics for evaluation in the MSEs (Table 3). Additionally, for responses to Questions 2 and 3, we prioritized objectives and management measures by the number of times they were selected (highest n) regardless of rank. For recreational black sea bass fishers, "catching the most pounds" was the number-one ranked objective in Question 2, however, "catching the largest fish" and "maximize the length of the season" were the most frequent responses. Given that recreational black sea bass fisher responses to Question 1 included "regularly catch large individuals/fish," "availability during cooler months," and "sustainability/legitimate season (keep it open)" (Table 2) suggest that the number-two ranked objectives may be of greater importance. Consequently, we chose all three as recreational fishing objectives for evaluation. For performance metrics, we chose to measure changes in the median of recreational catch, the proportion of legal-sized fish in the estimated population, and the exploitation rate as a proxy for season length (Bohaboy et al., 2022). Reducing discards was an additional objective that both a commercial and recreational fisher cited but did not rank in response to Question 2. Given the recent increase in discard mortality in the most recent assessment for black sea bass (SEDAR, 2018), we included this as an additional conceptual objective for both sectors and chose to measure the magnitude of discards as a performance metric. For commercial black sea bass fishers, "catching the greatest number of pounds" was the most common and number one-ranked conceptual objective in response to Question 2, and responses to Question 1 included "added source of income/family business;" therefore we selected "catching the greatest number of pounds" as the primary commercial fishing objective for the black sea bass MSE. However, commercial catches of black sea bass have consistently been lower than the proportion of the total allowable catch allocated to the sector (SEDAR, 2018), suggesting that attaining the TAC may not be a sufficiently realistic performance metric, therefore we chose to examine changes in the median of commercial catch. For the commercial and recreational cobia fishers, "maximize length of the season" was the number one-ranked objective in Question 2, therefore this was selected as the primary commercial and recreational fishing objective for the cobia MSE. Additionally, we selected "catching the largest fish," recreational cobia anglers' number two-ranked objective, as an additional recreational fishing objective. We used the same performance metrics identified for use in the black sea bass MSE. We chose exploitation rates as a performance metric for both commercial and recreational season length, and the proportion of legal-sized fish in the population, respectively. Conservation of the resource was not the number one-ranked objective in responses to Question 2 for any fishery or sector, however, recreational black sea bass fishers consistently ranked it second (Figure 2), and recreational fishers' responses to Question 1 suggested it was a high priority, e.g., "maintaining healthy stock of larger fish," "sustainability/keeping it open," and "sustainability/legitimate season (keep it open)" (Table 2). We interpreted these responses to mean that conservation, in the sense of keeping the fishery open in the long-term, was an important objective regardless of fishery and sector, therefore, we translated this into a conceptual objective designed to avoid fishery closures (SEDAR, 2018; SEDAR, 2020): maintain spawning stock biomass above the minimum stock size threshold (Table 3).

We synthesized responses from all questions to determine what HCR and management measures should comprise management procedures for implementation and simulation testing. In response to Question 3, "changing the size limit" was the highest ranked management measure among commercial fishermen and recreational anglers for black sea bass in response to Question 2 (Figure 2), and the reduction of discards was cited as a concern by both a commercial fisherman and recreational angler in response to Question 2. Additionally, "equitable harvest" was mentioned in response to Question 1 by recreational anglers for black sea bass (Table 2). Therefore, due to concerns over discards and the inequity in size limits across sectors, we chose to explore an 11-inch minimum size limit in both commercial and recreational fisheries, and a decrease in

TABLE 3 Conceptual objectives and performance metrics derived from participants' responses to interview questions.

Type of Objective	Species	Conceptual Objective	Performance Metric
Commercial Fishing	Black sea bass	Catch the greatest number of pounds	Changes in median of average catch
Recreational	Black sea bass	Catch the greatest number of pounds	Changes in the median of average catch
Recreational	Black sea bass	Catch the largest fish	Proportion of legal-sized fish in the population
Recreational	Black sea bass	Maximize the length of the season	Changes in exploitation rates as a proxy for season length
Recreational and Commercial Fishing	Black sea bass	Reduce discards	Magnitude of discards
Commercial Fishing	Cobia	Maximize the length of the season	Changes in exploitation rates as a proxy for season length
Recreational Fishing	Cobia	Maximize the length of the season	Changes in exploitation rates as a proxy for season length
Recreational Fishing	Cobia	Catch the largest fish	Proportion of legal-sized fish in the population
Conservation	Black sea bass/Cobia	Maintain SSB above MSST	% of simulations in which SSB remains above MSST

dead recreational discards by half (Table 3). Recreational cobia fishers ranked "changing allocation among sectors" as their most preferred management measure (Figure 2). We chose not to explore any management measures that would change the allocation further in favor of the recreational sector given the magnitude of the TAC landed by the recreational fleets. In responses to Questions 1 and 4, commercial fishermen for both black sea bass and cobia spoke of the value of the fishery in terms of economic importance and changing their business model or operations to maximize profits in response to management action (Table 2). This information is aligned with the prioritization of yield-based conceptual fishery objectives and is consistent with the aim of traditional maximum sustainable yield (MSY)-based management (Kell and Fromentin, 2007). Therefore, we selected a range of status quo HCRs that are explored in current stock assessments, specifically variations of the F-based reference point that will achieve MSY, e.g., F_{MSY} and fractions of F_{MSY}, including those with a P^* management buffer, for testing in both MSEs. Additionally, because the majority of participants cited no change to fishing behavior in response to changes to vessel/trip and bag limits, changes to minimum size limits, or seasonal closures, we only included the constant catch HCR in the implementation/projection model, as opposed to an HCR that includes a functional response in fishing to stock status (Berger et al., 2012).

We reconciled F-based constant catch HCRs with preferred management measures to develop a list of management procedures for implementation (Table 4). For black sea bass, the management procedures included a constant catch at F_{MSY} with no changes to minimum size limits or allocation by sector, 75% F_{MSY} with no changes to minimum size limits or allocation by sector, F_{MSY} with P^* = 0.4 with no changes to minimum size limits or allocation by sector, F_{MSY} with P^* = 0.38 with no changes to minimum size limits or allocation by sector, F_{MSY} with P^* = 0.4 with no changes to minimum size limits, but 50% less catch allocated to discard to simulate improved discard practices ergo higher black sea bass discard survival, and F_{MSY} with P^* = 0.4 with 11-inch minimum size limits for both recreational and commercial sectors and no change to allocation by sector (Table 4). F_{MSY} with P^* = 0.38 was included in the last two because it was the preferred alternative implemented for managing Southeast black sea bass in 2018 (Chip Collier, SAFMC, personal communication). For cobia, we chose to test the same four black sea bass management procedures without changes to size limits or allocation (Table 4). We chose F_{MSY}, 75% F_{MSY} and F_{MSY} with P^* = 0.4 because these are all management procedures used for projections in the most recent stock assessments (SEDAR, 2018; SEDAR, 2020).

Discussion

Using information obtained from semi-structured interviews with stakeholders, we were able to identify conceptual objectives and preferred management measures, and develop candidate management procedures for implementation and simulation testing; these constitute several elements of the MSE participatory modeling framework outlined by Goethel et al. (2019), and represent several key features of stakeholder engagement in MSE regardless of timetable (Punt

TABLE 4 Management procedures by species: black sea bass (BSB) and cobia (COB).

Management procedure	Species	Description/notes
F_{msy}	Black sea bass	Constant catch, no change to status quo minimum size limits
$75\%F_{msy}$	Black sea bass	Constant catch, no change to status quo minimum size limits
F_{msy} with P* = 0.4	Black sea bass	Constant catch, P* = 0.4 is approx. 92% F_{msy}
F_{msy} with P* = 0.38	Black sea bas	Constant catch, 13-inch size limit (rec), 11-inch size limit (comm) P* = 0.38 is approx. 94% F_{msy}; currently applied
F_{msy} with P* = 0.38 and 50% reduction in discard F	Black sea bass	Same as above with discard mortality reduced by 50% simulating improved discard practice
F_{msy} with P* = 0.38 and 11-inch recreational minimum size limit	Black sea bass	Constant catch with selectivity changed to reflect 11-inch minimum size limit in recreational fishery
F_{msy}	Cobia	Constant catch, 36-inch size limit; currently applied
$75\%F_{msy}$	Cobia	Constant catch, no change to status quo minimum size limits
F_{msy} with P* = 0.4	Cobia	Constant catch, P* = 0.4 is approx. 92% F_{msy}, no change to size limit
F_{msy} with P* = 0.38	Cobia	Constant catch, P* = 0.38 is approx. 94% F_{msy}; currently applied

P* is a management buffer; P* = 0.40 is approximately $92\%F_{msy}$ and 0.38 is approximately $94\%F_{msy}$. Those management procedures that are currently applied are noted as such in the description/notes.

et al., 2016; Deroba et al., 2019; Feeney et al., 2019). Our study demonstrates that conducting semi-structured interviews with stakeholders, specifically commercial fishermen and recreational anglers, in tandem with MSE tool development is a viable intermediate approach to a full MSE when direct stakeholder participation in MSE is not feasible.

Our study was not without some shortcomings. Without iterative stakeholder participation and feedback, we had to translate information obtained from interview responses into information that could be used in the MSE tool. The compartmentalization and distillation of information obtained from fishers is an ongoing concern in resource management (Holm, 2003) and who is doing the translating, and how the information is put to use by resource managers and scientists matters, therefore we must look critically at the translation process (Murray et al., 2005). Our participants chosen during the first phase was largely based on snowball sampling, however, most participants were recreational fishers who were chosen using a statistical sampling framework during Phase II. Most landings in Southeast marine fisheries come from recreational fishing (Shertzer et al., 2019), therefore we believe our approach was equitable. Another challenge in integrating experiential knowledge with quantitative frameworks is that it requires a process designed to receive it (Nadasdy, 1999; Stephenson et al. 2016; Steins et al., 2020); the design of our MSE tool and initial testing precluded the exploration of certain management scenarios that could have been developed from interview responses. For example, recreational black sea bass anglers ranked "changing the size limit to a slot limit" as their second most-preferred management procedure in Question 3 (Figure 2), and slot limits were the subject of much discussion in response to Question 5 (see Results). During initial testing of the MSE tool, we modified fishery selectivity in the OMs and implementation/projection model to reflect the implementation of a slot limit but could not obtain convergent model results. Similarly, although "seasonal closures" was the third most-preferred management procedure for both recreational black sea bass and cobia anglers (Figure 2), this conflicted with our goal of conditioning the OMs to reflect the most recent stock assessment estimates for black sea bass and cobia, which used non-seasonal models (SEDAR, 2018; SEDAR, 2020). We also acknowledge some sampling bias. In choosing fishers who have participated in the black sea bass and cobia fisheries for 10 or more years, we exclude those who may have exited either fishery due to past management actions. By selecting participants with long histories of fishing however, we may avoid the 'shifting baseline syndrome' sometimes associated with newer entrants to the fishery whose experience with fisheries management may be limited (Murray et al., 2010). We also acknowledge a heavy skew toward private anglers in terms of recreational fisher participation in interviews. Charter and headboat operations are an important component of recreational fishing economies in the Southeast US, and the captains, crew and clients are likely to have different motivations and perspectives concerning each fishery. Moreover, for black sea bass, private angling comprises the greatest proportion of landings and fishing mortality (SEDAR, 2018). For cobia, landings data and fishing mortality are aggregated by general commercial and recreational fleets (SEDAR, 2020), but MRIP catch estimates suggest that private angling and charter boats are equally responsible for the majority of fishing mortality in the Southeast US (National Marine Fisheries Service Fisheries Statistics Division, personal communication). Additionally, we focused on fishermen participating in the commercial pot fishery for black sea bass because it is the dominant source of fishing mortality in the commercial sector (SEDAR, 2018). This introduces a bias toward views of the commercial black sea bass pot fishery in commercial black sea bass responses. However, few fishers attended SEDAR, 2018, and those that did were participants in the commercial pot fishery.

One of the key features of MSE is the ability to identify tradeoffs associated with each management procedure (Bunnefeld et al., 2011; Punt et al., 2016). Many of the management procedures chosen for simulation testing based on the interview results were MSY-based, which have often failed to meet recreational objectives (Miller et al., 2010; Ihde et al., 2011). Recreational fisheries remain the dominant source of fishing mortality in the Southeast US (Shertzer et al., 2019), therefore, it is vital to engage with fishery stakeholders, specifically those from recreational sectors, to determine where those tradeoffs may occur. New intermediate approaches to engaging stakeholders and utilizing their data in MSE are being pioneered to determine whether management strategies meet recreational objectives (Bellquist et al., 2022). Although labor-intensive, our study represents a cost-effective alternative intermediate framework for stakeholder engagement in MSE. We anticipate that these approaches will become increasingly necessary as recreational fisheries outgrow commercial fisheries (Arlinghaus et al., 2019) and the cost of government implementation of MSE remains high (Aranda & Motos, 2006).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by North Carolina State University Independent

Review Board. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

MD is the first author for this work. JC is the senior author. All other authors shared an equal contribution as second authors. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1063260/full#supplementary-material

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EDITED BY
Steven Mackinson,
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REVIEWED BY
Anne-Marie Svoboda,
Ministry of Agriculture Nature and Food Quality, Netherlands
Marije Siemensma,
Marine Science &Communication, Netherlands

*CORRESPONDENCE
Justine Réveillas
justine.reveillas@gmail.com

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Integrating fishers' knowledge contributions in Marine Science to tackle bycatch in the Bay of Biscay

Cosma Cazé[1,2], Justine Réveillas[1,2*], Anatole Danto[1,2] and Camille Mazé[1,2]

[1]UMR 7266 LIENSs, Littoral Environnement et Sociétés, Centre National de la Recherche Scientifique, Université de La Rochelle, La Rochelle, France, [2]Apolimer international research network, Institut des sciences humaines et sociales, Centre National de la Recherche Scientifique, La Rochelle, France

The issue of bycatch is raising considerable political, mediatic and scientific attention. Bycatch is one of the main causes of at-sea mortality for small cetacean species and for seabirds. Scientists are raising alerts regarding the potential effects on the structure of the ecosystem, increasingly aiming for research-action. Decision-makers are facing a political trade-off, with increasing pressure from the European Commission and international nongovernmental organizations to implement mitigation measures such as space-time closure of the fisheries, which could present a risk of altering the well-being of the fishing industry in the short-term. The process of co-creation of knowledge on bycatch is key to understand better the fishers-species interactions and to develop regulations that are adapted to local specificities, towards an adaptive and inclusive socio-ecosystem-based management of the fisheries. But the knowledge co-creation process is hindered by tensions between the interests of stakeholders, the climate of mistrust, dense media coverage and power asymmetries between actors. In parallel, the fast rate of biodiversity degradation is calling for the rapid development of regulations. Understanding the complex system dynamics highlighted by these conflicts requires an analysis of the socio-political dimension of the interactions between fisheries and marine biodiversity. Based on a series of ethnographic interviews with the different stakeholders involved in the bycatch mitigation projects in the Bay of Biscay, this paper explores how co-creating knowledge through conflict and collaboration between researchers and fishers can generate collective learning for bycatch mitigation policies. We adopt an epistemological approach, with the objective to promote transparency in the exchange between researchers and fishers and to inform decision-making at various scales of governance. We argue that co-creation of knowledge on bycatch should not aim for consensus. We conclude that acknowledging the presence of conflicts between the stakeholders, and understanding their roots and their impact on the co-design process can allow identifying factors of path-dependency hindering the adaptive capacity of institutions. Moreover, we highlight the key role of the fishers' representative bodies in knowledge co-creation, and the importance to improve our understanding of fishers' perception of their political representation.

KEYWORDS

cetacean bycatch, seabird bycatch, knowledge co-creation, local ecological knowledge, co-design, conservation conflicts, controversy analysis, collective learning

Introduction

The impact of bycatch, or the incidental capture of non-targeted species in commercial and recreational fisheries (Rouby et al., 2022) raises concerns regarding biodiversity conservation (Hall et al., 2000). Bycatch is one of the main causes of at-sea mortality for small cetacean species, such as the common dolphin (*Delphinus delphis*) and the harbour porpoise (*Phocoena phocoena*), but also for seabird species (Dias et al., 2019; Rouby et al., 2022). The socio-genesis of bycatch as a political issue in France can be traced back to the emergence of whistleblowers in the 1970s, as scientific concerns grew on marine biodiversity degradation. Prior to this, the interactions between fishers and the marine megafauna were only considered by most actors as competition for the same food resources, and cetaceans were sometimes hunted and consumed (Fichou and Levasseur, 2004). The cetacean strandings have started to be recorded as statistical data by the *Réseau National Échouage* (RNE), a participatory science program created in 1972, forming a network of 350 correspondents, which documents the spatio-temporal trends in stranding numbers. The RNE is steered by a committee of scientists, managers and correspondents elected within the network, and it is coordinated by the Pelagis observatory, a research unit whose main missions are to support research in marine megafauna ecology and public conservation policies (Dars et al., 2020). From 1970 to 1993, 4,627 cetacean strandings were reported on the French Atlantic and Mediterranean coast (Collet and Mison, 1995). It was not until 1989 that researchers, noticing a significant increase in the number of cetacean strandings, became interested in the correlation with accidental captures (idem). This correlation was later confirmed by the Pelagis observatory, which concluded that 60% and, during peaks of strandings, up to 90% of the animals autopsied have traces of fishing gear (Peltier et al., 2019). In the Bay of Biscay, dolphin stranding increased significantly from 2016 onward, most of them with evidence of having been bycaught. The size of the bodies, the contemporary western cultural significance of the species, and the communication work of marine conservation organizations such as Sea Shepherd contributed to make the strandings a visible impact of fisheries on marine biodiversity.

The scientific concerns regarding the bycatch of seabird in France emerged in the French Southern and Antarctic Territories (TAAF) with the shift from bottom trawls to longlines for the fishing of the Patagonian toothfish in the 1990s, which led to a significant increase in the bycatch of three species of albatrosses and four species of petrels (Cherel et al., 1996; Tuck et al., 2003). The strong presence of scientists on the territories since the 1960s contributed, among other factors, to the estimation of the long and short-term trends in the species populations and to the identification of the vessels responsible for bycatch (Rolland et al., 2010; Weimerskirch et al., 2018). In the Atlantic coast, the first scientific projects to study the interactions between fishing activities and protected seabird species only started around 2010, thus little is known yet about the bycatch of seabirds in the area.

A normative framework aimed at mitigating bycatch was established at the European level and then at the national level in French law (Figure 1). In 1992, when concerns arose regarding the impact of driftnets on dolphin and seabird populations, the Commission of the European Communities decided to prohibit "any vessel from carrying on board or engaging in fishing activities with one or more driftnets whose individual or cumulative length exceeds 2.5 kilometers" (OJEC, 1992). This ban met a lot of resistance from the fishers and led to unintended consequences. Once driftnets were banned, fishing activity was shifted offshore by long-lining, where other species such as albatrosses and petrels started to be affected by bycatch (Euzen et al., 2017). Another European regulation was implemented in 1997 to ban the use of driftnets for the capture of certain migratory fishes such as albacore (*Thunnus alalunga*) and bluefin tuna (*Thunnus thynnus*) starting from 2002 (OJEC, 1997). It was not until 2011 that French law transposed the European driftnet regulations (JORF, 2011a). Another ministerial order was issued in 2011, to determine the list of marine mammals protected on the national territory and the modalities of their protection (JORF, 2011b). In 2019, a bycatch reporting requirement for fishers was introduced, requiring ship captains to report protected

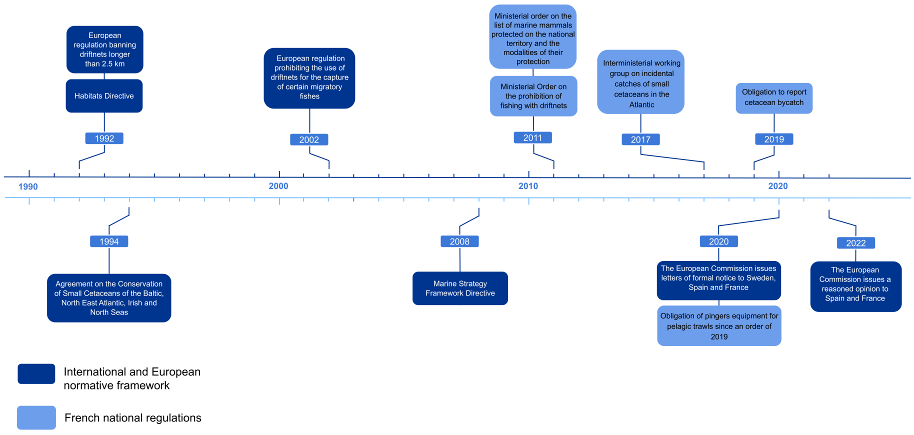

FIGURE 1
Evolution of European and national policies regarding the incidental capture of seabirds and cetaceans.

marine mammal specimens caught accidentally in fishing gear (JORF, 2018). The information provided by fishers is intended to advance research into the understanding and characterization of incidental catches, with the aim of preventing them. This declaration can be made through a digital declaration for vessels of more than 12 meters equipped with an electronic fishing logbook, while smaller vessels can use fishing paper's sheets (Ministry of Agriculture, 2022). Finally, from 26 December 2019, fishers have the obligation to equip pelagic trawls with acoustic deterrent devices, also called pingers, in the Bay of Biscay (JORF, 2019).

Despite the measures taken, the bodies of small cetaceans are regularly washed ashore, most of them with evidence of having been bycaught, and decision-making authorities are pressured by the European Commission to accelerate the mitigation of bycatch through the regulation of fishing practices. On 2 July 2020, the European Commission issued letters of formal notice to Sweden, Spain and France for failing to correctly transpose the obligations related to the Habitats Directive regarding the establishment of a coherent monitoring scheme of cetacean bycatch and the subsequent taking of conservation measures (Autier et al., 2021). On 15 July 2022, considering that France and Spain had not taken the necessary measures since their letter of formal notice, the European Commission sent them a reasoned opinion requesting that the two countries take the necessary measures to "prevent the incidental catch of dolphins and other protected species" within two months (European Commission, 2022). If France is still considered to fail to comply with its obligations after this date, the Commission may decide to refer the matter to the Court of Justice, a process which may entail financial sanctions, which can be a lump sum and/or a penalty payment, in case of sustained failure to comply with the European regulations.

The bycatch of seabirds in the Bay of Biscay are subject to significantly less legislative and political attention. Since the Bird Directive was established in 1979, there are no hard laws intended to reduce seabird bycatch in France, except the regulations regarding the use of driftnets. Fishers are not required to declare the catches of marine bird species nor to equip their vessels with repellent devices.

The main policy options to improve the selectivity of the fisheries operations are the implementation of technical measures, and the adjustment of when and where the fishing effort takes place (Calderwood et al., 2021), such as through space-time closure of fisheries, or through the closure of an area in a fishery to one or more gears for a temporary period when a bycatch threshold is reached (Dunn et al., 2010). Technical measures entail the deployment of repellents on other vessels than the pelagic trawls and the change of fishing practices. The measures are evaluated according to numerous factors such as estimated impact, management complexity, socio-economic impact, and financial investment.

The technical devices tested showed mitigated results. The effectiveness of the pingers was demonstrated for pelagic trawls (Morizur et al., 2012). The Necessity project showed a decrease in yearly common dolphin bycatches of about 70%, but the number of observations had to be doubled to hope to show a significant difference in the confidence intervals (Morizur et al., 2008). The PIC project showed a significant reduction in common dolphins bycatch of around 65% (Le Gall, 2020). The devices were first set up voluntarily and then made mandatory. Numerous projects were implemented by the fishers' representatives in partnership with scientists to test pingers on nets, but the repellents tested did not yet demonstrate their effectiveness (Morizur et al., 2009). In some cases, pingers on gillnets even present the risk to attract marine mammals such as the gray seal, who learn to associate the pinger sound with the fishing gear and easily accessible food resource, an unintended consequence that is called the "dinner bell effect" (Carretta and Barlow, 2011). Pingers can also increase the risk of excluding harbor porpoise from their feeding areas (Olesiuk et al., 2002). The effectiveness of techniques for birds, such as the weighting of lines was proven but is difficult to quantify (Jiménez et al., 2018; Santos et al., 2019).

Time-area closures are recommended by the International Council for the Exploration of the Sea (ICES) to limit cetacean bycatch, and they are considered to be the only effective measure according to the Pelagis observatory (Peltier et al., 2019). Environmental protection NGOs also advocate for time-area closures to achieve biodiversity conservation objectives. However, there is a risk that the measure triggers a shift of the fishing effort in the surrounding areas. Moreover, the closures are considered neither actionable nor acceptable by professional actors and their representatives because the large range of gears associated with bycatch makes its socio-economic application difficult. Time-area closures would entail a restriction of fishers' activities, who would be financially compensated by the State (by temporary cessation for example). This measure can require short-term losses, induced by the lost economic opportunity (Smith et al., 2020), but they have the potential to produce long-term net economic gains, depending on the distribution of benefits and costs among the fishing communities (Armsworth et al., 2010).

The economic condition of the fisheries in the European Atlantic coast is tense. The significant decrease in the size of coastal fishing fleets (Leaute, 2008) in a general context of depletion of the fishery resource, symbolized in particular by the first European Fleet Exit Plans, has left its mark on the communities of single-species oriented fishers. If public authorities already have enacted regulations constraining fishing activities in the past, the issue of bycatch is particularly controversial, and decision-makers are aiming to maintain the economic and social stability in the ports and to sustain national production. It is worth highlighting that the fishing sector in France represents only a small part of the economic activity of the country but it is an historical structuring activity of the French coastal areas (Meunier et al., 2013). Moreover, there is a political trend to enhance sovereignty on food production considering the increase in the trade balance deficit of fish and seafood products (FranceAgriMer, 2021).

Decision-makers are supporting the bloom of scientific projects to improve our understanding of bycatch, which is still the source of scientific uncertainties regarding populations of small cetaceans and seabirds (abundance, distribution) and incidental catches (rates, conditions) (Darrieu, 2018; Peltier et al., 2021). Research institutions and scientists are progressively building knowledge, in partnership with fisher representative bodies, to evaluate the circumstances, the magnitude and the impact of bycatch (target species, areas, periods), and to test escape and repellent devices.

In this paper, we present a diagnosis of the interactions between fishers and scientists with regards to bycatch mitigation projects in the Bay of Biscay. More specifically, we analyze the political and scientific approaches of integrating fishers in knowledge production and in decision-making processes on bycatch reduction. How do decision-makers, fishers and researchers interact to evaluate the options to reduce bycatch? How do they analyze and compare the sets of policies, techno-economic and behavioral options to reduce bycatch? We also explore the evolution of the cooperation dynamics between the different stakeholders, and the main sources of tension arising from collaborating on bycatch mitigation projects.

We analyze the co-construction of knowledge on bycatch for both cetaceans and seabirds. If the impact of bycatch on seabird populations receive less political and scientific attention in France, it is not less significant, with several species vulnerable to bycatch, such as the balearic shearwater, being severely endangered (Genovart et al., 2016). We do not mention projects to improve the selectivity of fisheries with regards to bycatch of fish species and discards.

We argue that the process of co-creation of knowledge on bycatch through conflict and collaboration is key to improve our understanding of the complex system dynamics at play, and to develop regulations adapted to local specificities, towards an adaptive socio-ecosystem based management of the issue. Conflict analysis contributes to highlighting the levers and blockages in the decision-making process regarding fishing policies and biodiversity conservation regulations. We assess the potential of knowledge co-creation to improve fishers' ability to find solutions to tackle the issue of bycatch. We conclude by presenting the lessons learned through conflicts between fishers and researchers to inform bycatch mitigation policies.

Method

This article is the result of a research project which aims to analyze controversies on seabirds and cetaceans bycatch in the Gulf of Biscay. The fieldwork combines several types of materials: archives, ethnographic interviews with a diverse set of stakeholders, observations in professional gatherings, participation in scientific conferences, and social science analyses (actor mapping, epistolary analysis, etc.).The interviews were conducted along the French Atlantic coast to collect qualitative data, favoring face-to-face meetings, and following a flexible course of discussion in order to adapt to the specificities of each actor. Data collection entailed the experiences of bycatch, the interactions between actors within and without the stakeholder group, the roles in the decision-making processes, and the perception of the different measures for bycatch reduction. Participation in scientific conferences and professional gatherings was used as an opportunity to collect additional feedback and to consider the actors' discourses and strategies in debates on bycatch. Although the choice of actors intended to include a diversity of expertises, the majority of fishers interviewed in this study are operating in small-scale fisheries. This ethnographic approach aims at understanding complex maritime and coastal socio-ecosystems (Danto et al., 2018), and exploring the relationships between knowledge and power (Mazé et al., 2017).

We acknowledge the limits associated with the categorization of stakeholders used for this publication, namely the social groups designed as “fishers”, “researchers”, “government” and “NGOs”. There is porosity between research institutions and decision-making bodies for example. The AGLIA, a fishers’ representative entity, has a hybrid governance structure composed of both public actors and professionals from the fishing sector. Likewise, within the same stakeholder group, important differences exist, such as between administrative bodies acting at the national and at the regional scale. There are also differences between scientific institutions: the two main institutions working on bycatch in the Bay, IFREMER and the Pelagis observatory, have different roles and are distinctively perceived by the other stakeholders. Fishers also can not be considered to be a united social group. The profession is heterogeneous, and there are power asymmetries between fishers. Different types of vessels, from France but also from other countries such as Spain and Belgium, are operating in the Bay of Biscay, fishing specific species, with various practices and interactions with marine biodiversity (Peltier et al., 2021).

Process of integrating fishers’ contributions

Tackling bycatch in the Bay of Biscay requires experimenting with technical solutions and regulating fishing practices in a way that is adapted to the specificities of the socio-ecosystem. The co-design of research projects is key to develop the knowledge necessary to implement efficient measures and to learn from experimentation at the “boat scale”. The notion of “co-design” is used here to refer to the co-creation of credible and legitimate ocean knowledge solutions (IOC-UNESCO, 2021) to reduce bycatch. In theory, fishers’ empirical knowledge can be leveraged to inform Western science and policy making in order to create applicable mitigation measures which would be adapted to local specificities. For example, fishers’ Local Ecological Knowledge could be used to determine which areas are to be managed, and when, to develop dynamic adaptive ecosystem management (Mazé, 2020). We use the notion of Local Ecological Knowledge to refer to the set of knowledge derived from daily interactions with the ecosystems, as opposed to Conventional Scientific Knowledge (Berkström et al., 2019), or expert knowledge (Lascoumes, 2001; Barthelemy, 2005), which is built from collecting data according to a scientifically designed methodology, and theoretically interpreted.

The fishers are mostly mobilized to contribute to the scientific measures of the magnitude of bycatch and to the test of technical devices. Yet, there are variations in the process of integrating their contributions and in the strategy of each actor in the knowledge co-creation process.

Evolution of cooperation dynamics

The collaboration dynamics between the actors evolved since the first projects, partly due to the sharp increase in cetacean strandings and the change of scope regarding the vessels responsible for bycatch. Numerous European and national projects on the bycatch of cetaceans were implemented between 2000s and 2010s in the Bay of Biscay, involving a diverse but small set of scientists, fishers representatives, and administrative bodies (Northridge et al., 2006; Morizur et al., 2008). These research projects were focused on pelagic trawlers, as they were the main fleet held responsible for the bycatch of small cetaceans in the area (Morizur et al., 2012). The OPs, fishers representative bodies also called *Organisations de Producteurs*, were involved in the monitoring of the fleet, and due to the relatively limited number of vessels compared to the gillnet fleet (Peltier et al., 2020b), they were able to monitor the fishing effort. The fishers’ representatives interviewed describe the collaboration in the first projects as pragmatic and focused on finding technical solutions. Long-term cooperation dynamics were not achieved but stakeholders were interacting with mutual respect. In 2019, communication between actors started to be altered by a lack of trust. While the projects had focused on pelagic trawls, the observation efforts showed that the gillnets also contributed to the risk of bycatch (Peltier et al., 2019).

Moreover, during winter 2016, a peak in cetacean strandings was observed, with 1,342 cetacean strandings recorded on the French coastline, of which 53.3% were common dolphins (Dars et al., 2017). During the following years, the level of bycatch stayed significantly higher than what had been observed before 2016. Preferring the approach of managing through science rather than managing through use (Barthelemy, 2005), the political focus in reaction to this peak of strandings was to support the production of new scientific knowledge on bycatch. As a result, there was an increase in the funding of research projects to further explore the ecological and social issues raised by bycatch, and the potential solutions to reduce its occurrence. Along with the increasing number of research projects on bycatch, the number of actors involved in the research process also significantly increased, creating a dense social environment with diverse collaboration dynamics and scientific approaches, as illustrated in Figure 2, which does

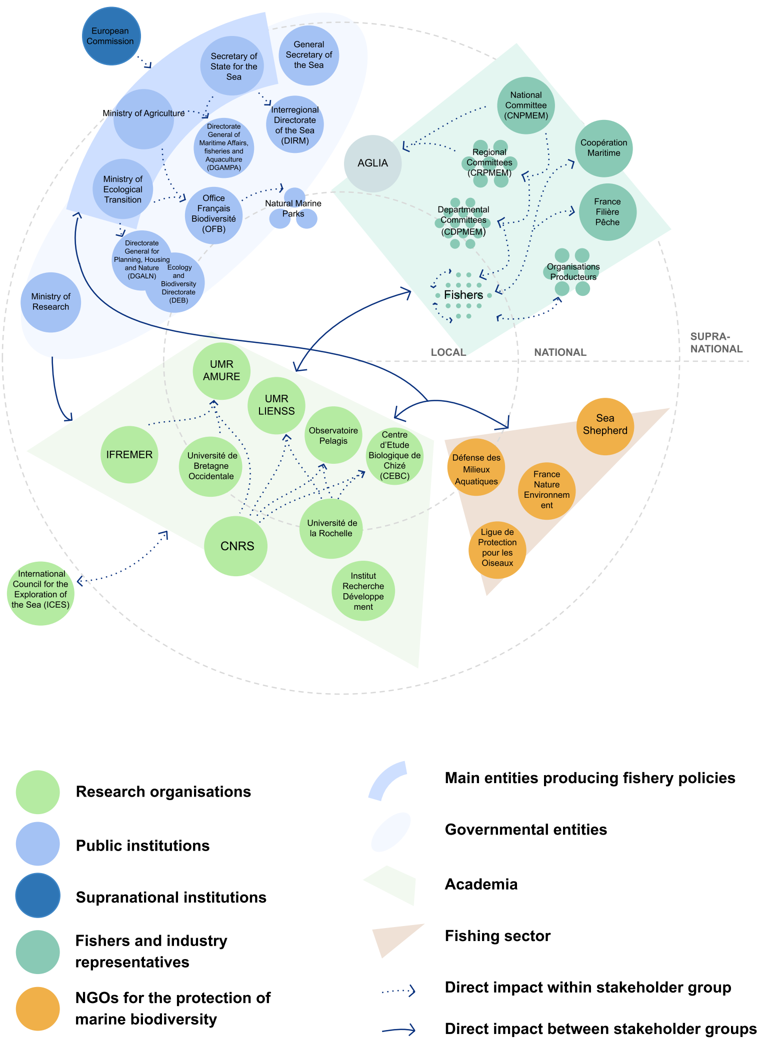

FIGURE 2
Sociogram of the actors' system involved in bycatch mitigation in the Bay of Biscay.

not intend to be exhaustive but represents the complexity of the actors' network (Figure 2).

The research projects on the bycatch of seabirds in the Bay of Biscay started significantly later than the projects on cetaceans, the first being the transnational program FAME in 2010, led in France by different organizations including the League of Protection for Birds (LPO). The project aimed at improving our knowledge of seabirds, mainly the Balearic Shearwater (*Puffinus mauretanicus*) and the Northern Gannet (*Morus bassanus*), and at raising awareness of the users of the sea, and it did not involve onboard observations. The research work on seabird bycatch in the area, and the related collaboration with fishers, then paused until a new set of projects started around 2020. Projects such as ARPEGI and CARI3P include fishers' representative bodies as partners and consider fishers' observations and proposals. The CARI3P project, for example, aims to characterize the incidental catch of Balearic shearwaters by longliners, gillnetters and purse seiner. The project collects fishers' observations regarding their knowledge of the species and on their experimentation of bird-scaring techniques, and the solutions that they envision. The program also aims to foster exchange between French fishers and Portuguese longline fishers who have worked on the fisheries-bird interaction programs.

Platform for discussion

Deliberative processes for remediation have also been implemented, such as the Interministerial national working group on incidental catches of small cetaceans in the Atlantic, created in 2017. This working group, led by the State Secretary for Sea (through the General Directorate of Maritime Affairs, Fisheries and Aquaculture) and the Ministry of Ecological Transition (through the Ecology and Biodiversity Directorate), is composed of a diverse set of stakeholders (administrations, scientists, NGOs, fishing professionals). The group meets regularly to discuss the latest results of the research projects on the interactions between fishing activities and small cetaceans, and the measures to limit bycatch in a sustainable manner. The initiative is nationally held, but it also aims to serve as a platform to organize collaboration with foreign counterparts operating in the Bay of Biscay, with the frequent participation of actors from border countries such as Spain and with the participation of the European Commission as an observer. The national group started with a limited number of members who previously collaborated in bycatch mitigation projects. The members interviewed mentioned that, as the number of people around the table increased, the dialogue dynamics progressively shifted to a sequence of presentations with limited opportunities for discussions. The degradation of the dialogue dynamics was taken into account by the organizing institutions, who decided to structure the national group into subgroups discussing specific dimensions of bycatch.

Data collection with and without the fishers

The current data collection on bycatch in France entails the estimation of bycatch rate (with observers deployed on vessels, number of stranding recorded, fishers' reporting), bycatch risk assessment (population distribution, areas of mortality, fishing effort, interactions with fishing gear), estimation of the impact of bycatch (threshold, abundance, cascade effects), and the measurement of the effectiveness of technical devices, such as pingers. Many scientific studies are mobilizing observers to collect data. In that case, fishers' participation is limited to accepting, or not, the observer on board. For example, the sea observation program Obsmer, led by the General Directorate of Maritime Affairs, Fisheries and Aquaculture, and co-funded by the European Union, collects data on the vessels, the catches, and the tidal environment from annual sampling realized with on-board observation since 2009, in partnership with IFREMER and fishers' representatives (IFREMER, 2022). Fishers' knowledge has also been integrated through surveys and voluntary statements in order to create a diagnosis of the fleets and to characterize the interactions on pilot sites (Pelagis observatory, 2022). Some research projects, such as the program Obsenpeche, are studying participatory science tools, with the aim to deploy a network of "sentinel fishers", using an application to report knowledge on bycatch, and to initiate a reflection on the evolution of fishing strategies. Other data collection methods bypass the fishers' and observers' onboard perspective regarding the interaction with cetaceans and seabirds, and the biases associated with it. The Pelagis Observatory organizes aerial observation campaigns of marine megafauna under the SAMM (Aerial Monitoring of the Marine Megafauna) program. This program is intended to produce an inventory of the spatial distribution of certain species in metropolitan waters, to estimate their abundance and to identify the preferential habitats of cetaceans and seabirds according to the seasons. The two SAMM campaigns in 2011 and 2012 allowed the observation of nearly 3,000 marine mammals and 35,000 seabirds (Laran et al., 2017). Another program aiming to estimate the rate of bycatch is using electronic observation devices to better understand the interactions between dolphins and gillnetters. The test of onboard cameras on vessels and the development of an automated algorithm for image processing by artificial intelligence to consider the extension of the system to 400 gillnetters was launched at the request of the ministry, in partnership with a diverse set of stakeholders (Ascobans, 2021).

Control over knowledge co-production

The control over the process of knowledge co-production is held by research institutions, but also by fishers' representative bodies. On one hand, scientists have the social capital and the legitimacy to have control over the methodology adopted (Bourdieu, 1976). On the other hand, fishers' representatives (national, regional and departmental committees, and fisher organizations, also called *Organisations de Producteurs*, OP) are almost systematically involved as partners. Communicating and collaborating with fishers on the numerous projects require logistics, hence the professional representative bodies (the regional and departmental committees and the OP, depending on the area) manage the different requests, distributing the corresponding surveys and requests among fishers. They play a decisive role, organizing data collection with the fishers, hence the research projects depend on their approval.

Incentives for knowledge co-creation

Researchers and fishers are drawn into knowledge co-production by different incentives. Careful analysis of incentives is crucial since the interactions of the stakeholders are unlikely to be socially or politically neutral (Armitage et al., 2007). For scientists, the approval of fishers to participate is decisive, as they need a representative sample to be able to draw conclusions. The significant statistical sample has been set by the European Commission at a minimum of 5% of the fishing effort for cetaceans (Peltier et al., 2016), and 10 to 20% for the bycatch of seabirds, since the bycatch of birds are rare events but when they occur, they can impact a significant number of individuals (Babcock et al., 2003). Engaging in knowledge co-production is also the opportunity to have more acceptable and objective results of the research projects, when the scientific experts finalize their diagnosis.

Fishers are contributing to scientific studies with the aim for transparency, and to contribute to rapidly finding technical solutions to reduce bycatch. Yet, the participation in research projects is not a core aspect of their work, and it is perceived as an additional constraint on their activities. Sometimes, a relationship of trust is already established if the fisher and the researcher have already interacted at other occasions. If this is not the case, for a research project to be accepted among the fishing communities, scientists need to highlight fishers' interests to participate. They are promoting the integration of fishers' feedback, of their expertise and knowledge of the marine ecosystems, in order to create more specific regulations, rather than applying regulations to all gears and fishing practices. Participating in a research project on bycatch would give them the opportunity to refute the data with which they do not relate.

Cooperation with researchers is not always voluntary, especially since the 2019 regulation requiring ship captains to report any occurrence of cetacean bycatch. The Ministry of Ecological Transition and Solidarity, with the help of researchers from the Pelagis observatory, have provided fishers with a guide on the declaration procedure (the species concerned, the steps to report the occurrence of bycatch in the fishing paper's sheets and in electronic fishing logbook) (Tachoires et al., 2018). However, the obligation of bycatch reporting is partially deficient, and the data collected are not very usable, as they suffer from numerous biases.

Regulations are adding legitimacy to scientists' approach. The regulatory framework in place becomes an argument for scientists to incentivize fishers to collaborate. Even if the rules put in place are not always legally binding, they can serve as an argument for scientists to convince fishers to take part in the projects. Researchers interviewed have given the example of Biodiversity Law of 2016 (JORF, 2016), stating that risk assessment must be realized in fisheries, or soft laws such as the National Action Plan 2021-2025 for the Balearic Shearwater.

Conflicts hindering co-creation

The knowledge co-creation process for bycatch reduction in the Bay of Biscay is hindered by several, interrelated factors of tension constraining collective learning and limiting the capacity of actors to come up with shared solutions.

Different interests and narratives for the sustainability of the fishing sector

Fishers and researchers collaborate with the common objective to improve knowledge on the species vulnerable to bycatch and to implement effective solutions to limit the occurrence of accidental captures. Indeed, for fishers, cetaceans and seabirds arouse respect and consideration, and bycatch induces significant costs related to the degradation of fishing gears. Pursuing this common objective, numerous disagreements arise from the interactions between the different actors involved in bycatch mitigation projects.

The definition of the problem and the set of solutions perceived as acceptable vary not only according to the state of the resource but also according to the interest perceived by the actors (Lapijover, 2018). Indeed, the actors involved in the process have different perspectives regarding the impact of bycatch on marine biodiversity depending on their interests. The research projects have not yet established a commonly agreed upon knowledge basis, resulting in divergence regarding the perceived importance of the issue. For fishers, cetaceans and seabirds are the signal for the presence of fish, but they are also competitors. The fishers are perceiving that the phenomenon of depredation is increasing, and depredation, especially when using gears such as straight nets to fish red mullet, is considered to have a significant negative effect on fishers' catch. The conflicting perceptions of the impact of fishing on cetacean and seabird populations create friction in the process of co-creation. Fishers tend to consider their individual experiences on a single vessel rather than the impact of the fishing sector as a whole, thus if they perceive that their activity does not have a significant impact on cetaceans and seabirds, they tend to disagree with the use of the notion of emergency with regards to bycatch in the Bay of Biscay, and with the hierarchy of concerns for fisheries management resulting from it.

The stakeholders also disagree on the solutions envisioned by fisheries scientists and managers to reduce bycatch, such as time/area closure, change of vessel, and economic compensation. Fishers have economic incentives to invest in acoustic repellents, but they perceive limited interests in interrupting fishing in specific areas. Different data are mobilized by each actor in order to defend their respective vision regarding policy priorities. Most professional actors consider that since there were 467,673 common dolphins counted in the European waters of the Atlantic in 2016 (Hammond et al., 2017), the population is not in danger of extinction in the short-term, thus implementing measures such as time-area closures now would be a political demonstration of excessive environmentalism. On the other hand, some researchers consider that waiting until a species is declared endangered to implement conservation measures significantly reduces the probabilities of successfully preserving this species, and thus they highlight the need to adopt a long-term vision in today's policies. Each actor refers to a specific part of the knowledge on bycatch, according to which he develops an interpretation of the sector's history, a vision for its evolution, and a strategy to defend this vision (Catanzano and Rey, 1997).

Actors' views and values are polarized resulting in different narratives for the "sustainability" of the fishing industry. The beached dolphin bodies become a symbol of the impact of fishing on marine ecosystems, and call into question the interrelationships between humans and nature, and more specifically the industrial exploitation of the ocean (Clouette, 2022). Faced with this question, fishers argue that, in order to satisfy the current national demand for seafood, the corresponding fishing techniques must be maintained, giving the example of fish sole and scampi that cannot be caught with fishing traps. The actors have different perceptions of the socio-ecosystem, and of the behaviors of actors perceived as at risk (Lapijover, 2018). The knowledge exchange deteriorates, as the actors are entrenched in their position regarding the transformations necessary to reach sustainability, resulting in path-dependency. The notion of path-dependency refers to the observation that, even if a more "efficient" solution is known than the solution currently chosen by an individual (in terms of technology or practices for example), this solution is not necessarily adopted (Palier, 2014) due to the presence of "lock-ins" (Goldstein et al., 2023). Steins, Mattens and Kraan observe that the uptake of more selective gears in the Netherlands, even if the innovation is fisher-led, depends on a complex interplay of social, policy and science-related factors, among which the fishers' intrinsic motivation and beliefs about sustainable fishing, and perceptions about the motivations and behaviors of other fishers (Steins et al., 2022).

Dichotomy between two worlds

The disagreements are reinforced by the perceived dichotomy between the worlds of academia and fisheries, as the measures envisioned do not always meet the reality faced by fishers (Suuronen, 2022). For the fisher, the environmental manager, the decision maker and the natural scientist belong to the sphere of technocratic power (Barthelemy, 2005), which is considered too far removed from the realities on the sea. The fishers are pointing to a lack of knowledge of the field, and of their working conditions, and often invite decision-makers, scientists and journalists to get on board to see for themselves. Indeed, fishers are generally aware of the basic requirements for the sustainability of fishing, but due to the harsh circumstances of their work, it is challenging for them to undertake these transformations (Suuronen, 2022). Fishers and their representatives highlight a gap between what is required from them, and the core mission of their profession. This feeling of distance between bureaucratic professions and sea labor can lead to doubt about the relevance of the different scientific approaches, and to the rejection of the entire knowledge co-creation process.

Climate of mistrust

If co-creation of knowledge requires building trust between the different parties (Hakkarainen et al., 2021), trust can be eroded very quickly, as a result of the failure to meet a commitment or because of an unexpected regulation for example (Armitage et al., 2007). Although the researchers and fishers' representatives are realizing an important work of communication to improve the collaboration dynamics, researchers and fishers are in a defensive position, sharing doubts about each other's intentions.

The change in scope of the responsible vessels altered the relationship of trust between fishers and researchers: the finding that pelagic trawls were not the only vessels responsible for cetacean bycatch induced suspicion from scientists regarding the willingness of fishers to collaborate.

Researchers' doubts regarding fishers' motivations are also based on the significant difference between the number of accidental catches declared by fishers and the number of strandings recorded on the Atlantic coast. Indeed, qualitative surveys in the human and social sciences reveal, within small fishing communities, a tendency (unquantifiable for the moment), to under-report, for fear of administrative reprisals, of NGOs, or even of neo-rural and neo-coastal inhabitants. As soon as the fishers do not comply with the regulation to disclose bycatch, they are associated with "reluctant" partners whose refusal to report is a convincing sign of its unwillingness to collaborate. Researchers assume that the fisheries feel threatened by the possibility that research projects contribute to the development of new regulations and do not disclose all the information that they hold. The question of data reliability becomes more acute as restrictions on fishing effort are tightened and, consequently, tensions between fishers and scientists increase (Deldreve, 2010).

The fishers' defensive position is due to the assumption that sharing data could lead to more regulations. While the fishing profession is traditionally associated with freedom, the inflation of rules and requirements are perceived by some fishers as an infringement of freedom. The fishers interviewed also mentioned their apprehension of the socio-economic impact of regulations such as the reduction of sole quotas in the Bay of Biscay, sole being one of the main targets of the gillnetters. Hence the fishers are facing a conflict of interest, acknowledging the value of their integration in bycatch mitigation projects, but having limited incentives to share catch information, fearing that their participation may play against them (Calderwood et al., 2021). The research on change management models for fisheries has highlighted the impact of intrinsic motivation factors concerns on the resistance to change fishing practices, the most impactful factors being the concerns that change will be costly and painful, perceived lack of incentives to offset any catch loss, perceived loss of cover over the fishing operations and uncertainty about the future, including how fishers may be affected by change.

Controversies around the conventional scientific approach to data production and interpretation

If the limits of integrating fishers' knowledge considering the existing conflict of interest are highlighted by scientific institutions, conventional scientific knowledge production is also at the heart of controversies, for being accused of normativity with political ends. The role of researchers in the development of bycatch mitigation policies is generating debate over the acceptable level of normativity in sciences. Indeed, scientific experts who contribute to the establishment of norms take ethical and political positions (Roy, 2001), which have direct implications for the cooperative relationships between fishers and researchers (Deldreve, 2010). Scientific objectivity is questioned in the discourses of the fishers: on the one hand, IFREMER researchers are accused by small-scale sustainable fisheries of being too dependent on the fishing industry. On the other hand, the Pelagis observatory is considered by other professional actors to have an ecological bias. The rationality so specifically attributed to natural, "hard" sciences (Naim-Gesbert, 1999; Darrieu, 2018) is questioned, since the professional actors perceive that scientists are tailoring their methodologies to the results they are aiming to get, pointing at a lack of coherence in the scientific approach.

Moreover, fishers and their representative bodies report the lack of tangible results from their involvement in the research projects on bycatch, except for the test of technological devices. Fishers perceive that their contributions did not translate into the identification of concrete solutions: the outcomes of the research projects were for the most part scientific publications, and the possibility to apply time-area closures is still considered an option.

Finally, there are important research gaps regarding fishers' Local Ecological Knowledge (LEK), and few projects explicitly mention the intent to pair LEK with Conventional Scientific Knowledge. Fishers are generally rather considered by researchers as "cooperating users" (Barthelemy, 2005), representing a potential source of scientific data useful for bycatch management, although scientific projects sometimes organize discussions such as seminars of cross sensibilization in order to integrate fishers' feedback and expectations on scientific studies. It is assumed that fishers hold knowledge regarding the techniques which are the least and the most likely to cause bycatch. Yet academic methodologies tend to disregard fishers as holders of empirical knowledge. Since the main opportunity to share their experience is through participating in researchers' data collection, their refusal to cooperate as participants to conventional scientific methods also leads to their non-participation as holders of this empirical knowledge.

Persistent uncertainties

Numerous uncertainties remain regarding the occurrence of bycatch which wears out the motivation of the different actors to engage in knowledge co-creation. The cause of the sharp increase in cetacean strandings is yet to be scientifically explained. A possible explanation would be a change in distribution of the population relative to the fishing grounds where fisheries posing the greatest risk of bycatch operate (Peltier et al., 2021), since the results of several observation campaigns suggest that the abundance of the common dolphin's population has recently increased in the Bay of Biscay (Van Canneyt et al., 2020). However, the abundance estimates have a high margin of uncertainty which makes the statistical detection of change (Murphy et al., 2019) and the estimation of long-term trends challenging (Lapijover, 2018). The ICES raised that for any particular European Union Member State, it is nearly impossible to establish whether the observed trend in the local abundance of common dolphins represents a shift in distribution (ICES, 2019). Likewise, little is known yet about the rate of occurrence and the types of practices and the vessels responsible for cetacean and seabird bycatch in the Bay of Biscay.

The data collection in research projects on bycatch has limits. Biases have been identified in observer programs, such as "the deployment effect", stemming from the lack of a sampling strategy, as the presence of observers depends on the willingness of the fishers; and "the observer effect", i.e., the change in fishing practices when an observer is present (Benoît and Allard, 2009; Faunce and Barbeaux, 2011; Amandè et al., 2012; Murphy et al., 2019; Peltier et al., 2020a). Moreover, the models to estimate bycatch from stranding data and from observer programs provide "ranges" with a large amplitude. For example, the work by the ICES Working Group on Bycatch (WGBYC), which collates and assesses information on bycatch monitoring and assessment for protected species, estimated in 2016 from observer programs the bycatch of common dolphins to be between 1,607 and 4,355 in ICES zone VIII, and between 1,400 and 4,800 from stranding data along the French Atlantic coastline (ICES, 2018).

There are different ideological positions regarding the process of data interpretation with regards to scientific uncertainties to conclude on the best measures for bycatch reduction. At the level of the strategic actor, uncertainty is a fundamental resource for negotiation between different interests (Lapijover, 2018). Some stakeholders argue that there are still too many uncertainties about the magnitude of the problem, and thus about the urgency of the situation, to apply constraining regulations on fishing activities, while others argue that the data available is sufficient to justify these measures. The negotiation process is well illustrated by the debates around space-time closures, and the use of a threshold to determine when and where the closures should take place.

Media, science communication and activism

The media coverage of these strandings is significant and can be compared to that of news items. Marine mammals arouse emotions in the public, due to their cultural significance, being perceived as "iconic" animals (Lorimer, 2007; Danto et al., 2020; Mathur, 2021). The conflicts, the blood, the bodies of sea mammals are all visually powerful and tend to trigger public reactions (Geistdoerfer, 1984). The organizations dedicated to marine biodiversity conservation are leveraging these emotions through the media to raise awareness of civil society and to call the attention of the decision makers, in order to move the issue of bycatch further up in the political agenda. The choice of words such as "killing" or "slaughter" to describe fishers' work plays on the emotional relationship with the marine mammal, stronger than the one shared with the fish or the seabird and is questioning the responsibility of the fishers (Clouette, 2022). The NGOs also use statistical surveys from research projects on bycatch in their communication, since data plays a key role in engaging an audience (Desrosières, 2014; Clouette, 2022).

Fisher representatives are pleading that the discourses of the NGOs in the media fail to present all the elements to grasp the complexity of the issue, and the uncertainties about the nature of the interaction. This tension is leading to numerous, sometimes violent altercations between some fishers and Sea Shepherd. This resentment was already present in 1994, when the media picked up on a conflict between French and Spanish fishers over the ban of driftnets, which they dubbed the "tuna war" (Lequesne, 2002). This new regulation was not well received among French fishers, who perceived that they were condemned "in the face of the fantastic media hype" (Antoine, 1995).

Both researchers and fishers perceive that collaboration dynamics are hindered by the media coverage and by the conflicts with the NGOs. Fisher representatives consider that researchers' science communication strategy contributes to fuel the NGOs' anti-fisheries discourse and to the oversimplification of the issue. Direct conflicts between fisher representatives and scientific institutions arose regarding the content of posts on social media for example, where representative bodies plead that the publications are not reflecting the work done and draw hasty conclusions on the stranding figures by failing to specify the context in which the data is elaborated and the attenuation factors to be taken into account when interpreting the numbers.

Discussion

Socio-ecological conflicts tend to be seen as negative phenomena to be avoided and "resolved" as quickly as possible by finding win–win solutions, through cooperation, negotiation and consensus seeking (Fisher and Ury, 1981; Ury et al., 1988; Temper et al., 2018). In the case of bycatch mitigation, the conflicts hindering knowledge co-production have complex and profound roots, with important political, historical, social, environmental and cultural components. The conflicts highlight two key underlying identity issues: the establishment of the unquestionable legitimacy of scientific expertise and the image of fishing, either perceived as a diversified and legitimate activity or as a destructive harvesting activity, and of fishers, either considered as responsible producers or as unconscious predators (Deldreve, 2010).

Temper et al. argue that conventional conflict resolution approaches have limited potential to successfully deal with such socio-ecological frictions, and that they can lead environmental conflicts to become recurrent as they offer little opportunities for developing robust democratic and sustainable agreements for the use and management of the environment and territories (Temper et al., 2018). They suggest that conflicts are rooted in situations that are perceived as unjust, and that, by expressing a questioning of the status quo, conflicts can have constructive potential (Lederach, 1995; Dukes, 1996; Temper et al., 2018). Analyzing the points of friction related to bycatch mitigation, and identifying power asymmetries and institutional failures, can help understanding the transformations necessary to take into account the social and environmental issues in the decision-making process regarding the management of a marine socio-ecosystem faced with anthropogenic pressures.

Actions taken to shift social–ecological systems through transformation towards more sustainable trajectories can have negative social impacts and exclude people from decision-making processes (Bennett et al., 2019). Co-creating knowledge with fishers requires understanding the governance structures for fishers, considering power asymmetries in the governance and management of the ocean (Caze et al., 2022), and the economic domination that some fishers undergo (Clouette, 2021). The literature on transformation research calls for a greater integration of politics and power, by considering the decision-making process behind the measures leading to the transformations of the system and of the practices, and by tracking winners and losers in the transformations, with the aim for societal justice. For example, if the measures taken by the government are mobilizing economic incentives, such as penalties or subsidies, the difference of impact on small-scale and industrial fisheries should be considered. The impact on small-scale fisheries has already been used as an argument from fishers' representatives to protest against a new regulation. In 2014, when the European Commission formulated a proposal to ban all driftnets with the aim of reducing bycatch, among other objectives, considering the circumvention of the regulation of 2002, fishers' representatives in France protested, arguing that the use of driftnets was used by small-scale, sustainable fisheries. If the conflicts in co-designed bycatch mitigation projects reveal a perceived injustice and gaps in the current governance system, can it also be a tool to start a process of transformation to reach a more equitable and inclusive management process? Can knowledge co-creation be a way for fishers, as agents of transformation, to improve their ability to find solutions to reduce bycatch and to adapt to future regulations? In other words, beyond a greater understanding of the issue at hand, what is the political impact of the knowledge co-creation process in this particular case?

In order to assess whether conflicts in co-designed bycatch mitigation projects in the Bay of Biscay can foster the empowerment of fishers to tackle the issue of bycatch, it is necessary to understand the decision-making processes and the science-policy interactions at play.

The decision-making process shaping the pathway of the fishing industry is cross-sectoral and multi-scalar, thus the policies result from a process of mutual adjustment between different actors. The three distinctive entities currently responsible for producing national policies on fishing are the Secretary of State for the Sea, the Ministry of Agriculture and Food Sovereignty, and the Ministry of Ecological Transition and Territorial Cohesion. In the French government, a Secretary of State has almost the same functions as a Ministry, with the exception that the Secretary of State only attends the Council of Ministers when the agenda includes a question concerning their ministerial department. The management of the resource was for a long time carried out by the Ministry of Agriculture, and the management of fishers and vessels has long been disconnected from the management of fishery resources and from biodiversity conservation. The inherent scientific work was partly carried out by a higher education and research institution under the supervision of this same ministry, since fisheries constitutes in the history and epistemology of French sciences a branch of agronomy. This distinction has led to difficulties in the implementation of public policies that are not necessarily always coordinated on the field.

Various successive reforms, marked by the spirit of the New Public Management (Barone et al., 2018), led to the closure of a large number of administrative maritime services. The concept of New Public Management emerged in the early 1980s in the United Kingdom and New Zealand, and then gradually spread to many countries, including France. It is based on the main idea that the public sector, organized according to bureaucratic structures and principles, is inefficient and that it would be desirable to draw inspiration from private sector principles (Pollitt and Bouckaert, 2011). In the maritime administration, the service that originally constituted the first territorial level of Maritime Affairs, called the "Syndic des gens de mer", which was considered as a referent for fishers, was closed, as well as the Maritime Affairs Quarters, with the subsequent disappearance of the Chief Administrator of the Quarter, the second point of contact with fishers for more political or serious matters (Danto, 2021). The increasing centralization of institutional bodies could negatively impact the implementation of the policies to mitigate bycatch, policies to which the fishers often do not lend any legitimacy. Moreover, fishers' access to speech in the social and political system is variable, depending on their social position and of their network, which accentuate the power asymmetries within the fishing communities in a context of administrative centralization. The fishers' representative bodies play a crucial role to bridge the communication gap, connecting fishers with policymakers and researchers, yet little is known so far about their actual role in the decision-making process, and fishers' positions with regards to this representation. Improving our knowledge of the "invisible" professional fishers who are not members of OPs and refuse contacts with the Committees, as well as of the level of satisfaction of fishers with regards to the representative democracy within the maritime political sphere, could contribute to a better apprehension of fishers' reception with regards to new fishing policies and biodiversity conservation regulations.

The balancing of ecological concerns within the social, economic, cultural and democratic spheres of the decision-making process is shaped and constrained by different factors that can be distinguished in three categories: values, rules and knowledge (Colloff et al., 2017). First, the choice of bycatch mitigation policies is impacted by the preferences, and thus by the values of decision-makers: fear of social unrest in the Atlantic ports, incentives to maintain the fishing industry, duty of protecting marine biodiversity … Then, the institutional context in which the decision-makers operate determines the prescribed and proscribed actions and the associated bodies of laws and social norms for how rules are applied (Colloff et al., 2018). In France, the European Union has an exclusive competence over "the conservation of the biological resources of the sea within the framework of the Common Fisheries Policy". This strategic competence gives the European institutions a central and widely discussed role (Khalilian et al., 2010; Lapijover, 2018), and it is exercised by the use of different instruments, such as European Directives. The Habitat Directive, the Birds Directive, and the Marine Strategy Framework Directive (MSFD) are all impacting the science-policy approach to bycatch mitigation in the Bay of Biscay. The MSFD, for example, aims to set a European strategy for the marine environment that intertwines acquisition of scientific data and implementation of management measures, while taking into account the local specificities. The Directive demonstrates the intertwining of scientific knowledge and decision-making processes, giving a central place to scientists and decision-makers, but it does not mention the integration of other representations of the marine environment (Lapijover, 2018).

If the government is not complying with the European norms, the European agencies can directly exercise pressure through an infringement procedure. The interactions between the different scales of governance which shape the institutional context of bycatch mitigation policies are taking place in arenas that are highly distant to fishers' reality. This mechanism does not prevent a State from following a strategy that is divergent from the European norms, as it has often been the case with regards to French political decisions.

Finally, decision-makers formulate policies according to their understanding of the world, which is defined by the political use of scientific expertise (Latour, 2018), but also by their experiential knowledge and world views. Knowledge production on bycatch emerges as a key step to the management of an issue that remains the subject of uncertainties, hence participating in knowledge production through the academic system could theoretically be a lever for empowering stakeholders to take an active role in shaping the policies for sustainability (Caze et al., 2022). Power is linked to deliberation, learning (and who defines what type of learning), the choice of indicators for measuring outcomes, and the sharing of risk (Lascoumes, 1994; Armitage et al., 2007). However, in this situation, the scientific approach to integrate fishers' knowledge is often limited to data production, and fishers' representatives are not systematically integrated at the step of interpretation of the projects' results to inform policy making and develop bycatch mitigation tools such as thresholds. In some cases, research projects are concluded by negotiation on measures to take based on the project results, and fisher representatives are given the opportunity to be represented in the different operating committees to discuss and express their disapproval. Consultation, as an operation to collect the opinions of the actors concerned, does not lead to the sharing of decision-making power, nor does it guarantee that the opinions expressed will be taken into account. The government, which is responsible for implementing the European directives from which most of the research work stems, has the final word on the measures to be applied.

The empowerment of fishers to mitigate bycatch through the participation in research projects is also questionable due to the controversies regarding the impact of science on decision-making. When scientists present their assessments of the bycatch impact analysis with plausible ranges of values, recognizing the uncertainties in their conclusions, policymakers must choose a single value, knowing that the subtleties of a variance or confidence interval are generally beyond their grasp. Political arbitrage is not only determined by political will, since the research projects did not result in the identification of a silver bullet solution for bycatch. Scientists argue that uncertainty should not justify inaction, especially since for many of them the reality of the impact, in view of the state of knowledge and data available, is largely underestimated (Deldreve, 2010; Peltier et al., 2020b). However, the interpretation of scientific results by policymakers has most often led them to choose the least constraining option for fishers in the immediate term, even if this option has negative consequences in the medium and long term (Deldreve, 2010). Only a few binding regulations exist, such as the ban on driftnets. Moreover, researchers highlight that the current governmental incentives to pursue research can be interpreted as a political strategy to postpone political arbitrage. Indeed, research projects on bycatch are criticized for being instrumentalized in order to validate either conservation or exploitation policies, depending on the research institutions and on the political directives.

The decision-makers' approach to learn from the conflicts could suggest that controversies and alternative practices have had little impact on the genesis of knowledge and management methods. But it is difficult to evaluate the influence of the different sources of knowledge in the negotiation process informing the political arbitrage, due to the opacity of the process of construction of the political strategy. It is understood that scientific knowledge, although indispensable, could not be sufficient in view of the uncertainties that weigh on the data, the variables to be considered, and more broadly on the complex and uncertain realities of the marine and associated social environments. Recognizing the limits of the scientific approach when managing situations of crisis and high uncertainty is part of a more general reflection on the limits of representative, delegative democracy, where political actions are produced by central authority bodies which define both the objectives and the means to achieve them (Deldreve, 2010; Latour, 2018). This raises an interesting question about the extent of power-sharing that is required to find solutions for bycatch mitigation. The different manifestations of power in the conflicts, and the way power emerges and evolves through control, resistance, and solidarity, influence collaboration and learning (Armitage et al., 2007). The issue of the debates regarding whether the power gap is a factor blocking or facilitating transformation is critical for determining what "knowledge co-production" means for the future of fisheries science in settings where research is mobilized to foster innovation.

Recommendations

There are contradictions in the needs of the actors involved in the process of knowledge co-creation that does not lead to a holistic, silver bullet solution for bycatch. The complexities associated with the issue of bycatch requires to reject ready-made solutions, and instead compose a "situated knowledge", emphasizing the local and contingent connections. Collective commitment in bycatch mitigation projects, through conflict and collaboration, can be an opportunity to engage in collective learning (Cundill and Fabricius, 2010) and to inform decision-making processes to create inclusive and just biodiversity conservation policies.

The limits of the scientific approach highlighted by the conflicts with the fishers suggest that reform cannot be driven only by providing evidence that the current status quo has to change. Acknowledging the presence of conflicts between the stakeholders and understanding their roots and their impact on the co-design process can allow the identification of factors of path-dependency hindering the adaptive capacity of institutions. Conflicts can also prepare the system for change, and disagreements can become catalysts for social change and generate positive friction, if the necessary negotiating processes are in place to allow discussion among different narratives for the sustainability of the fishing sector.

The process of knowledge co-production on bycatch should be pursued, with the aim to foster a change in perspective of the actors involved, and a greater understanding of the other, creating incentives to think beyond dogmatic positions. Ensuring that the process will generate collective learning requires acknowledging the perceived dichotomy between academia and the fishing activities and to continue the effort of acculturating scientific and administrative structures to the working conditions of fishers. The collaboration between scientists and fishers has a very strong vocation to convey concepts produced in science to societal actors, but it requires to create the appropriate framework to be in capacity to share a common vocabulary (Fabricius and Cundill, 2014). Social science scientists can play a key role when shaping such a framework (Geistdoerfer, 2007), as well as a supranational organization dedicated to the issue, inspired by existing organizations, integrating the issue of ecological knowledge in their management processes (Danto, 2022).

Transformation of the fishing sector cannot be achieved without the fishers. As the research projects on bycatch progressively improve our understanding of the human-species interactions, national policies should be designed to empower fishers to foster the emergence of alternative practices through experimentation and through the sharing of good practices.

When negotiations fail to move further, and the actors are entrenched in their position, activating other levers in parallel of the political debate can help to recreate dialogue between the stakeholders. The current national strategies to reduce bycatch of small cetaceans and seabirds should be regularly updated with concrete actions to support the experimentation of alternative practices in order to rapidly find applicable solutions. For example, creating economic incentives for fishers to change practices.

The actors are placing a lot emphasis on the test of technological innovations to reduce bycatch. Market-based approaches or technological innovations are, in many instances, insufficient to produce sustainability transformations (Scoones et al., 2015). Accelerating long-term structural transitions also requires leveraging change of the social groups' standards, by contesting dominant social and political structures, and to reconsider the macro-economic dynamics of food production, as well as the deep cultural patterns interrelated with these dynamics (Geels and Schot, 2007).

Improving the quantitative and qualitative data and the sharing of other forms of knowledge provided by the fishers requires creating incentives for the different fishers to further contribute to the research projects, but also overcoming the resistance to non-scientific knowledge sources. Continuing to assess the potential of a hybridization of knowledges, with scientists, naturalists, and fishing professionals experimenting practices to reduce bycatch, is key to eventually creating the foundations for an inclusive decision-making framework.

Knowledge co-creation is a lengthy process which presents the risk of slowing down the transformation of the fishing sector. Yet, enough time needs to be dedicated to consult all stakeholders when conceptualizing the project, as well as to present them the methods of data analysis, and to give feedback on how the consultation has been integrated, or not, in the project. Particular attention should be given to the process of data interpretation and to the composition of the committee responsible for concluding on the measures to be taken.

The conflicts on bycatch mitigation relate to questions of identity, tradition, modes of production and individual consumption, which are often barriers to set alternative governance systems to foster the transformation of human-nature interrelations. Lessons can be drawn from the conflicts on bycatch mitigation to experiment adaptive management and set up a polycentric governance system. Adopting a critical and reflexive approach in bycatch research can contribute to the identification of best practices with regards to the role of governance in conservation conflicts.

The lack of consideration of fishers' needs and voice can undermine support of constituents and produce opposition, potentially undermining the long-term success of sustainability initiatives. Restoring a climate of trust requires understanding the needs, concerns, and motivations of the groups of fishers (Calderwood et al., 2021). The conflicts analyzed in this paper emphasize the critical importance of fishers' motivation and readiness to adapt to bycatch reduction policies. Fishers' fears and doubts should be taken seriously, and the objectives and solutions must be meaningful to them (Ears and Pol, 2022; Suuronen, 2022).

There are still important knowledge gaps regarding how to evaluate the outcomes of co-design processes in a context of tension. Further research should be realized on methods to measure to what extent collective learning is generated and how it enhances the resilience of communities beyond the research projects. Further studies should also be realized on the interactions between fishers and scientists with regards to bycatch mitigation and on fishers' perception of their political representation.

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CC did the bibliographic research and wrote the article. JR assisted in the writing and literature search. AD provided assistance with the bibliography. CM is the research project leader and assisted with the bibliography. All authors contributed to the article and approved the submitted version.

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EDITED BY
Nathalie A. Steins,
Wageningen Marine Research
IJmuiden, Netherlands

REVIEWED BY
Julia Calderwood,
Marine Institute, Ireland
Martin Pastoors,
Pelagic Freezer-trawler Association,
Netherlands

*CORRESPONDENCE
Cian Kelly
cian.kelly@ntnu.no

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Capturing big fisheries data: Integrating fishers' knowledge in a web-based decision support tool

Cian Kelly[1*], Finn Are Michelsen[2], Karl Johan Reite[2], Jeppe Kolding[3], Øystein Varpe[3,4], Are Prytz Berset[5] and Morten Omholt Alver[1]

[1]Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway, [2]Fisheries and new Biomarine Industry, SINTEF Ocean, Trondheim, Norway, [3]Department of Biological Sciences, University of Bergen, Bergen, Norway, [4]Norwegian Institute for Nature Research (NINA), Bergen, Norway, [5]GAGN AS consulting, Ålesund, Norway

There is increasing interest in utilizing fishers' knowledge to better understand the marine environment, given the spatial extent and temporal resolution of fishing vessel operations. Furthermore, fishers' knowledge is part of the best available information needed for sustainable harvesting of stocks, marine spatial planning and large-scale monitoring of fishing activity. However, there are difficulties with integrating such information into advisory processes. Data is often not systematically collected in a structured manner and there are issues around sharing of information within the industry, and between industry and research partners. Decision support systems for fishing planning and routing can integrate relevant information in a systematic way, which both incentivizes vessels to share information beneficial to their operations and capture time sensitive big datasets for marine research. The project Fishguider has been developing such a web-based decision support tool since 2019, together with partners in the Norwegian fishing fleet. The objectives of the project are twofold: 1) To provide a tool which provides relevant model and observation data to skippers, thus supporting sustainable fishing activity. 2) To foster bidirectional information flow between research and fishing activity by transfer of salient knowledge (both experiential and data-driven), thereby supporting knowledge creation for research and advisory processes. Here we provide a conceptual framework of the tool, along with current status and developments, while outlining specific challenges faced. We also present experiential input from fishers' regarding what they consider important sources of information when actively fishing, and how this has guided the development of the tool. We also explore potential benefits of utilizing such experiential knowledge generally. Moreover, we detail how such collaborations between industry and research may rapidly produce extensive, structured datasets for research and input into management of stocks. Ultimately, we suggest that such decision support services will motivate fishing vessels to collect and share data, while the available data will foster increased research, improving the decision support tool itself and consequently knowledge of the oceans, its fish stocks and fishing activities.

KEYWORDS

decision support, interface, knowledge, experience, observations, model

1 Introduction

There is a global movement towards better understanding and utilization of data and experience of fishers in order to inform research activity and management decisions (Johannes et al., 2008; Stephenson et al., 2016; Dyrset et al., 2022). This is due to an increasing awareness that it is advantageous to consider fishers' knowledge, as the quantity of information available to modern fleets is vast given the temporal and spatial extent of global fisheries operations, which is estimated at four times the spatial extent of agriculture (Kroodsma et al., 2018). Such knowledge includes the experiences of fishers themselves and information processing systems onboard, and is considered part of the best available information (Stephenson et al., 2016). This information can be used in stock assessment, marine spatial planning and mapping species abundance and distribution (Holm and Soma, 2016). Modern applications to real-time monitoring of vessel tracks can screen for illegal fishing activity and map the global footprint of effort (de Souza et al., 2016; Kroodsma et al., 2018). Remote sensing of environmental variables may be a cost-effective method of supporting fishing activities (Santos, 2000). The recent paper from Jones et al. (2022) demonstrates how high resolution data from the US reference fleet has contributed to abundance indices for several stocks, while footprints of fishing vessels can inform planning of offshore wind projects. A similar Norwegian reference fleet program found that gathering species and age composition data from fishing vessels is a cost-effective method of sampling and producing CPUE time series for cod, haddock and redfish (Hjelle et al., 2021).

Given the multitude benefits of using fishers' knowledge to inform policy, it begs the question why it's underutilized? For catch data, there is the issue of bias in samples for density estimates, as catch logs exclusively record instances of fishing activity, neglecting areas not targeted by fishers, which biases predictions of species distributions (Karp et al., 2022). Also, given the unsystematic way much of fishers' knowledge is handled, it is often neglected (Hind, 2015). This means that although the quantity of information is high, the quality is highly variable and potentially skewed. It's challenging to filter from individual knowledge claims to scientific input that is legitimate and salient for decision-making (Brattland, 2013; Röckmann et al., 2015). Regardless, there is the charge that biologists don't take fishers ecological knowledge seriously, where such information can avert collapses of spawning stocks (Johannes et al., 2008).

In addition to the benefits to decision makers of incorporating fishers' knowledge, there are increasingly clear incentives for fishers to contribute in meaningful ways. The historical trajectory of the Norwegian fishing industry has been to long-term sustainable harvesting. For example, advances in fish finding equipment, with the uptake of echosounders and sonar, has improved vertical and horizontal profiling of fish and led to more offshore and targeted exploitation of stocks (Nakken, 2008; Gordon and Hannesson, 2015). Advances in mechanical winches for trawling gear reduced the labour involved in hauling nets, and introduction of non-rotting synthetic fibres made nets pressure resistant, increasing catch efficiency (Hamre and Nakken, 1971; Jennings et al., 2001). A modern purse seiner makes particularly effective use of the listed advances, and is relatively fuel efficient, using approximately 0.1kg of fuel per kilo of fish (Schau et al., 2009). In addition to technological developments, structural changes to the fleet, from introduction of tradeable quotas, decommissioning schemes and general movement of labour away from the industry, have reduced overcapacity and increased operating margins (Standal and Asche, 2018; Fisheries Directorate, 2021). However, such technological advances are a double-edged sword. The cumulative impact of technological innovation, especially mechanical hauling, led to increased catch rates and the collapse of the North-East Atlantic herring stocks in the 1970s (Fiksen and Slotte, 2002; Gordon and Hannesson, 2015; Standal and Asche, 2018). Therefore, prudent management of stocks is essential alongside such developments.

Such modernization of the industry means vessels spend long periods at sea with advanced equipment such as echo-sounders and sonars, covering vast geographical areas, and thus, have access to large quantities of information. To utilize such information effectively, collaboration between researchers and fishers is important. Increased knowledge of the environment fishers operate within can contribute to achieving long-term objectives. In this work, the first objective is to supply fishers with information that reduces time spent searching for fishing grounds, while simultaneously reducing fuel use of vessels. The second objective is to build a system that automatically captures and stores data gathered while vessels are at sea.

Decision support systems (DSS) are tools that can integrate knowledge sources to achieve these objectives. Formulations of DSS include: manufacturing DSS that help deliver products and services to customers, clinical DSS used to improve healthcare delivery using clinical knowledge and patient information, and organizational DSS used to inform decisions on complex activities within a large organization (e.g. governmental body), through integration of knowledge such as norms and roles in the organization (Jacob and Pirkul, 1992; Sala et al., 2019; Sutton et al., 2020).

In the maritime context, the major application of DSS tools have been in the shipping industry, aimed mainly towards optimizing speed and routes of vessels and avoiding collisions between vessels (Lazarowska, 2014; Bal Beşikçi et al., 2016; Lee et al., 2018). As described in Gilman et al. (2022), forms of shipping DSS can be applied to support fishing route optimization. In this article we will refer to such computer based tools in the context of supporting stakeholder decisions in the fishing industry specifically. In this context, DSS that have been applied to support management decisions in spatial allocation of effort and bycatch management (Truong et al., 2005; Granado et al., 2021). Moreover, they have been used to provide model estimates on presence and size of fishing banks directly to fishers, thus reducing time and fuel spent on fishing operations (Iglesias et al., 2007). There are a wide range of actors who may benefit from such tools, from managers to ship owners and skippers. As researchers, it's important that research knowledge is integrated with the needs of industry to facilitate uptake of tools Röckmann et al. (2015). In this way, DSS can provide a vital link between research and the fishing industry, where two way information transfer can garner interest in results of research as directed towards their operation, while at the same time encouraging more engagement between parties.

The Fishguider project began in 2019 as a science-industry research collaboration aimed at both reducing fuel use and search time of the Norwegian fishing fleet and fostering two-way information transfer between fishers and researchers. Importantly, this was an industry directed project, where an umbrella organization of motivated fishing companies was founded to partially fund work activities, under the name of the North Atlantic Institute for Sustainable Fishing (NAIS). In consultation between NAIS and researchers, a DSS tool was conceived of as an appropriate method to co-create knowledge necessary to achieve long-term objectives of industry. Such co-creation of knowledge between research and industry is an effective way of building mutual trust between researchers and fishers (Holm and Soma, 2016). Additionally, the delivery of such a software solution is well placed for systematically capturing and sharing data between participants, and supporting management decisions through production of salient and legitimate knowledge. A key component of the project is the participation of fishers in the pilot program to ascertain the feasibility of the DSS tool. There is evidence suggesting that participation can increase in science-industry collaborations if results are perceived to be positive for industry (Calderwood et al., 2021).

In this article, we present the conceptual framework for the DSS tool being developed as part of Fishguider and it's current status, reflecting on similarities to other DSS tools mentioned above. The capacity to systematically capture and share information through a user interface is explored and we discuss how data-driven input and experiential knowledge inform the development of this interface. In addition, a questionnaire is presented, detailing fishers' experiences of which factors are most relevant when considering when and where to fish. Finally, we consider challenges in interpreting, capturing and sharing knowledge through this project.

2 Literature on DSS tools in the fisheries context

DSS tools are described as computer-based programs that integrate diverse information sources in order to support complex decision-making processes (Truong et al., 2005; Bal Beşikçi et al., 2016; Granado et al., 2021; Gilman et al., 2022). In a DSS, computer output virtually represents the real fisheries system, reducing uncertainties that constrain decision making (Truong et al., 2005). Decisions that require support systems usually address problems where there are competing interest groups, such as fishing effort allocation. Therefore, human participation and intervention are essential in the process (Bal Beşikçi et al., 2016; Gilman et al., 2022). In this way, DSS plays a supporting role in decision-making, rather than an executive role. Regardless, there are a multitude of areas where they can give insight, as shown in Table 1. The two broad applications are within fisheries management and industry-related optimization. A diverse range of inputs are used, from data-driven input such as remote sensing and vessel speed to knowledge based input from interdisciplinary collaboration and stakeholder engagements.

Fishers face many practical issues when searching for fishing grounds, such as uncertainties in weather conditions, quality and location of fish, and prices and costs being variable. In the face of these issues, they must make concrete decisions on how to organise fishing activities. The scales of fishing activity decisions can be separated based on duration into three categories: strategic, tactical and operational decisions. Strategic decisions (weeks to months to years) refers to long-term planning of location and timing of fishing based on expectations of both the market and fishing possibilities (Reite et al., 2021). Tactical decisions (hours to days) are decisions about which fishing grounds to visit, the number of grounds to visit and where and when to return to port to land catches (Granado et al., 2021). Long-term tactical decisions may involve, for example, planning of whether to target herring or mackerel based on market prices (Reite et al., 2021). Short-term tactical decisions include motion planning of fishing vessels and controlling position and course of vessels relative to schools of fish (Haugen and Imsland, 2019; Haugen and Kyllingstad, 2021; Kyllingstad et al., 2021). Operational decisions (near real-time) involve immediate control of the vessel, such as speed and heading of fishing vessels between waypoints defined through tactical decisions Granado et al. (2021). Assuming waypoints are clearly defined, operational decisions can be informed through routing optimization, which has been addressed using DSS tools in the shipping industry to reduce fuel consumption (Bal Beşikçi et al., 2016; Granado et al., 2021). However, defining strategic and tactical decisions is a complex task for fishing vessels searching for fish, given the uncertainties in stock distribution and abundance at these scales and therefore, the Fishguider DSS tool is designed to support these decisions.

DSS tools are designed with of a number of interconnected components. Fundamentally, they require high quality data sources, where data can be obtained from remote sensing of environmental variables such as sea surface temperature, weather archive data, information systems on board such as positional data, as well as manual input from ship operators (Iglesias et al., 2007; Bal Beşikçi et al., 2016; Lee et al., 2018). Data can also be gathered from national or global databases, such as historical catch data, where the data is directly relevant to fishers

TABLE 1 A selection of literature sorted chronologically on decision support in fisheries and shipping, describing the input used and the area of application.

Article	Input	Application
Lane and Stephenson (1998)	Interdisciplinary knowledge	Co-management of fisheries
Truong et al. (2005)	Fisheries-dependent data	Optimize fishing schedules
Koutroumanidis et al. (2006)	Time series modelling of fisheries landings	Fisheries management
Iglesias et al. (2007)	Remote sensing	Prediction of fishing banks
Carrick and Ostendorf (2007)	Spatial information and survey data	Economically sustainable fishing activity
Jarre et al. (2008)	Knowledge-based logical system	Ecosystems approach to fisheries management
Vinu Chandran et al. (2009)	Remote sensing	Identify potential fishing grounds
Azadivar et al. (2009)	Systems approach- optimization of schedules	Spatial management of stocks
Dowling et al. (2016)	Questionnaire and stock assessment	Management strategy evaluation
Hobday et al. (2016)	Dynamic ocean modelling	Fishing activity
Bal Beşikçi et al. (2016)	Vessel speed	Reducing fuel consumption of ships
Reite et al. (2017)	Vessel operation and energy system	Reducing fuel consumption of ships
Lee et al. (2018)	Vessel speed	Reducing fuel consumption of ships
Macher et al. (2018)	Stakeholder engagement	Management Strategy evaluation
Skjong et al. (2019)	Combining onboard sensors and mathematical models	Generic decision support
Granado et al. (2021)	Vessel speed and heading	Fishing route optimization
Macher et al. (2021)	Transdisciplinary partnerships	Ecosystem based management in fisheries
Reite et al. (2021)	Oceanographic simulations, catch data analyses	Prediction of fishing grounds
Gilman et al. (2022)	Categorization of mitigation	Bycatch management

operations and can improve their situational awareness. This data is uploaded to a database, where information is compiled and can be queried directly by the user. There is also typically a model solver which takes input and produces estimates of relevant information. Often the problems are complex and require pattern detection through machine learning and data mining algorithms, where artificial neural networks have been particularly effective (Bal Beşikçi et al., 2016).

This information is mapped to a user interface, where the user (fisher or manager) may query databases directly (Bal Beşikçi et al., 2016). User interfaces are typically tuned to the experience and requirements of the user. Information is often displayed in interactive layers which compile the most salient knowledge for decision making. For example, (Granado et al., 2021) describes decision layers developed for fishers to display routes based on an optimization algorithm which allows for interaction with the user. In addition, explicit costs associated with decisions may be displayed, such as in management decisions where there are multiple conflicting objectives such as safety and economic viability (Gilman et al., 2022).

3 Case study: The fishguider DSS tool

3.1 Description

The Fishguider DSS tool was requested by fishing companies working together in an umbrella organization called North Atlantic Institute for Sustainable Fishing (NAIS), who spend much time and fuel searching for fishing grounds, while lacking systemized knowledge to assist in making informed decisions on where and when to fish. The system desired should aid in communication of information between fishing vessels and allow them to both contribute and ascertain relevant information to minimize uncertainties when operating. Importantly, the fishers involved are motivated to collaborate with researchers and understand the ecosystem they operate within. The interested parties wish to build a knowledge base to ensure present and future sustainable harvesting. Specifically, a DSS system may aid in handling decisions made in light of the complexities of climate change, the potential shifts in distributions of fish stocks and instabilities in fuel prices. Improving the situational awareness through knowledge co-creation will help the fishers meet these demands, specifically aiding with strategic and tactical decision making.

The DSS is currently designed as a proof of concept which can be refined and scaled for industrial use. The scaling of the system relies in part on connecting more vessels to the project. Therefore a pilot programme of vessels is underway, where they are now utilizing the system during the fishing season. Participants are from a variety of fisheries, targeting both demersal and pelagic species, with different gears, quotas and sizes of vessels. At the time of writing, there are 19 vessels involved with the pilot project. Of those 6 are classed as coastal vessels, 3 large coastal, 7 ocean-going trawlers and 3 ocean-going purse seiner. In addition, 16 of these vessels are above

21m in length. These classes determine the quotas and areas where the vessel operates. For example, ocean-going vessels cannot operate within fjords without special permission. For pelagic species, the fishers are most active from October to December when herring overwinter near the coast and in Northern fjords and then again January to March during the spawning migration and spawning for the herring, while mackerel are mainly targeted during their wintering cycle in southern Norway from September to December when the market prices are highest, although there is inter-annual variability (Varpe et al., 2005; Nøttestad et al., 2016; Ølmheim, 2021; Reite et al., 2021). The following sections describe the DSS tool according to its data sources, model-based inputs and the user interface (Figure 1).

3.2 Knowledge sources for DSS

3.2.1 Experiential

In an effort to build a tool that is useful for the fishers, a survey in the form of a questionnaire was designed and 13 of the skippers in NAIS responded. The questionnaire was conducted by phone in 2020 in Norwegian and answers were translated into English. An online or paper-based solution were not possible due to logistic challenges with communication. The skippers surveyed are the most actively involved in the project. They target both pelagic and demersal species, but we learned from project meetings that they perceive the most immediate use of the tool in targeting herring and mackerel. Therefore, the questionnaire focused on these two species.

There were two categories of questions asked. The first related to the importance of a variety of factors in deciding when and where the new fishing season should begin (Figure 2). This set of questions corresponded to strategic decisions. The second related to to the importance of factors during the season (Figure 3). This set of questions corresponded to tactical decisions. The survey was designed to gauge the information fishers in NAIS consider important, regardless of availability, in making decisions to choose fishing grounds. Questions were chosen based on wide-ranging project meetings between researchers and active fishers in NAIS. Fishers expressed the importance of a full ecosystem understanding in decision-making, from plankton to whales, and therefore, questions of this nature were included.

Respondents were asked to rate the importance of items from both categories on an evaluative rating scale from 1 to 6, 6 being the highest value. Items were categorized based on their importance to fishers now and their potential importance in the future. The questionnaires displayed are the results for questions related to the targeting of herring. The mean values for the 13 respondents are displayed in the horizontal barplots (Figure 2 and 3). Given the sample surveyed, we don't assume this is completely representative of the fishing industry as a whole, especially given the number of large vessels involved. Additionally, social factors such as business structures and working rhythm may influence strategic and tactical decisions (Schadeberg et al., 2021). Nevertheless, the survey offered relevant input to the design of the support tool in order to make it

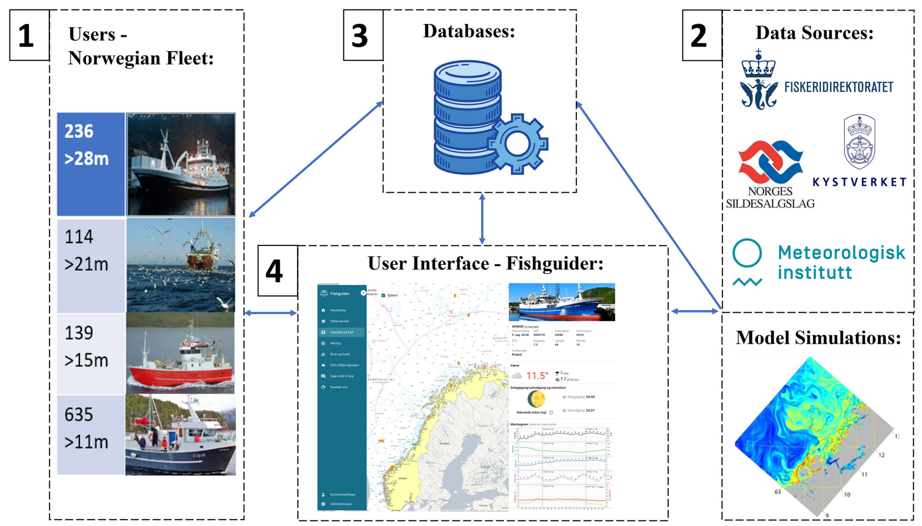

FIGURE 1
Conceptual model of the Fishguider tool: 1) The Norwegian Fleet of vessels over 11m in length who may contribute information, both from experiential knowledge and from information systems onboard vessels (such as satellite and acoustic data). 2) Fishers can access external information, such as meteorological forecasts, real-time auction prices and relevant model output. 3) The data sources are collected in databases developed in conjunction with the project. 4) The final user interface is a web portal that displays relevant layers to the skipper. The design of the interface is largely driven by the requests of participating fishers.

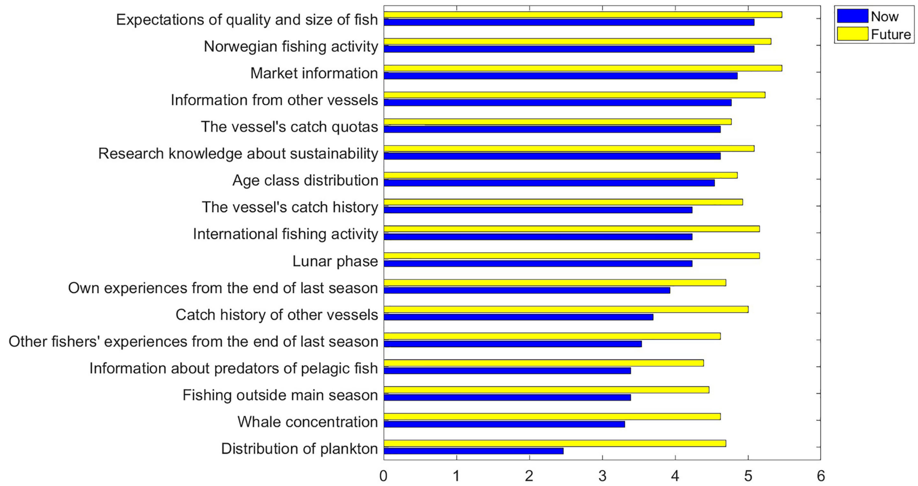

FIGURE 2
Response to Question: How important are the following factors when deciding when and where the new fishing season should begin? The blue bars indicate how important they are now, while the yellow bars signal the importance of better information in the future. The bars display the mean value (N = 13).

relevant for industry implementation, which was our main objective. A table of questionnaire responses for both herring and mackerel can be found in the appendix, with additional informal commentary from respondents included (Appendix A).

Generally, practical considerations such as the vessel's quota, catch history and Norwegian fishing activity are important now and are considered important in the future in strategic decision making (Figure 2). Ecological information such as whale concentration, plankton forecasts and information about predators are not strategically utilized now, but attaining such information is perceived as useful in the future.

Similarly, when asked what factors are important in tactical decision making, plankton forecasts and distribution of seabirds and whales are not utilized now, but such information may be valuable in the future (Figure 3). It must be noted that the perspective of fishers on the data they use today is likely based on their ongoing assessment of the quality of data available, while the question of future utility is made under the assumption that high quality data may be readily available. In real-time fishing activity, communication with other vessels, market forecasts and weather forecasts are seen as the most important factors to consider.

The questionnaire, complimented by meetings with fishers, has informed the development of the web portal over the past two years. Many of the information sources fishers deem important are publicly available and a major part of the work is compiling these in one place. Currently, communication between fishers is being facilitated through messaging options in the portal, weather forecasts are attained from the meteorological institute, such as wind speeds and swell at the vessels' location, and oceanographic data (particularly ocean currents), plankton and fish distribution data from model simulations are included. In addition, based on project meetings, it was discovered that fishers deemed the lunar phase an indicator of the timing of the initiation of herring spawning migrations. This factor was thus included in the questionnaire, and has been integrated into the support tool (Figure 4). Finally, the catch history of vessels, market information such as auction prices and vessel quotas, and the trajectories of individual vessels are now being connected to the portal. In the next sections, we explore the major knowledge sources available for the DSS tool.

3.2.2 Data-driven

In addition to the fishers'experiences as obtained from the questionnaire, data is being gathered from several sources. The catch and activity reporting (ERS) and Vessel Monitoring System (VMS) are electronic reporting systems for fisheries data provided by the Norwegian Directorate of Fisheries (https://www.fiskeridir.no/English/Fisheries/Electronic-Reporting-Systems). Whereas ERS data includes vessel positions for fishing activities such as 'in catch operation', 'pumping' and 'steaming' to and from harbour, VMS data includes more detailed position data for all types of vessels with a length of 15 meters and above, logged at minimum one hour sampling frequency. The ERS logs replaced physical logs of catches in 2005 where there is a principle of reporting all Norwegian fishing activity, with widespread adoption (https://www.fiskeridir.no/English/Fisheries/Electronic-Reporting-Systems).

Automatic identification systems data (AIS) are, like VMS data, detailed position data for all types of vessels. There are many sources available such as Marine Traffic (https://www.

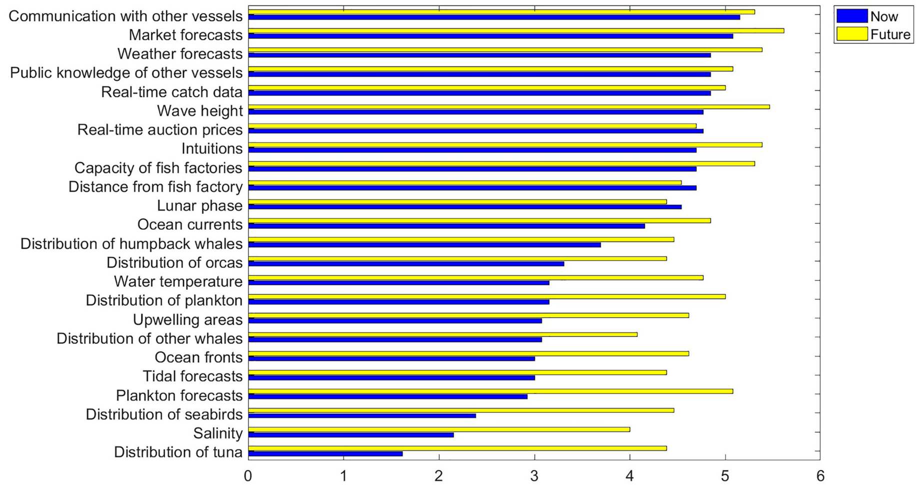

FIGURE 3
Response to Question: How important are the following factors for choosing a fishing spot during the season? The blue bars indicate how important they are now, while the yellow bars signal the importance of better information in the future. The bars display the mean value (N=13).

marinetraffic.com/en/ais/) and The Norwegian Coastal Administration (https://www.kystverket.no/en/navigation-and-monitoring/ais/access-to-ais-data/), which provides AIS data in real time, either as raw data or online traffic information displayed in charts. AIS data is primarily used by coastal administration to avoid shipping collisions and locating a given vessel quickly in an emergency situation. Given the time sensitivity needed to avoid collisions or respond to emergencies, data is transmitted approximately every 10 seconds. ERS, VMS and AIS data are complementary data for monitoring fishing vessel movements which are being integrated in the DSS tool.

The Norwegian Fishers' Sales Organization for Pelagic Fish (or *Norges Sildesalslag* in Norwegian: https://www.sildelaget.no/) is a fisher-owned sales organization that trades fish through an electronic auction. Fresh catches are offered to buyers while vessels are at sea, after the catch is registered over phone, and a commission price on the value of each catch is payed by the fisher (0.65 percent of each catch). Real-time auction prices are highly relevant to direct decisions on fishing, as reflected in the questionnaire responses, and will be integrated in the DSS tool (Figure 3).

Finally, vessels in the Norwegian fleet continuously gather observations using sonar and echosounder, but this data is usually discarded. A future version of Fishguider is expected to collect, aggregate and make decision support based on a fleet supplying such observations, and this work has begun.

3.2.3 Model simulations

Model simulations of conditions alongshore and offshore the Norwegian coast are currently being integrated into the DSS tool. Ocean model estimates of sea surface temperature, current and salinity are loaded from a model called SINMOD (Slagstad and McClimans, 2005). The output from this model has a 4km resolution and is centered on the Norwegian Sea. The model has a time resolution of 10 seconds. An eulerian model of the copepod species Calanus finmarchicus has been coupled to the SINMOD model, where plankton distributions are mainly driven by atmospheric fields including wind, air temperature and precipitation, river discharge, and bottom topography (bathymetry) (Wassmann et al., 2006). This species is a key prey item for many pelagic stocks in the Norwegian Sea. In addition, a model of the spawning migration of herring is coupled to SINMOD, where information on current, temperature and bathymetry are used to drive the fish motion towards their spawning areas (Kelly et al., 2022). All model ouputs are loaded to the web portal in near real-time.

Minimizing the gap between the true system and the model estimates depends on integrating as many vessels into the project. Capturing of data by vessels included in the project can strengthen input to these models, which improves their predictive capacity. An Ensemble Kalman Filter setup has been designed to allow assimilation of observation data into the migration model (Kelly et al., submitted). In the long-term this can develop larger datasets for studying effects of climate change, understanding life cycles and migrations of fish, and providing input into stock assessment.

3.3 Databases

Both national and international databases are being integrated into the web portal. FishGuider is currently being

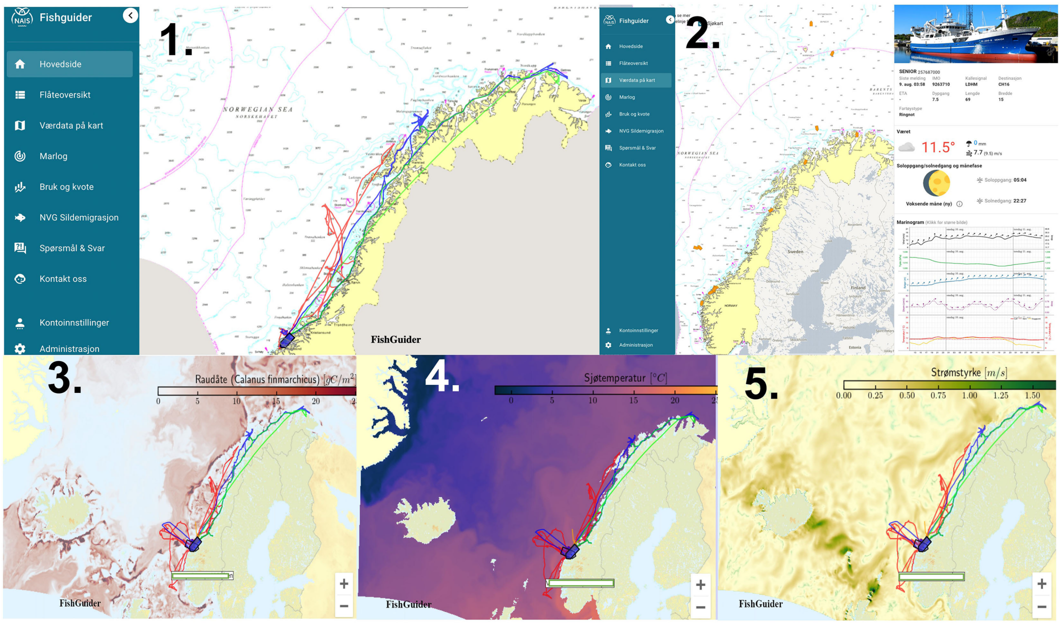

FIGURE 4
A selection of output layers in the Fishguider portal, with Norwegian text: 1) Homepage with tabs for various layers centered on the Norwegian Sea. The red, blue and green lines are the tracks of individual vessels based on GPS coordinates. 2) Weather data and forecast from the position of one of the NAIS vessels based on meterological institute data. 3) Modelled *Calanus finmarchicus* distribution and abundance in grams of carbon per meter squared 4) Sea surface temperature output on a single day in degrees Celsius. 5) Horizontal components of current velocities in meters per second.

integrated with FiskInfo (https://fhf-prod.azurewebsites.net), Kystverkets NAIS service (https://nais.kystverket.no/), BarentsWatch (https://www.barentswatch.no/en), Marine Traffic (https://www.marinetraffic.com/en/ais/), Ocean Resource Watch (https://resourcewatch.org/dashboards/ocean-watch) and other complementary information tools.

3.4 User interface

The user interface of Fishguider web portal provides layers of information tailored to the needs of the fisher. As mentioned, it has been curated according to the experiences of fishers, considering important features when planning fishing operations and in real-time (Figures 2, 3). The web portal has a fleet overview tab, which details the vessels involved in the project and their specifications. There are also messaging possibilities and contact points for the fishers, if they have any difficulties with usability of the tool. The tracks that are displayed in the interface are based on GPS transmitters installed onboard, which are being trialed (Figure 4). This interface has facilitated information flow between fishers and researchers, where fishers now have access to spatiotemporal data on current, temperature, nitrate, plankton and herring from research-based models developed, while researchers have access to observations from vessels which provide input to the models (Figure 4). This input can allow improvement of the accuracy of the model predictions, while also correcting errors in model output.

4 Takeaways

4.1 Knowledge co-creation

Such collaborations between industry and research may rapidly produce extensive, structured datasets for research and input into management of stocks. Involving enough fishers and/or vessels improves collaboration and will give more access to quality information. In general, the more vessels involved, the better. The vessels involved are representative of a subset of the coastal and oceanic fleet in Norway. The project results are presented at project meetings and industry conferences, such as Norfishing and The Midsund Conference (*Midsundkonferansen*). In this way, both participants and industry at large can provide input and feedback on the design of the tool. Additionally, as fishing companies are partly funding the project, key results are communicated to these larger audiences. Fishers seem interested to participate and share data on condition that the platform will yield useful input in guiding operations.

Sharing of information between researchers and fishers is key to achieving this. Given that the fishers themselves are interested in this work, they have been quite open to sharing vessel data. Due to competition between fishers there is a potential scepticism in sharing information, but this issue has become less important the last decade, as individual vessel quotas are the main limiting factor, less vessels participate and there is more transparency because of open data sources (AIS, VMS, ERS). By limiting the spread of information to those who contribute, this should not be a big issue for this project in the future. Furthermore, engagement with the DSS tool will develop the user experience and friendliness of the application, which in turn will encourage more participants to join the project.

The questionnaire results give insight into what fishers deem important factors in strategic and tactical decision making. However, the small sample size and evaluative scale used means we cannot gauge the prioritization of factors by fishers. Further work should consider ranking factors and matching available knowledge based on this. It is important to avoid the inclusion of all desired sources in the DSS tool at the cost of adequate user experience.

4.2 Research-based inputs

Collaboration between fishers and scientists has provided direct results that are salient for decisions regarding fishing activity. For example, fishing routes can be optimized to meet strategic, tactical and operational decisions (Granado et al., 2021). Spatially and temporally explicit maps of fish distribution are particularly useful for planning operations, and can be obtained through analysing remote sensing data (Iglesias et al., 2007). In our work, a migration model has been implemented to estimate the development of the herring spawning migration (Kelly et al., 2022). Lifting the modelling of fish migration, implementation and visualisation of the model to a level that gives the fishers useful additional information and promotes more active engagement with the tool.

Coordinating the various ideas and requirements from the diverse set of fishers is challenging, as there can be variability in the problems they face, depending on the target stock, vessel size and fuel consumption. Additionally, when asked about the utility of various factors in the future, almost all were considered useful in some way, especially research output which is not capitalized upon today (Figure 2 and Figure 3). Therefore, continuous dialogue and soliciting of feedback from fishers is central to qualifying the true importance of information for decision making. Understanding the behaviour of fishing vessels themselves is also important and progress has been made on categorizing activities automatically based on position, speed and heading of vessels (de Souza et al., 2016).

4.3 Advisory processes

Finally, DSS tools can contribute to advisory processes by reducing uncertainties involved in executive decision making. For example, offshore wind farms are planned along the coast of Norway, and the potential conflicts with industry may be anticipated and captured through understanding the movements of fishing vessels. Firstly, the formalized knowledge of fishers is relevant input into decision-making on management of stocks throughout the season. Fine grain information about individual vessels can improve CPUE indices, an important input for stock assessments (Campbell, 2004). Secondly, the legality of fishing activity can be monitored through automatic detection of vessel activities (Arasteh et al., 2020). Automatic monitoring of activity from data they can contribute, may be more desirable and less invasive than physical monitoring through observers or drones. Thirdly, collaboration between researchers, fishers and managers can improve decision-making on these issues. Of crucial importance is that the knowledge base is considered legitimate to decision-makers (Röckmann et al., 2015).

5 Conclusion

The Fishguider project has developed a functional pilot of a DSS tool which is being used for testing and development of the interface, databases and models, while simultaneously helping connect more vessels to the project. Currently, only small number of companies are involved, but the entire Norwegian fleet of fishing vessels are seen as potential participants. Fishguider was setup to primarily facilitate environmentally sustainable fishing activity by reducing search time and fuel consumption of fishing vessels. As the project has evolved, fuel prices have risen, and concerns about climate change have grown, making DSS tools like this one even more crucial. The knowledge being created should therefore be central to fishing activity, marine research and management going forward.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

CK: Wrote the manuscript and created figures and tables. FM: Provided details about model and observations inputs. KR: Provided information about the fishing industry and decision support literature. JK: Proofread the manuscript and provided additional references. ØV: Proofread the manuscript, provided feedback and added discussion points. AB. Provided details and images of the Fishguider tool. MA: Gave detailed feedback. All authors were involved editing a shared version of the manuscript in overleaf. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author AB is employed by GAGN AS consulting.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1051879/full#supplementary-material

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EDITED BY
Salvatore Siciliano,
Fundação Oswaldo Cruz (Fiocruz), Brazil

REVIEWED BY
Xiujuan Shan,
Yellow Sea Fisheries Research Institute (CAFS), China
Laura Uusitalo,
Finnish Environment Institute (SYKE), Finland

*CORRESPONDENCE
Nathalie A. Steins
nathalie.steins@wur.nl

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A will-o'-the wisp? On the utility of voluntary contributions of data and knowledge from the fishing industry to marine science

Nathalie A. Steins[1*], Steven Mackinson[2], Stephen C. Mangi[3], Martin A. Pastoors[4], Robert L. Stephenson[5,6], Marta Ballesteros[7], Kate Brooks[8], James A. McIsaac[9], Matthew R. Baker[10], Julia Calderwood[11], Barbara Neis[12], Emily M. Ogier[13] and Dave G. Reid[11]

[1]Wageningen Marine Research, Wageningen University & Research, IJmuiden, Netherlands, [2]Scottish Pelagic Fishermen's Association, Fraserburgh, United Kingdom, [3]MRAG Ltd., London, United Kingdom, [4]Pelagic Freezer-trawler Association, Zoetermeer, Netherlands, [5]Department of Fisheries and Oceans Canada, St. Andrews Biological Station, St. Andrews, NB, Canada, [6]Department of Biological Sciences, University of New Brunswick, St. John's, NB, Canada, [7]Fisheries Socioeconomic Department, Centro Tecnologico del Mar-Fundación CETMAR, Vigo, Spain, [8]KAL Analysis, Elsternwick, VIC, Australia, [9]T. Buck Suzuki Environmental Foundation, Victoria, BC, Canada, [10]North Pacific Research Board, Anchorage, AK, United States, [11]Marine Institute, Galway, Ireland, [12]Department of Sociology, Memorial University of Newfoundland, St. John's, NB, Canada, [13]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia

For future sustainable management of fisheries, we anticipate deeper and more diverse information will be needed. Future needs include not only biological data, but also information that can only come from fishers, such as real-time 'early warning' indicators of changes at sea, socio-economic data and fishing strategies. The fishing industry, in our experience, shows clear willingness to voluntarily contribute data and experiential knowledge, but there is little evidence that current institutional frameworks for science and management are receptive and equipped to accommodate such contributions. Current approaches to producing knowledge in support of fisheries management need critical re-evaluation, including the contributions that industry can make. Using examples from well-developed advisory systems in Europe, United States, Canada, Australia and New Zealand, we investigate evidence for three interrelated issues inhibiting systematic integration of voluntary industry contributions to science: (1) concerns about data quality; (2) beliefs about limitations in useability of unique fishers' knowledge; and (3) perceptions about the impact of industry contributions on the integrity of science. We show that whilst these issues are real, they can be addressed. Entrenching effective science-industry research collaboration (SIRC) calls for action in three specific areas; (i) a move towards alternative modes of knowledge production; (ii) establishing appropriate quality assurance frameworks; and (iii) transitioning to facilitating governance structures. Attention must also be paid to the science-policy-stakeholder interface. Better definition of industry's role in contributing to science will improve credibility and legitimacy of the scientific process, and of resulting management.

KEYWORDS

collaborative research, fishers' knowledge research, experiential knowledge, stakeholder engagement, fisheries science, trust, co-production of knowledge, science-industry research collaboration

Introduction

Science-industry research collaboration (SIRC) in fisheries is at a crossroads. SIRC, in our experience, is driven by a clear willingness on the part of the fishing industry to voluntarily collect and provide information to science in support of management, and by a growing interest within the scientific community to collaborate with fishers and their associated organizations ('the fishing industry') (Holm et al., 2020a; Steins et al., 2020a; Mackinson, 2022). For many, SIRC is seen as the way forward for cost-effective, improved data collection (Johnson and Van Densen, 2007; Wendt and Starr, 2009; Kraan et al., 2013; Stephenson et al., 2016; Mangi et al., 2018; Thompson et al., 2019). Experience shows that SIRC done well, can also increase transparency and communication, build capacity amongst fishers and scientists, improve societal relevance of research, and build a collaborative rationale for durable solutions (Karp et al., 2001; Johnson and Van Densen, 2007; Johnson, 2009; Innes and Booher, 2010; Doerner et al., 2015; Mackinson and Middleton, 2018; Mangi et al., 2018; Thompson et al., 2019; Holm et al., 2020a; Steins et al., 2020a; Mackinson, 2022).

In the field of gear technology, SIRC goes back many years (Feekings et al., 2019). However, in fish stock assessment and ecosystem science, input to science from the fishing industry has generally taken the form of recording and submitting a narrow range of fisheries-dependent types of data, such as statutory data on landings and fleet effort generated by industry, and data from sampling on board of fishing vessels by scientific observers. Since the turn of the 21st century some individual scientists and research projects have been more receptive to the benefits of direct participation of industry in gathering scientific data and exchanging knowledge (Stanley and Rice, 2007; Hind, 2015). Furthermore, openness to Indigenous knowledge became required in some regions of the world. Also, the need for active stakeholder involvement is now explicitly acknowledged in international policy frameworks such as the United Nations' Sustainable Development Goals (UN, 2015), and its guidelines for small-scale fisheries (FAO, 2015). As part of its criteria for research grants, Europe's Responsible Research and Innovation policy and actions (Owen et al., 2012) demands partnerships with industry and delivery of outcomes that address societal issues. These criteria encourage researchers to gather and access data through engagement with the fishing industry (Johnson and Van Densen, 2007; Doerner et al., 2015; Hind, 2015; Dubois et al., 2016; Stephenson et al., 2016; Mackinson and Middleton, 2018; Nursey-Bray et al., 2018; Baker et al., 2019; Bentley et al., 2019; Thompson et al., 2019; Holm et al., 2020a; Raicevich et al., 2020; Steins et al., 2020a).

In addition to the ability to collect and share quantitative data, the fishing industry also possesses important *"experiential knowledge"* (Stephenson et al., 2016) that can give context, and help with the interpretation of quantitative scientific and industry data and findings. Nevertheless, experiential knowledge routinely gets little consideration, often being qualified as biased or 'anecdotal' (Johannes and Neis, 2007) and thus not fit for purpose in science for management advice. Both quantitative and experiential information sources can be unique in the evidence and insight they offer and are relevant for enhancing scientific understanding of the marine environment (Neis et al., 1999; Bentley et al., 2019). They can inform the development of responsive management systems, as fishers are often the first to notice changes at sea. They can also contribute to the inclusion of social and economic considerations in fisheries management frameworks (Stephenson et al., 2018; Foley et al., 2020; Stephenson et al., 2021), hypothesis testing (Stanley and Rice, 2007) and coping with uncertainty (Dankel et al., 2012).

Despite a rich global literature on different forms of SIRC, there are only a few peer-reviewed publications where SIRC projects made a difference in scientific assessments as part of advisory processes (Melvin et al., 2002; Röckmann et al., 2015; Hesp et al., 2017; Duplisea, 2018; Bentley et al., 2019; Chagaris et al., 2020; Clegg et al., 2021; Howell et al., 2021). This indicates that while the value of using industry data and knowledge contributions and SIRC partnerships is increasingly recognized, there are still challenges about how to engage in

SIRC in a way that delivers good quality information considered trustworthy within the constraints of established, evidence-based decision-making processes. These challenges relate to both the mechanics of the scientific advisory system and opinions on how to govern its integrity (Linke et al., 2020).

This paper addresses questions about the utility of *voluntary* data and knowledge contributions from the fishing industry to enhance the evidence base used to inform fisheries science and ultimately, management. We combine insights from a literature review, our own experiences, and findings from structured expert discussions in regional workshops in Australia/New Zealand, the Americas and Europe, to investigate and characterize the conditions that determine whether voluntary data and knowledge contributions from the fishing industry are, should, or could be considered useful; or not. Our objective is to disentangle challenging, intertwined issues related to personal and institutional perceptions and practices around using industry information in assembling 'the best available information' for science.

We focus on 'voluntary contributions' – as opposed to 'statutory requirements' – including situations where the fishing industry by its own initiative or choice engages in SIRC as active contributors of their data and knowledge. Voluntary contributions may include situations that are more transactional in nature, but still characterized by deliberate choices over the extent to which fishers contribute. This would include, for example, the chartering of commercial vessels by scientific institutes to undertake fish stock surveys and responding to questionnaires and researcher requests for interviews. In this paper, the term 'fishing industry' encompasses both *fishers*, i.e., those who fish – whether it be small-scale, large-scale, independent, contractual, and irrespective of their gender, and *fishing organizations*, i.e., those higher-level entities such as alliances, associations, companies, cooperatives and unions, that represent fishers, fleets, or sectors. Fishers and fishing organizations are present in many science and management forums, making it hard to separate their voluntary contributions. That said, we recognize that they may encompass groups with different value systems, including around how they share their knowledge and with whom, and that the fishing industry is extremely heterogeneous around the world depending on the types of fisheries and even within the same métiers (Schadeberg et al., 2021), governance systems and cultures. Where separation of contributions by fishers and fishing organizations is important to the discussion, we make that distinction. The same thinking applies to the words 'scientists' and 'science' and the groups and phenomena they describe. Our focus on voluntary industry contributions is explicitly directed at regions with well-developed scientific advisory systems because this is where issues about the transition in governance and participatory approaches in fisheries are matters of debate rather than necessity (Stilgoe et al., 2013; García et al., 2016; Holm et al., 2020b; Linke et al., 2020; Macher et al., 2021).

In the next section, we outline our approach to identifying three key issues inhibiting systematic integration of voluntary industry contributions to science: (1) concerns about data quality; (2) beliefs about limitations in useability of unique fishers' knowledge; and (3) perceptions about the impact of industry contributions on the integrity of science. We will then review these issues. In particular, we focus on understanding the utility of voluntary contributions in specific applications and how they might affect confidence in the integrity of information, processes and science organizations. In summing up, we expose the dilemmas associated with using voluntary industry contributions and what it means for how the future of fisheries science is best conducted in the emerging frameworks for responsible research and innovation.

Method

Investigative critique

This research triangulates findings from a literature review, causal explanation (Nachmias and Frankfort-Nachmias, 1976), and expert judgement. The first five authors (Steins, Mackinson, Stephenson, Mangi, and Pastoors) originally set out to develop a comparative analysis of international experiences of SIRC projects using a review of the literature to arrive at tangible recommendations for sustained integration of knowledge generated through co-creation between fishers and scientists within the institutional frameworks for science and management. While conducting the review, these authors found few published examples where SIRC projects had made a difference in science or management, prompting them to confront their beliefs and wonder whether they were perhaps being led astray by a will-o'-the wisp[1]. This resulted in a new approach towards developing an investigative critique of the evidence around SIRC, formulating explanations in the form of the most vexatious and thorny questions related to involvement of fishers and the fishing industry in the provision of data and knowledge for science. A deliberately provocative approach was adopted, rooted in experiential observations of implicit bias against voluntary contributions. This enabled us, as confessed proponents of SIRC, to confront ourselves and the readers with the difficult questions that we might otherwise be expected to avoid.

1 *Will-o'-the-wisp is an atmospheric ghost light seen by travelers at night, especially over bogs, swamps or marshes, and is said to mislead travelers by resembling a flickering lamp or lantern. In literature, will-o'-the-wisp metaphorically refers to a hope or goal that leads one on but is impossible to reach, or something one finds sinister and confounding.* https://en.wikipedia.org/wiki/Will-o%27-the-wisp *and* https://historydaily.org/will-o-the-wisp-deadly-fairy-lights.

The original authors drew on their own knowledge of the literature and experience in SIRC or scientific advisory settings to identify five key elements associated with resistance to the use of voluntary knowledge contributions in scientific evidence to support management: (i) threats to quality; (ii) lack of reliability; (iii) threats to the integrity of science; (iv) concerns about the uniqueness or lack of added- value in SIRC; and (v) inconsistent availability. We then articulated potential explanations for these elements in five provocative statements intended to expose 'the elephant in the room[2]. We then carried out a literature review to assess the evidence to support or refute these statements (see Supplementary Materials). We focused on voluntary data and knowledge contributions, rather than statutory requirements, because they demonstrate an appeal from the fishing industry for engagement with science beyond that which is mandatory. Furthermore, it is here where questions about conflict of interest, trustworthiness and reliability make some scientists and receivers of scientific advice start to feel concerned. However, we did not neglect the importance of contributions linked to statutory reporting in the critique. In some contexts contributions linked to statutory reporting are also subject to the same issues of trust or conflict of interest and reliability as such data is also the industry's responsibility The evidence was drawn from referenced case studies from regions with well-developed fisheries assessment and scientific advisory processes.

Regional workshops

Having collated our evidence, the original team then identified a group of scientific experts with backgrounds in natural and social sciences and in fisheries research, advice and management, SIRC, and science-policy interfaces and invited them to participate in expert panels. Twenty-eight international colleagues agreed to meet to discuss whether arguments for and against the five provocative statements were justified. The meetings took the form of three online workshops for the following regions: Europe, Australia/New Zealand and the Americas. Each workshop was facilitated by a chair recruited from outside the original author group (authors Ballesteros, Brooks, and McIsaac). Chairs also prepared the resulting meeting reports (see Supplementary Materials). Participants received an evidence document ahead of the meeting and were asked to fill out a short assessment report and point to additional references or observed evidence relevant to the discussion. During the workshops, the original five authors introduced each of the 5 elements with a provocative statement to prompt discussion (see Supplementary Materials). They subsequently participated as observers as participants discussed each statement. Following the regional workshops, participants who could commit to an active role in the writing process joined the author group. All authors were involved in analyzing emerging themes from each workshop, as well as the separate evidence supplied by individual participants. Analysis took place *via* two online author meetings, joint working documents and by email correspondence, resulting in a rich and substantial volume of documented information (see Supplementary Materials).

Workshop discussions resulted in the merger of the original five key elements into three main issues relating to (1) the quality of voluntary contributions by the fishing industry; (2) the uniqueness of fishers' knowledge; and (3) the integrity of science (Figure 1; definitions in Table 1). Using this refined 'lens' for our approach, in the remainder of this paper, we look to identify with confidence, what, where and when there is utility in including the data and knowledge products of SIRC as evidence in assessment and scientific advisory processes, and the utility of the SIRC process itself in achieving this. We use 'quality' and 'uniqueness' as the key metrics of utility. We also explore important issues about notions of 'integrity' because they are linked with perceptions about utility.

Definitions

Beyond the clarification already made in the introduction regarding definitions for 'voluntary' and 'fishing industry', during discussions and subsequent analysis, it became clear that a common vocabulary was needed. For example, participating social scientists used the term 'data' to refer to all information and knowledge, whereas natural scientists generally referred to data as quantified information and were inclined to link experiential knowledge to 'anecdotal' information. For this reason, we developed a number of operational definitions for the main terminology used in this paper (Table 1).

Findings: Utility of fishing industry contributions to science

Compared to statutory fisheries data, there is limited evidence that either voluntary data from the fishing industry or experiential knowledge are systematically used in well-developed systems for fisheries assessment and management advice. This observation is in contrast to the keenness routinely expressed by industry in various fora to get involved in supporting the provision of scientific evidence (Graham et al., 2011; Doerner et al., 2015; ICES, 2019d), and with the growing interest by the scientific community to collaborate to improve the knowledge base for fisheries management (Holm et al., 2020a; Steins et al., 2020a; Mackinson, 2022). This lack of use

2 *The elephant in the room' is a metaphor to refer to an obvious major problem of issue that people avoid discussing or acknowledging because it makes at least some of them uncomfortable or is personally, socially, or politically embarrassing, controversial, inflammatory, or dangerous.* https://en.wikipedia.org/wiki/Elephant_in_the_room.

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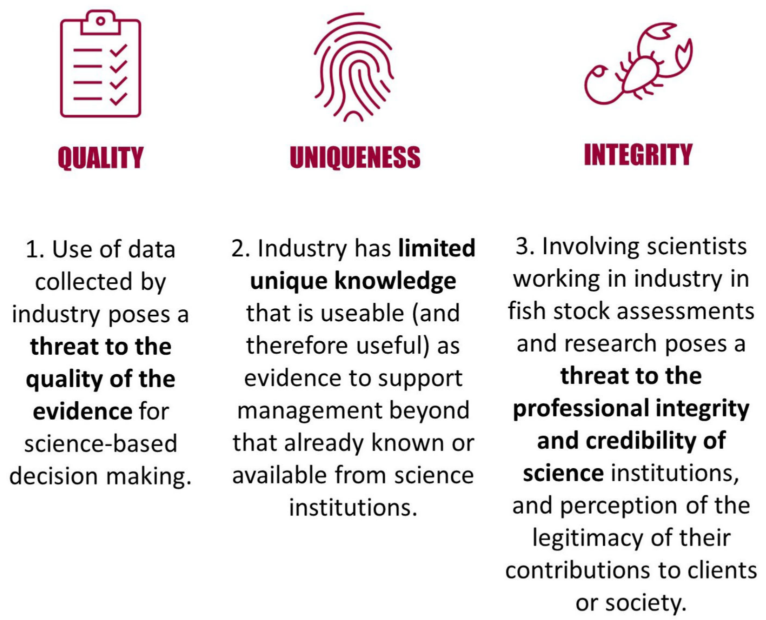

FIGURE 1
Analytical framework: Three key issues and associated provocative statements.

of voluntary data persists despite clear drivers in policy frameworks and funding mechanisms to facilitate stakeholder contributions to science [e.g., (Bradley et al., 2019; ICES, 2021c; ICES, 2021b)]. Our analysis suggests this is rooted in perceptions about the quality of voluntary industry contributions, uniqueness of fishers' knowledge and integrity of science (Figure 1).

Issue 1: Quality of voluntary industry contributions

Provocative debate prompt: Use of data collected by industry poses a threat to the quality of the evidence for science-based decision-making (Figure 1).

This statement is rooted in beliefs that voluntary contributions from industry cannot live up to the quality standards and consistent availability that should be expected of scientific data; additionally, that voluntary contributions are driven by opportunistic motives implying bias, or that information provided is 'anecdotal' and therefore not suitable. Evidence shows that concerns about quality issues related to industry data are indeed legitimate. Work on observer programs has shown disparity between data collected by fishers and observers, where the former are keen to record data on species they exploit or are more familiar with, while ignoring other species in the catch (Mangi et al., 2016). Similarly, positive bias has been observed in fishers' sampling data versus scientists' in stock surveys where both were using the same methodology (Mayfield et al., 2011). In this regard, fishers may not be equipped with the necessary professional education, skills and understanding of sampling design to collect data that meet scientific standards (Calderwood et al., 2021a), or have received instructions from scientists that were unclear or open to interpretation (Kraan et al., 2013; Stenevik et al., 2020). Also, self-sampling schemes may suffer from low sampling rates thereby increasing uncertainty in results (Starr, 2010; Clegg et al., 2022). Another quality concern is that the process of engaging in SIRC is associated with bias in relation to who participates and thus, where and which data are collected, as voluntary data collection often involves the same group of selected or motivated fishers (Kraan et al., 2013; Raicevich et al., 2020; Steins et al., 2020a).

Quality may also be affected when industry is constrained from engaging in SIRC due to limited finances or available time. They may underestimate the extent of the commitment and continuity of resources required for sustained research (Starr, 2010), making it difficult to ensure that data provision persists (Lordan et al., 2011; Mangi et al., 2015; Mangi et al., 2018; Raicevich et al., 2020; Steins et al., 2020a; Van Helmond et al., 2020). Continuity may also be affected when committed fishers leave the fishery (Jones et al., 2022) or when there are trust issues, for instance, when participating fishers or their peers fear the information they provide will be used against them, serving only to punish efforts of collaboration (Carruthers and Neis, 2011; Kraan et al., 2013; Mangi et al., 2015; Röckmann et al.,

TABLE 1 Operational definitions of terminology (in alphabetical order).

Term	Definition
Best available (scientific) information	Refers to not only the data, information, knowledge used for assessment and decision-making, but also the framework and processes that ensure this information is solicited, reviewed and evaluated, including objective-setting. The information may include environmental, biological, technical, economic and/or social data. The process should be iterative and targeted to address specific needs and aims and must be transparent, open, inclusive and objective. It should include independent review, validation, and be central to and embedded within management mechanisms (Lynch et al., 2018; ICES, 2019a; Su et al., 2021).
Co-production of data, information and knowledge AKA Mode 2 science	Scientific knowledge that is co-produced with stakeholders in academic-industry/stakeholder interactions. Compared to Mode 1 science, Mode science 2 is characterized by: (1) a context of application; (2) transdisciplinarity; (3) heterogeneity in terms of organizations involved; (4) reflexivity, in that is a dialogic process that incorporates multiple perspectives; (5) a novel quality control approach, where traditional peer-review is supplemented by additional criteria (socio-economic, cultural, political) (Hessels and van Lente, 2008)..
Data	Individual facts, figures, signals and measurements that are products of observation. Data represent the properties of objects, events and their environments but lack meaning or value as data are without context (Ackoff, 1989; Rowley, 2007).
Fishers' Experiential Knowledge	Contextual knowledge and sensitivity about the social-ecological system as a result of fishers' or fishing communities' experiences from working in that system and its associated socio-economic, cultural, technological, physical or other changes, often over many generations (Johannes, 1981; Neis and Felt, 2000; Perry and Ommer, 2003; Haggan et al., 2007; St. Martin et al., 2007; Hind, 2015; Stephenson et al., 2016). Experiential knowledge includes Traditional Ecological Knowledge with a focus on Indigenous peoples (Johannes, 1981) and Local Ecological Knowledge with a focus on fishers rooted in communities with a long history of engaging in particular subsistence, commercial or recreational fisheries (Neis and Felt, 2000).
Fishers' Knowledge Research	A body of research that does not regard science and fishers' knowledge as two separate entities but suggests that data from measured observations and experiential knowledge of fishers should be included in scientific assessments in support of management. Fisher's Knowledge Research covers a broad spectrum, from providing observational-based data or experiential information to scientists to full participation and acceptance of experiential knowledge as part of using the best available information (Stephenson et al., 2016).
Fishing industry	Generic catch-all term representing both fishers, i.e., those who fish whether it be small-scale, large-scale, independent, contractual, and irrespective of their gender, and the fishing organizations, i.e. those higher-level entities such alliances, associations, companies, cooperatives and unions, that represent fishers, fleets or sectors.
Information	Extracted from data, through processing, analysis and organization, to add value to the understanding of a subject [broadly based on (Ackoff, 1989; Rowley, 2007)].
Integrity of science	Defined as research that is: (1) reliable – as it ensures research quality; (2) honest – by being transparent, fair, full and unbiased; (3) respectful – for participants, stakeholders and the social, cultural and natural environment; (4) accountable – for its design, organization and wider impacts (ALLEA, 2017).
Knowledge	Facts, information, and skills acquired through experience or education, resulting in theoretical or practical understanding of a subject (Jenkins, 2004).
Knowledge – fishers' knowledge	Both a body of knowledge held by individuals or groups of fishers or fishing communities and a process of producing and assembling that knowledge through observations, trial and error, contextual experiences and research.
Knowledge – scientific knowledge AKA Mode 1 science	Both a body of knowledge and a process of producing knowledge in which that knowledge is produced and organized in systematic ways and according to general principles. Processes of observation and experimentation are typically used to produce empirical scientific knowledge and support scientific theory building. This traditional interpretation of scientific knowledge is also referred to as Mode 1 science (Hessels and van Lente, 2008).
Mode 1 science	See Knowledge – Scientific knowledge above.
Mode 2 science	See Co-production of data, information and knowledge AKA Mode 2 science above.
Quality of research	Narrow definitions of quality used in disciplinary research focus on scientific excellence and relevance, with established disciplinary criteria and processes for evaluating research quality (Belcher et al., 2016). We define Quality from a Mode 2 science perspective. Good quality 'transdisciplinary research' (Tress et al., 2005) meets 4 principles: (1) relevance – the importance, significance, and usefulness of objectives, process and findings to problem context and society; (2) credibility – robustness and trustworthiness of knowledge produced; (3) legitimacy – research is perceived as fair and ethical by end-users; (4) effectiveness – research contributes to positive change in the social, economic and/or environmental problem context (Belcher et al., 2016).
Statutory data	Fisheries-dependent quantified data that fishers or the fishing industry must provide to national authorities and science organizations as part of legal obligations. Examples of statutory data include landings and effort data, discards data from observer schemes, biological data on species, results of gear selectivity trials, data on the frequency of interactions with vulnerable species, economic performance data and social metrics.
Uniqueness of knowledge	Knowledge that is the result of fishers' experience and observations, which cannot be derived from other sources.

(Continued)

TABLE 1 Continued

Term	Definition
available from fishers	
Voluntary contributions	Data, information and knowledge actively contributed to science by industry's own initiative or willingness to engage in SIRC. Examples of voluntary contributions can be similar as those mentioned under statutory data; they may also be transactional in nature such as chartering their vessels for research surveys. Voluntary contributions are always by the fisher's own choice.

2015; Barz et al., 2020; Wätjen and Ramírez-Monsalve, 2020; Calderwood et al., 2021b; Cvitanovic et al., 2021; Ford and Stewart, 2021). Finally, data may be withdrawn because of opportunistic motives, as was the case for a stock assessment by the International Council for the Exploration of the Sea (ICES), where *"a fishing industry offered survey data they had funded but withdrew the information when the inclusion resulted in a lower Total Allowable Catch [advice]"* (ICES, 2014).

Evidence also shows, however, that concerns about the quality of industry data can and have been successfully addressed through a variety of methods including training, development of sampling standards, interviewing, and systems of verification and validation (Neis et al., 1999; Stephenson et al., 1999; Johannes et al., 2000; MinPI, 2011; Kraan et al., 2013; Mion et al., 2015; Fry et al., 2018; Mangi et al., 2018; ICES, 2019d; Keane et al., 2019; Thompson et al., 2019; Flores Martin, 2020; Raicevich et al., 2020; Stenevik et al., 2020; Suuronen and Gilman, 2020; Van Helmond et al., 2020). Further, concerns about data quality are not unique to industry but also apply to science (Liggins et al., 1997; Benoit and Allard, 2009; Cartwright, 2019; Gismondi et al., 2020; Fernandes et al., 2021).

Using fishers to collect data allows for dealing with time, cost and spatial and temporal restrictions associated with scientific catch sampling programs (Poos et al., 2013; Jones et al., 2022). When many vessels of a fleet are involved in sampling, geographical coverage can be extensive and fully representative of the area fished by this fleet. The number of trips sampled can outweigh limitations of small sample sizes from each vessel (Bjørkan, 2011; Pennington and Helle, 2011; Kraan et al., 2013; Gawarkiewicz and Malek Mercer, 2019; Jones et al., 2022). Voluntary fishing industry data, including from fish processors, may exceed that collected by government or third-party sampling schemes in amount and distribution (Mackinson et al., under review; Power et al., 2007; Rochette et al., 2018; Dunn, 2020; Kenyon et al., 2022). Such sampling can go beyond providing data on catches, and can contribute to surveying parts of the stock not targeted in the same way that fisheries-independent scientific surveys do (Gerlotto et al., 2012; Schram et al., 2021). In addition to fish stock assessments, industry data have also contributed to an improved knowledge base or validation of by-catch data regarding seabirds, marine mammals and Endangered, Threatened and Protected species (Bjørkan, 2011; Fangel et al., 2015; Fry et al., 2018; Moan et al., 2020). Such voluntary industry contributions, provided they are done well, all contribute to improving quality of data collected by science institutions.

To overcome concerns about consistent, long-term availability of voluntary industry data, most long-term SIRC initiatives rely on an assortment of remuneration options, such as remuneration for haul specific logbook data or discard samples (Kraan et al., 2013; Jones et al., 2022); payment of net income differences with comparable vessels not involved in research (Schram et al., 2021); additional quota allocations (Kindt-Larsen et al., 2011; Van Helmond et al., 2016); or payment for ship and crew hire (Ressler et al., 2009; Gallaudet, 2021; Hoff et al., 2021). In this context, it is important to note that concerns about long-term availability of data and information are not exclusive to industry contributions. There is a perception that fisheries-independent data collection has a high level of funding security, because it is usually embedded in (inter)national agreements. But this is not a guarantee that such scientific sampling schemes will continue. For example, the ICES stock assessment for North East Atlantic mackerel was impacted by Norway's decision to step out of the egg survey to pursue a swept-area survey (Spijkers and Boonstra, 2017). In Canada, the 4WX larval herring survey was eliminated after 22 years (Stephenson et al., 2015) during a time of fiscal restraint within government. Also in New Zealand, statutory data systems have suffered from continuity of quality (Langley, 2014; Middleton, 2021). Equally, major changes in commercial fisheries due to policy decisions, such as fishery closures, can result in the termination of long-term Catch per Unit of Effort (CPUE) series used in assessments. Finally, there are continuity issues in scientific data collection in relation to a changing world. For example, in the context of climate change, scientific surveys that are standardized to allow for time-series development of relative changes in fish stock populations may miss important changes in stock dynamics (Karp et al., 2022). Here, fishers' knowledge contributions can assist evaluation of the need for potential changes in survey design.

In considering the quality of voluntary industry contributions, concerns about the trustworthiness and reliability of such data, as well as conflict of interest (see issue 3), make some scientists and receivers of scientific advice worry. However, issues with data quality and reliability are not unique to industry. In this context, it is worth reflecting on experiences with existing statutory data collection, which share related concerns about reliability. For instance, catch misreporting or aggregation of species into generic groups may lead to incorrect interpretations of fishing pressure on stocks and affect the quality of assessments and the advice upon which they are based (Patterson, 1998; Bradley et al., 2019). Despite these concerns, statutory catch data collection schemes remain a cornerstone of information for assessments. Another example is observer bias, a known issue, even when highly trained scientific observers collect data (Liggins et al., 1997; Benoit and Allard, 2009; Kraan et al., 2013; Suuronen and Gilman, 2020). Observer bias is accepted implicitly, whereas information provided by industry is more heavily scrutinized (Kraan et al., 2013; Berg et al., 2022; Clegg et al., 2022).

When specific concerns about the quality of data contributions from industry have been addressed, as is best practice for any source of data, there is no reason why such information should not be used in scientific research. Indeed, fisheries-dependent data are often the only available source for assessments of commercially important fish stocks when there are financial, spatial or temporal limitations to fisheries-independent data collection. This is the case for Alaska, Australia, Canada and New Zealand. Potential shortcomings of voluntary industry contributions can be mitigated by co-design of sampling schemes and putting in place necessary quality control measures in the same way as implemented by most scientific institutes or science organizations. But the presence of such quality control systems does not mean that issues and concerns regarding quality can always be fully eliminated. There are numerous examples in well-developed scientific advisory systems where data and methodological errors were detected after scientific advice was given (Hilborn and Peterman, 1996; Spijkers and Boonstra, 2017; ICES, 2019c; SWFPA and SFA, 2021; ICES, 2022). Mostly, the evidence trail for these is transparent, but not always. For example, in the ICES assessment for blue whiting, the 2010 survey estimate was initially included in the assessment (ICES, 2010) and later withdrawn because it was considered to be an outlier, i.e., quality issue, without a clear explanation (ICES, 2012).

There is evidence that fishers' motives for data collection can be short-term and motivated by a combination of objectives such as deriving immediate financial gain, improving fishing opportunities, and providing evidence to impact decision-making (Woo et al., 2013; Dubois et al., 2016). This will also influence their decisions to be involved in long-term data collection. While scientists' objectives for data collection are unlikely to be driven by opportunities for personal financial gain, scientists do have interests to consider, such as research grants, project objectives and publication track records. Scientists also often share fishers' motivations to influence others' views. This is a reality of the competition for scientific knowledge and differences in opinion that exists in science; even if the 'scientific approach' seeks to be neutral, treating different viewpoints as testable hypotheses, without a stake in any particular result. However, SIRC experiences also show that it is wrong to assume that by default the industry has only short-term, opportunistic motivations with regards to voluntary data collection. The industry also recognizes the importance of long-term data collection, including funding these schemes (Starr, 2010; Mackinson and Middleton, 2018; Pastoors, 2021). The motivations for SIRC projects are often founded upon a desire to contribute knowledge and data to a continuous improvement process for stock assessment and advice, and also to provide internal business intelligence information relevant to skippers and owners. Examples are European pelagic industries that work on the development of standardized commercial CPUE series for data-limited stocks (Pastoors and Hintzen, 2020; Quirijns and Pastoors, 2020). They have also implemented self-sampling data collection schemes to clarify biological questions on the duration of the spawning period of mackerel and the linkage between populations in the western area and the North Sea (Pastoors, 2021; Kenyon et al., 2022; Mackinson, 2022). The Dutch demersal industry initiated a dedicated survey for North Sea turbot and brill in response to ICES advice that highlights the need for such a survey (ICES, 2019b; Schram et al., 2021). Other motivations for funding voluntary data collection include, for example, requirements to provide evidence in support of sustainability certification schemes or providing information for developing fisheries management plans, including harvest control rules and protection of spawning and nursery areas (Steenbergen et al., 2017; Holm et al., 2020a).

Increasing recognition and experience of the benefits of industry participation in catch sampling and surveys (Poos et al., 2013; Doerner et al., 2015; Mangi et al., 2018; Gawarkiewicz and Malek Mercer, 2019; Holm et al., 2020a; Steins et al., 2020a; De Boois et al., 2021; Jones et al., 2022; Mackinson, 2022), combined with government budget declines, and increasing data and information demands to service ecosystem-based advice and management (Ballesteros et al., 2018; Bradley et al., 2019), have led to increased delegation of responsibilities and costs of sampling from government to industry. Such delegation can also contribute to the development of trust relations. It is widely recognized that SIRC can contribute to developing mutual trust (e.g., St. Martin et al., 2007; Holm et al., 2020a; Steins et al., 2020a; Ford and Stewart, 2021; Macher et al., 2021; Köpsel, 2022) and to industry's perceptions about the legitimacy of science (Murray et al., 2008b; Johnson and McCay, 2012; Röckmann et al., 2015;

Stephenson et al., 2016; De Boois et al., 2021; Su et al., 2021). Once trust has been established the degree of integration of industry data (Stephenson et al., 2016; Cvitanovic et al., 2021) and unique experiential knowledge (Steins et al., 2020a) may evolve. However, in our experience, acceptance of this experiential knowledge in well-developed scientific advisory systems for fisheries and ecosystem management tends to be problematic.

Issue 2: Uniqueness of fishers' knowledge

Provocative debate prompt: Industry has limited unique knowledge that is usable (and therefore useful) as evidence to support management beyond that already known or available from science institutions (Figure 1).

Most SIRC projects have focused narrowly on working with fishers on gear and selectivity research, using fishers to help collect basic biological and catch information or using industry vessels for science-directed survey observation platforms. Whereas engagement with measurable industry data is growing, experiential knowledge seems to be overlooked. Globally, fisheries scientists struggle to include information that is not quantitative or is considered to be 'anecdotal' (Johannes and Neis, 2007) and, while potentially beneficial to providing important context, is not regarded as fit-for-purpose in quantitative science or usable in receiving systems that prefer fisheries-independent information and independent sampling. Using experiential knowledge also suffers from even more pronounced suspicions than measurable industry data regarding opportunistic motives and efforts to frame alternative explanations to scientific findings (Issue 1, previous section). These perceptions persist despite the existence of policy frameworks in regions with well-developed scientific advisory systems that prescribe or include binding requests to use the best available information, including fishers' knowledge (MinPI, 2011; Owen et al., 2012; Lynch et al., 2018; ICES, 2020a). In these contexts, the question is whether and under what conditions experiential knowledge, due to its unique nature, can be used and is therefore useful as evidence to inform management beyond that already known or available from science institutions.

Some experiential observations are perceived as relevant and fit readily into assessment-related evaluation, e.g. the impact of tide conditions on catchability. But often experiential information does not fit easily into the established assessment structure and therefore is perceived as unsubstantiated evidence used in an attempt to influence management. One example is where fishers' knowledge of fish distribution and how it changes leads them to question the utility of random sampling as a scientific research design (De Boois et al., 2021). This is one of the contexts where experiential knowledge is overlooked or often dismissed as being 'anecdotal', even when the collective experience of individual fishers or fishing communities point to changes in a stock that may affect the appropriateness of a particular survey design. What makes 'anecdotal' information considered to be less true useful for monitoring change is not necessarily that it is less true, but that it is regarded as not 'systematic' (Wilson, 2009). For example, stock assessment science tends to be based on large spatial scale units, discrete sampling techniques, and standardized sampling protocols, whereas experiential knowledge is often more localized and is based on different and often variable temporal scales and continuous sampling practices and technologies (Perry and Ommer, 2003; Wilson, 2009; Karp et al., 2022). These are some of the reasons why experiential knowledge is often considered unusable in fish stock or ecological assessment models; particularly those that are already data-rich (Mackinson and Nøttestad, 1998). Most stock assessment protocols lack the flexibility to incorporate experiential knowledge in a meaningful way.

Dismissing fishers' experiential knowledge as 'anecdotal' and thus not useable may have serious unintended consequences. Several examples illustrate that dismissing information from fishers came at a high price. These include the cod stock collapse in Canada (Finlayson, 1994; Neis et al., 1999; Rose and Kulka, 1999) and the ICES Northeast Atlantic mackerel assessment (Spijkers and Boonstra, 2017; ICES, 2019c). Indeed, where scientists have made efforts to include experiential knowledge in quantitative fisheries science, it can make significant contributions. In Canada, systematically collected information from experiential knowledge furthered understanding of relevant variables in the northern cod assessments such as stock structure, identification of spawning areas, technological creep and spatial dynamics (Neis, 1992; Neis et al., 1999; Murray et al., 2008a; Murray et al., 2008b; Johnsen et al., 2009). Within ICES, fishers' experiential knowledge was successfully used to improve the Irish Sea ecosystem model for informing the fisheries stock assessment process (ICES, 2020b). The model that included experiential information performed the best overall statistical fit, capturing the biomass trends of commercial stocks. It also replicated the increase in landings of benthos and epifauna, which were poorly simulated in the model that only used scientific data (Bentley et al., 2019). These examples also highlight that, like fishers, scientists also make assumptions about how fisheries and ecosystem dynamics work.

While scientists' assumptions may be rooted in existing science findings, their assumptions are also based on their own experiences or perceptions, and therefore it must be noted that scientists' assumptions may be flawed, just like fishers' assumptions can be. For example, fishers' knowledge successfully challenged scientists' assumptions about past landings by providing insights on discards and high-grading (Palmer and Sinclair, 1997; Duplisea, 2018). In Alaska, scientists' assumptions for a 'safe counting protocol' for bowhead whale migration led to meaningless scientific estimates. Eventually, after 14 years, a revised and more satisfactory monitoring program based on Inuit fishers' knowledge was adopted (Johannes et al., 2000).

It is true that experiential knowledge may not always be available in a form that is fit for quantitative assessmentsor evaluating the options among alternative management approaches, but there are also alternative ways of incorporating it into science and management. The private Marine Stewardship Council certification program developed a qualitative, risked-based assessment methodology for the evaluation of data-limited fisheries against its standard for sustainable fisheries (MSC, 2022). This precautionary methodology for stock and ecosystem assessment relies heavily on qualitative appraisal of fishers' experiential knowledge. Also, science organizations have been known to use experiential information from fishers in validating or cross-checking scientific findings. For example, between 2002 and 2014, the international Fishers' North Sea Stock Survey (FNSS) provided a qualitative assessment of fishers' perceptions on relative changes in abundance, fish size, discards and recruitment of eight species compared to the previous year (Napier, 2014). Although the relevant ICES stock assessment group could not use the FNSS results in their quantitative models and the survey was considered to be *"non-quantitative and subjective [in] nature"* (Napier, 2014; Stange, 2017), the group responsible for drafting ICES advice occasionally used the results of the FNSS qualitatively for sense-checking of stock assessment results. The survey was discontinued due to declining fishers' participation, possibly caused by frustration about lack of uptake by ICES (Stange, 2017). In Australia and New Zealand, fishers' experiential knowledge has also proven to be useful in understanding changes in CPUE trends, particularly when no or limited fisheries-independent data are available. After all, CPUE deviations do not necessarily have to be related to changes in stock abundance but can be related to technological changes, changes in fisher behavior resulting from market/economic drivers or regulatory changes (Johnsen et al., 2009), or changes in fish behavior (Fernö et al., 2011).

Experiential knowledge from fishers is also useful for guiding assumptions and interpreting results from Management Strategy Evaluations (MSEs). Most MSEs are largely based on relatively complex simulation tools that have a very simplistic representation of fishers' decision-making and behavior. The same applies to mixed fisheries models and displacement models (Nielsen et al., 2018; Wijermans et al., 2020). Information from the fishing industry can be used to test assumptions and generate more realistic expectations on the type of changes that may be assumed when management measures change, thus making fisheries and ecosystem models and MSEs more informative for management (Steenbergen et al., 2015; Pope et al., 2019; Wijermans et al., 2020; Schadeberg et al., 2021). One example is the development of a harvest strategy for the Australian Southern and Eastern Scale Fish and Shark Fishery. Separate quantitative and qualitative stakeholder information-based MSEs were done, including projecting the same set of indicators under the same set of alternative harvest strategies. Both showed very similar results. The qualitative MSE was, however, *"instrumental in helping industry confront a range of systemic problems and issues in the fishery, and was used in part as the basis for a successful call for assistance in restructuring the fishery to achieve the changes that were identified as needed"* (Smith et al., 2007). Information on fishing strategies, including economic and social aspects is also key in evaluation of 'full spectrum sustainability' (Foley et al., 2020), which extends the traditional focus of MSEs on ecological and economic to include social, cultural and institutional considerations (Stephenson et al., 2018). As attention to these 'human dimensions' of fisheries management increases, the need for, and role of, fishers' experiential knowledge will also increase (Stephenson et al., 2021).

Scientists also have used experiential knowledge to find alternative explanations for scientific observations. For example, in the case of a camera monitoring scheme as part of North Sea cod management, the apparent behavior of the fleet did not follow scientific predictions, which were based on incorrect assumptions. Subsequent interviews with fishers resulted in a logical, but unconsidered, explanation for these changes (Van Helmond et al., 2016). Engaging with fishers in research and, by extension, with their experiences does not always result in changes to science but can add to the sum total of knowledge on both sides, as with the collaboration between commercial fishers and government scientists related to Pacific rockfish off British Columbia that ranged from hypothesis formulation through data analysis (Stanley and Rice, 2007).

Other areas of fisheries science where fishers' experiential knowledge has been used is in the documentation of new or invasive species (Azzurro et al., 2019), reporting of ecological change (Keane et al., 2019), enhancing the underpinning of the science base for protecting vulnerable species and habitats (Gass and Willison, 2005; Colpron et al., 2010; Bjørkan, 2011; Kraan, 2015), establishing the relationship between vessel size, gear size and catching capacity (Reid et al., 2011), and in survey gear technology (Cotter, 2004; Reid et al., 2007; DeCelles et al., 2012; Johnson and McCay, 2012; De Boois et al., 2021; Jones et al., 2021).

Even where fishers' experiential knowledge is very relevant, linking it to phenomena at a broader spatial and temporal scale such as those used to study stock dynamics, requires that it is systematically collected, structured and made available. This is often not the case when changes are being observed in real-time and require management action (Wilson, 2009). The unique nature of experiential knowledge means that 'interdisciplinary expertise' (Tress et al., 2005) is needed to make experiential knowledge systematically accessible in forms that are useable to aid in knowledge transfer to bridge gaps between fishers and natural scientists. Gathering experiential data and information through interviews, for example, not only requires skills in interview techniques but also scientific rigor around sampling to help ensure those sampled are considered by their peers to be most knowledgeable (Davis and Wagner, 2003). Since fishers' experiential knowledge is socially distributed and shared by actors involved, also crew, shore-based personnel and processors need to be included, depending on the research question at hand (Palsson, 2000). Using this knowledge also requires consideration of variability in experiential knowledge related to ecological patchiness and change over time. This is crucial to research that seeks to use experiential information for historical reconstruction of fisheries and changing fish ecology, for understanding shifting effort, for documenting migration patterns, stock structure, spawning areas including those now extinct, the location of deep-water corals, endangered species abundance, and changing fishing strategies and dynamics (Neis et al., 1999; Murray et al., 2008a; Colpron et al., 2010; Dawe and Neis, 2012; Paterson et al., 2018; Bentley et al., 2019). Furthermore, researchers have to be aware that information providers, for all kinds of reasons, may deliberately provide erroneous information, may suffer from *"personal or generational amnesia"* (Papworth et al., 2009), or experiential bias (Shackeroff and Campell, 2007; Raicevich et al., 2009; Slooten et al., 2017).

Attention to both ecological and social variability in fishers' experiential knowledge is critical in research design, including ensuring participants' information collectively captures the full temporal, spatial and technological scale of relevant fisheries, to ensure appropriate contextualization. This concern bridges both interview-based research and participatory or collaborative research design. However, most marine institutes and science organizations do not have sufficient social science capacity, and marine social scientists often reside in academia instead of applied science organizations. Moreover, the institutions involved in science for advice tend to get by on fisheries-independent and fisheries-dependent statutory data. Where attempts are being or have been made to incorporate contributions from industry, receiving science systems focus on basic biological data provided by industry and are slow in expanding research design and science capacity. They tend to lack capacity to deal with data and information beyond the natural sciences, even when it concerns quantifiable socio-economic data. Incorporation of experiential knowledge requires involvement of social scientists and substantial financial resources; fisheries scientists would have to be trained in social science epistemology and methods to foster interdisciplinary approaches and social scientists would have to be structurally included in fisheries research frameworks including funding (DePiper et al., 2017; Macher et al., 2021; Moon et al., 2021). Too often, fishers' experiential knowledge is considered to be 'nice-to-know', something to be documented in academia so that it does not get lost to mankind (Johannes, 1981), instead of as an important source of information that can be applied to further understanding of fisheries and marine ecosystem dynamics, due to the costs and governance changes needed to incorporate it.

Issue 3: Integrity of science

Provocative debate prompt: Involving fishers, representatives, or industry-scientists in fish stock assessments and research poses a threat to the professional integrity and credibility of science institutions, and perception of the legitimacy of their contributions to clients or society (Figure 1).

This statement seems paradoxical in view of global efforts by science-policy systems to make the required adaptations to accommodate industry information as part of using 'best available information' policies. But nonetheless the point of view is still prevalent. Examples of science institutions where the goal of industry participation is operationalized are the New Zealand system with its Research Science and Information Standard (MinPI, 2011; Mackinson and Middleton, 2018), NOAA fisheries science (Lynch et al., 2018; Link et al., 2021), the Canadian science advisory peer review process (CSAS, 2021) and various stakeholder engagement initiatives within ICES (Dickey-Collas and Ballesteros, 2019; ICES, 2019c; ICES, 2021c). Such efforts have a strong focus on quality assurance including Conflict of Interest (COI) and Code of Conduct policies. Preconceptions remain however that opportunistic motives may lead to 'tainted' data contributions from industry (Issue 1 section) and that fishers' knowledge, as well as input from industry-employed scientists, should not be trusted because of a perceived threat to the integrity of the science profession and the credibility and even legitimacy of science in support of management. These claims might sound overly dramatic, but such lines of thought pervade scientific and management arenas, even if rarely explicitly articulated.

For example, such thinking may have informed the narrative directing to events in New Zealand that led to the dissolution of Trident Systems, an industry-led, not-for-profit organization established as a research provider in 2012 (Middleton, 2018). Trident was founded with the support of the Ministry of Primary Industries and worked collaboratively with government research providers and industry. In debates associated with the New Zealand fisheries management system (Melnychuk et al., 2017; Slooten et al., 2017), there appears to be some lack of understanding that 'data provided by the industry' are diverse. For example, catch, effort and landings data are provided by industry but as part of statutory obligations and are subject to verification by government. However, other data are voluntarily provided by the industry. Trident was considered to be an example of how use of both statutory data and industry contributions to science in support of management could be organized (Mackinson and Middleton, 2018). Nevertheless, Trident's integrity was publicly questioned. This appeared to be triggered when Trident became engaged in the development of video monitoring for fisheries observation, which in an NGO press release was confused with the government's responsibility of fisheries compliance (Greenpeace-NZ, 2017; Johnston, 2017; Middleton and Guard, 2021). Subsequently, the New Zealand fisheries research system was subjected to a COI review (Jenkins and Wallace, 2019). Trident decided in 2019 *"that it was not possible to meet their objectives of improving the efficiency of fisheries data collection and extracting greater value from fisheries data in an environment in which Trident's industry ownership had become a barrier to its participation in Government funded or supported research"* (Middleton and Guard, 2021). It took several years to establish a role for an industry-led research provider, but little time to have its foundations pulled away.

Other examples are found in the US and the ICES context. In the US, legal mandates in relation to 'best available scientific knowledge' constrained use of proven experiential knowledge (Lynch et al., 2018; Link et al., 2021). In the case of Atlantic bluefish, use of fishers' experiential knowledge was blocked by preventing the scientists from using what they felt was their best scientific judgement (Wilson and Degnbol, 2002). Events around the US Trawl Survey Advisory Panel, set up to integrate scientists' and fishers' expertise in developing a new and improved survey trawl net and gear, show how notions about 'objectivity' resulted in the demise of the panel (Johnson and McCay, 2012). Established to increase the credibility and legitimacy of science, industry members left the panel when the Science Centre unilaterally decided to order trawl doors, as in relation to *"something as important as a resource survey [they could not] allow themselves to be seen as fully cooperative with the industry"* (Johnson and McCay, 2012). Such thinking was also exposed in high level discussions in the ICES council and, to a lesser extent, in the advisory committee, where not all members agreed on the merits of opening up science work to be more inclusive of contributions from industry or other stakeholders. Some perceive this as not appropriate, despite many good governance measures ICES has put in place to maintain the professional integrity and credibility of its expert groups (Dickey-Collas and Ballesteros, 2021) and workshops that have sought to foster dialogue about transparency and objectivity on the quality of science (Doerner et al., 2015; ICES, 2019c; ICES, 2019d; ICES, 2021c).

Preconceptions about industry involvement in generating scientific evidence or about the personal integrity of industry-employed scientists may encourage beliefs that such involvement potentially jeopardizes the credibility of the science organizations involved in the advisory process. This is a particular concern in cases where industry disagrees with specific management actions, does not have confidence in their scientific basis, or mistrusts the science or management institutions or processes (cf. (Dubois et al., 2016). Whilst there are only a few documented cases where scientists and scientific consultants employed by the fishing industry or other stakeholders have 'bent' scientific evidence in favor of the industry or conservation purposes, or have contested the scientific process (Starr et al., 1998; Loring, 2017; Moore et al., 2018; Le Manach et al., 2019; Kraan et al., 2020; O'Brien, 2022), such cases have contributed to the perception that stakeholder-employed scientists should be regarded with suspicion. However, there are also cases where scientists from marine institutes or academia, using their institutional credentials in the name of the scientific advice committee they are a member of, have acted as advocacy scientists in support of stakeholder views (Rice, 2011; Steins et al., 2020b; Mossler, 2021; Harris, 2022; Hutchings, 2022) or have selectively used information in science communications as a commodity seeking to polarize views to highlight debate and garner readership, instead of promoting understanding (for example, Pauly et al., 2013; Harris, 2022). Finally, there are also (mostly un-documented) examples from Europe and Canada where government, not industry or conservation stakeholders, has put pressure on scientists to advocate specific positions (e.g., Hutchings, 2022). Related to this, in most scientific advisory systems there tends to be a rather close link between government-employed scientists and the clients of advice: policy makers (e.g., Wilson, 2009; Dankel et al., 2016). This close science-policy relation, while it also pertains to issues of integrity and independence, is usually taken for granted. Inclusion of industry contributions in the scientific process in and of itself does not necessarily compromise credibility. Institutional credibility is based on the capability to create authoritative, replicable, and trusted information (Cash et al., 2002). As long as data and information used meet scientific quality standards and process, origin does not matter.

In ICES, discussion about industry participation in expert groups started when it was decided to include all names of expert group and workshop participants as authors in reports. For a number of years, ICES assessment groups had already included scientists employed by industry (Dickey-Collas and Ballesteros, 2021). Despite initial reservations, the data and information industry-employed scientists bring to the table is considered useful, and in many cases innovative (Mackinson, 2022). There have been no signals from these groups to the advisory committee or the council that this led to bias in assessment results. However, when it comes to participating in post-assessment stages, there are different procedures for stakeholder-employed scientists compared to scientists from marine institutes or academia. This is due to concerns about how clients and stakeholders will perceive the independence of the advice. This is also why in ICES, engagement with stakeholder interest groups is limited to workshops and advice drafting groups (Dickey-Collas and Ballesteros, 2019).

In Canada, diverse members of the fishing industry have been participating more actively in the provision of information and for some time in the assessment peer reviews of the Canadian Science Advisory Secretariat (Stephenson et al., 1999; Winter and Hutchings, 2020; CSAS, 2021). In cases where scientific consultants or industry-employed scientists critically reviewed or even contested government stock assessments, this brought benefits including intensive peer-review, the ability to bring data from all parties to the process, and improved understanding and trust. It has been shown that this contributed to substantially improved assessments (Starr et al., 1998) and therefore to scientific credibility. Also, in New Zealand, the assessment system reinforces healthy scrutiny of data and assessments (Mackinson and Middleton, 2018).

The credibility of science is closely linked to its legitimacy (Röckmann et al., 2015; Su et al., 2021). It is widely acknowledged that industry-employed scientists, can contribute to increasing the legitimacy of science within industry in their role as 'boundary spanners' who recognize the value of fishers' knowledge and are able to communicate on both sides of the boundary between scientific and fishers' knowledge (Johnson, 2011). Where industry and the scientific community consider the integration of industry contributions to be a way forward to increasing legitimacy of science, other stakeholders may perceive this differently. The earlier example of Trident Systems, where NGOs have successfully questioned the legitimacy of science from industry-management partnerships, is a case in point. Equity and fairness principles are obvious issues of concern that call for reflection on more inclusive participatory approaches to evidence-building based on stakeholders' capability and availability. Obviously, the fishing industry is linked with vessels out at sea with the possibility of making and contributing observations, and many industry organizations and fishers are also acutely aware that fisheries-dependent and fisheries-independent data are required for stock assessments as a basis for management. But experience-based knowledge comes from diverse sources, and the scientific process needs to be open to accepting and using industry observations as part of 'best available information'. For example, in Australia, Resource Assessment Groups provide peer-review of scientific data and information and advice on stock status, economic status of the fishery and ecosystem impact. They include members from science, industry and, where relevant, members from conservation interests and recreational and Indigenous fisheries (AFMA, 2021). In Canada, assessments and peer review under the Canadian Science Advisory Secretariat process increasingly include NGOs (CSAS, 2021). In ICES, NGO representatives can be invited as workshop member or obtain observer status for advice drafting groups (Dickey-Collas and Ballesteros, 2019). It is also conceivable that like industry-employed scientists, scientists employed by NGOs will become involved in assessment working groups. The ICES national delegates have the discretionary power to nominate experts on the basis of their reputation and scientific credibility, not on behalf of a specific employer. However, adding scientists employed by stakeholders to scientific expert groups in itself is unlikely to solve potential legitimacy challenges of scientific advice, as perceived credibility of science is also part of the equation (Röckmann et al., 2015). Quality assurance, transparency and accountability are key aspects of the integrity of the processes and procedures governing the production of scientific advice. In this context, stakeholder engagement throughout the scientific advisory process contributes to dialogue and improved understanding, and hence to perceptions about its credibility and saliency. However, as is shown in a comparison of Canadian and EU scientific advisory processes, it is important to clearly distinguish between the science, irrespective of the source, and 'interest driven' input and be transparent about this (Winter and Hutchings, 2020).

Discussion

Is sea-change upon us?

Despite the normative calls for participatory research and consistent evidence of SIRC benefits in the literature, fisheries science in regions with well-developed scientific advisory systems remains firmly rooted in traditional 'Mode 1' knowledge production (Hessels and van Lente, 2008) and associated approaches and beliefs (cf. (Su et al., 2021). In our evidence, we recognize important contributions of SIRC, but we do not yet see overwhelming evidence of a sea-change towards the systematic integration of industry contributions and more transdisciplinary fisheries science as part of 'Mode 2' (Hessels and van Lente, 2008) approaches.

Any such sea-change is hindered by three interrelated issues that are embedded in traditional Mode 1 ways of thinking about science: (1) concerns about the quality of industry contributions; (2) beliefs about limitations in the useability of unique fishers' knowledge; and (3) perceptions about the impact of industry contributions on the integrity of science. Our assessment of each of these issues suggests that the first and second can easily be addressed through a combination of mechanisms. The third issue, which entails perceptions from a variety of stakeholders with different belief systems, is more difficult to tackle. It is an important inhibiting factor for 'mainstreaming' knowledge co-production in fisheries science, even when the first and second concerns have been successfully addressed. We will discuss ways forward following a brief summary assessment of each of the three concerns.

Summary assessment of the three statements

The first issue, that use of industry data and information poses a threat to the evidence for science-based decision-making, can be addressed through recognizing that such contributions do not pose a threat, but rather raise challenges and have limitations related to the conditions of their application. Concerns about industry's independence and conformity with the same procedural standards of collecting data, formatting, verification and submitting information as other data sources are certainly legitimate. Quality concerns and underlying beliefs about opportunistic motives that result in bias and lack of consistent availability are not exclusive to industry or other non-scientific stakeholders, but equally apply to all participants, including scientists. Voluntary industry contributions are most often made on the basis of good will and, when this is done in collaboration with scientists, usually adhere to basic agreed data collection standards. We need to appreciate that industry data have their limitations, and that industry is not monolithic, with significant variability in types of fisheries, vulnerability to overfishing, resources to apply to contributing to science and influencing management, and often competitive interests within and across fleet sectors. This has implications for data collection, its use, and for motivations to participate in SIRC or full industry-driven research programs. The same applies to science, and this also affects if and how SIRC are set up, including consideration of power and how data and information are used.

The second issue, that industry has limited unique knowledge that is useable (and therefore useful) as evidence to support management beyond that already known or available from science institutions, is flawed. Doubt has been cast on fishers' experiential knowledge because of mis-perceptions that it is inherently decontextualized and local, hence 'anecdotal', or pressing a particular agenda, but these characteristics are variable. It is undeniable that experiential knowledge can be valuable and when drawn systematically from a range of fishers with careful attention to sampling, can be structured and applied quantitatively and qualitatively. Qualifying experiential knowledge as unusable entails an inherent risk that management will not be based on the best available information, particularly when fishers see in real time what is happening on the grounds and scientific assessments (forecasts) show a delay in appreciating the actual situation. The paradigm in well-developed scientific advisory systems that an assessment is only a 'good' assessment if it is fully quantitative, is thus not only problematic but results in limited input to management decisions. Moreover, it is associated with social justice issues: from this perspective fishers, fisheries or nations having limited access to quantitative data and assessment models would never be able to evaluate the status of their fisheries resource and the effectiveness of management measures. Our evidence shows that, where interdisciplinary efforts were made to systematically make experiential knowledge available in regions with well-developed science systems, this contributed to improving the scientific knowledge base and understanding of variability in stock and ecosystem dynamics and impacts of these on fisheries.

For both the first and second issues, it is important to acknowledge that not all data and information are the same and these should be used in a way appropriate to the source and the intrinsic limitations therein. While some voluntary industry contributions may be suitable for use in traditional stock assessments or as structured evidence to support management decisions, others may be more useful in interpreting and validating model outcomes or (re)setting model parameters, or for full spectrum sustainability evaluations (see Supplementary Materials for an overview of applications for industry contributions in fisheries and marine ecosystem science). In cases where information from the fishing industry has been sought for inclusion in scientific analysis, we found it has also served as a mechanism to open dialogue, benefiting both fishers and scientists. This is particularly important considering prevailing trust issues, which relate, for both sides, to the trustworthiness of the data and the scientific process, as well as to trust by fishers that their contributions are not being used against them in the translation from scientific advice to management measures.

Trust is also an underlying theme in the third issue identified: the concern that involving the fishing industry in science poses a threat to the professional integrity and independence of the scientific institutions and, hence, perceptions of the legitimacy and credibility of their advice. We found some evidence for these concerns, but even more examples were identified where industry involvement benefited the scientific process. There may be some documentation bias here, as published evidence for misbehavior is difficult to find; perhaps this is also illustrative of the discomfort of addressing this issue. Where industry or other stakeholders criticize scientific work, this should be embraced rather than merely dismissed as being politically motivated; all scientists should welcome critical review of their work, including when it is not from their disciplinary peers. Furthermore, there is an irony in 'condemning' the situation where the industry, by being actively involved in the scientific process, becomes more 'literate' and subsequently uses the knowledge they obtained to criticize the scientific advice or influence management discussions. Advocacy by stakeholders is inextricably bound to the governance domain. This does not mean that these stakeholders cannot be part of producing credible, quality assured science. Indeed, there is ample evidence that credible science contributes to increasing the legitimacy of science.

Collaborative research has had an impact in terms of building trust between fishers and scientists in improving research findings, in creating a situation where fishers are more willing to cooperate, and in capacity building for fishers and scientists. But much of this impact is limited to the domain of dedicated research projects, many of which are useful for science and policy but are not really being structurally integrated into routine scientific processes. Hence, SIRC tends to remain limited to successes at local or regional levels. It has proven difficult to change science and management systems that are based on routines. Examples where SIRC really made an impact on the science that informs fisheries management are either largely invisible or scarce, but the opportunities have been equally scarce. Without a doubt, *"it is easier to organize collaborative research than to make it count"* (Holm et al., 2020a). This is problematic, because many projects that use fishers' knowledge are aimed at making an impact on the science that informs management. There are, of course, various reasons for this. ICES, for example, has only recently started to think about how to integrate industry data, while at the same time there are still many problems with the data from scientific institutes which need to be sorted out (ICES, 2019d; ICES, 2021b; ICES, 2021c). The bottom line is that if findings from fishers' knowledge projects aimed at improving the knowledge base for management are not used, research collaborations will be eroded along with carefully built trust (Johnson and McCay, 2012; Steins et al., 2020a). This, in turn, will impact trust in management.

Ways forward

The scope of fisheries evaluation in the modern context of sustainability is becoming more comprehensive (Foley et al., 2020; Stephenson et al., 2021) making explicit the limitations of conventional research. There is increasing need to integrate ecological with economic and social factors. Further, addressing the increased uncertainties associated with climate change and other factors, as well as the potential of introducing additional uncertainty to assessments, means that the traditional systems of data gathering and assessment will need to be adapted for this purpose. Current assessment and management structures will no longer be able to get by with the statutory and fisheries-independent data that has been available from within government departments or science institutions. Information on fishing strategies, economic and social aspects in fishery evaluation is key information, most of which has not traditionally been collected by government and scientific institutions. Industry is better able to contribute such information. In addition to bridging social, economic, and fishing behavioral knowledge gaps, industry contributions of quantitative data and experiential knowledge are relevant for a broad spectrum of fisheries science applications (see Table in Supplementary Materials). For responsive management *"we must tap from a diversity of sources and we must find ways to use this knowledge to build a complete picture"* (Wilson, 2009). We anticipate that the future of fisheries evidence will be based on much the same principles as held now, but with a broader range of data, information and knowledge providers, and more transparent agreed processes. Its credibility and legitimacy rely upon (a) respecting and making the most of different sources of knowledge to learn as much as we can, and (b) the need to verify the knowledge through evidence or reasoned argument and carefully balancing and assessing the strengths and weaknesses of different types of knowledge, as we have undertaken to do here.

We aimed to identify with confidence, what, where and when there is utility in including the data, information and knowledge contributions of science-industry research collaboration as evidence in regions with well-developed scientific advisory systems, and the utility of the SIRC process itself in achieving this. The answer is not breaking news: SIRC is context-dependent and shaped by the institutional framework within which it takes place, so the utility 'depends' on the case. In addressing these questions, we provide systematic and robust evidence for: a) practitioners to assess the suitability of SIRC on a case-by-case basis; b) researchers to explore the implications for theoretical developments in knowledge production; c) policymakers to gain a better understanding of what SIRC entails for scientific support and management performance.

The evidence shows SIRC's potential contributions, limitations and constraints. The analysis details associated challenges and reviews the methods to cope with them, illustrated with examples. While no panaceas apply, entrenching SIRC calls for action in three specific areas:

i. Knowledge production has to advance towards alternative science modes that ensure effective SIRC, fostering accountability of both scientists and industry in the process.
ii. Quality Assurance frameworks, including COI provisions, need to become part of the institutional context to tackle objective and perceived pitfalls, generating credibility and transparency.
iii. Governance structures should facilitate the move towards alternative science modes that rely on plural sources of information, by providing arenas for continuous dialogue, building trust to manage real and perceived threats to the integrity and independence of scientific advice, and financial support.

Move towards alternative modes of knowledge production

The integration of fishers' knowledge requires current scientific assessment and advisory systems to actively embrace and facilitate transdisciplinary modes of knowledge production (Tress et al., 2005; Hessels and van Lente, 2008; Stephenson et al., 2016). Consequently, besides industry expertise, expertise from a broader range of scientific disciplines must be mobilized. Many scientific advisory systems do not yet include expertise from the social sciences to assist in making fishers' experiential knowledge systematically accessible and available. This is not necessarily because they are unwilling to do so, but may be because their clients, including governments, do not ask for 'full spectrum advice' (Foley et al., 2020; Stephenson et al., 2021). A way forward is to demonstrate to recipients of advice what full spectrum advice could look like, as ICES has recently done in its Aquaculture Overview for the Norwegian Sea Ecoregion (ICES, 2021a) or NOAA Fisheries in the context of integrated ecosystem assessments for marine regions in the USA (Levin et al., 2016). Operational advances towards alternative modes of knowledge production requires: (a) funding for full spectrum advice; (b) effective learning across disciplines (epistemology, developing joint methodology, training and developing interdisciplinary trust (DePiper et al., 2017; Thompson et al., 2019; Macher et al., 2021; Moon et al., 2021); and (c) addressing potential ethical issues (Carruthers and Neis, 2011), power imbalances and related threats to social justice that could be affected by uneven SIRC initiatives.

Appropriate quality assurance frameworks

Moving towards alternative modes of knowledge production will require agreement on appropriate processes for validation and quality control. Acknowledging the challenges to credibility, integrity and independence posed by the use of measurable industry data and experiential knowledge, we argue that there is a suite of methods and processes able to cope with them. Formalized and transparent quality assurance systems for all data contributions, irrespective of their source, will be needed to ensure rigor in design and quality of data collection and verification and in its use for analysis. These should include: (a) documented sampling designs, methods and quality controls applied through the data chain; (b) documentation of the source(s) of data and information, by whom it was collected and when and where; (c) documentation of any assumptions, hypotheses and data inconsistencies, as part of a risk assessment with regards to data quality; (d) development of data sharing agreements that define rationale for sharing these data and information and constraints on their use; (e) transparent, documented coding systems for data; (f) independent validation and peer-review. We refer to the report of the ICES Workshop on Standards and Guidelines for Fisheries-dependent Data for a comprehensive overview of international examples of quality assurance processes (ICES, 2021c). A particular challenge here is that meeting the same standards could be difficult when fish and fisheries straddle multiple jurisdictions.

Agreed processes for quality assurance should, as much as possible, be in place before data are collected and delivered[3]. Many scientific organizations already have some form of quality assurance in place. Adapting these to be applicable and receptive for contributions by the fishing industry and other non-scientific actors will therefore be a gradual, iterative process. It is important that all non-scientific actors who may be contributing data and information are informed with the appropriate data collection processes (ICES, 2021c). Training and communication are key here, as well as having 'boundary spanners' (Johnson, 2011). Scientists employed by stakeholder groups and who work closely with colleagues in science organizations should be well-equipped for this role (Mackinson, 2022). In this context, concerns about professional integrity can be a sensitive topic, but one that is nonetheless important to address. Joint reflection on *"whose hat [scientists] are wearing"* (Dankel et al., 2016) is likely to be more effective in overcoming such concerns.

Conflict of Interest protocols are a formal way of organizing transparency about who participates in scientific processes. Conflicts of interest related to data collection and knowledge contributions are different from other situations where COI may occur, such as scientific meetings and review panels. In the latter case, COI may be handled by balancing representation of participants and adoption of well-established review protocols (e.g., ICES, 2020a; CSAS, 2021; NPRB, 2021). While standards for managing COI in scientific meetings are not directly applicable to data and knowledge contributions, the underlying principles are relevant, and have a direct relation to quality assurance. Standards for COI management should be extended to include managing perceived or actual COI in the collection and application of data for use by scientific advisory systems. The purpose should be to protect the legitimacy of advice when data-collectors with potential conflicts of interest are involved (ICES, 2021c). In this context, we note that the European fishing industry has voluntarily established a Code of Conduct for industry observers attending ICES meetings (NPWG, 2016b) and for industry-affiliated scientists (NPWG, 2016a) to allay potential COI concerns, which seems testament to their willingness to engage in SIRC. Development of implementable standards for managing COI should not only address the additional legitimacy-risks introduced by third-party participation in data collection, but also manage the risks that may already be associated with the data collection performed by scientific institutions. A standard for managing conflicts of interest in data collection should therefore clearly address requirements for transparency and documentation.

3 We note challenges associated with unplanned or rare events on the water (e.g., superpod convergence). Information on such events is imperative in understanding ecosystem function, yet it would be difficult for fishers to guarantee quality assurance before collecting data on these occurrences.

Facilitating governance structures for alternative modes of knowledge production

Guidelines for SIRC stress the importance of communication (Johnson and Van Densen, 2007; Mackinson et al., 2017; Mangi et al., 2018; Steins et al., 2020a; De Boois et al., 2021; Jones et al., 2022). This includes communicating about the purpose of data collection, why it is done in a certain way and its limitations. It also includes communicating about preliminary and final results and how these have been used. Expectations management is key here, particularly when fishers are contributing towards development of time-series or when use of fishers' experiential knowledge is not yet part of established routines. Communicating about things that went wrong is also essential. Both expectations management and being open about mistakes are closely linked to building trust relations (Mangi et al., 2018; Cvitanovic et al., 2021). Communication should not be limited to those directly involved in collaborative research, but also to a wider stakeholder audience. After all, once the collaborative science gets into the policy and societal domain, trust in its quality and integrity is key. Trust is *"a critical precondition underpinning successful knowledge exchange [and] evidence-informed decision-making"* (Cvitanovic et al., 2021). Trust issues do not resolve themselves by merely setting up appropriate scientific quality assurance systems. These also require continuous dialogue between all parties involved to manage real and perceived threats to integrity and independence of scientific advice, though this is by no means a panacea (e.g., Delaney et al., 2022). Extensive stakeholder-oriented communication does not necessarily come naturally to many scientists and science organizations and is often at the bottom of research budgets or not seen as a priority task. Fundamental change is needed, for example by allocating specific roles and budgets to boundary spanners in transdisciplinary science. Trust-building strategies are a crucial part of ways forward in integrating industry contributions in science; proposals on how to do so have been made in a recent publication by Cvitanovic and colleagues (Cvitanovic et al., 2021).

Enabling scientific advisory systems to move towards collaborative approaches also requires financial support. This includes facilitation of balanced voluntary industry contributions to science. It would be naive to think that an industry-led data collection program can run indefinitely on the good will of fishers, particularly when science-led programs are government-funded. Direct funding is an obvious route, but financial support can also take indirect forms, such as additional quota allocations. In areas where responsibilities for data collection are increasingly delegated to industry, we also see that costs are downloaded to industry with potential negative impacts on younger, less established fishing enterprises and on opportunities to expand the research disciplinary focus to include social science. Expecting industry to fully pay for data collection also brings along equity issues, as not all industries have sufficient financial means and human capital to organize data collection. The impacts of this became clear in Australia, where cost recovery policies for fishery-independent data collection have been introduced in some jurisdictions and vary considerably in what costs are attributed to industry and to public good (Cox, 2001). For smaller-scale, lower value fisheries cost of these programs are more burdensome given they do not gain the advantages of efficiencies of scale (MFA, 2020). The implication is that the evidence-base for management of these latter fisheries has to rely on less fishery-independent data and therefore higher uncertainty and more precautionary harvest settings as a result. In cases where profitability of fisheries declines due to decreasing fishing opportunities or increasing costs, the result may be that the industry has a perverse incentive to cease or narrow the scope of data collection. Thus, while one could argue that acceptance and use of voluntary industry contributions is likely to be the greatest reward to fishers for engaging in science support, there are limits to what can be expected on the basis of fisheries' scale and profitability. These must be well-considered. As part of ways forward, we recommend a review of current funding and alternative support mechanisms for fisheries data collection involving the industry and the development of best support practices.

In our search for explanations for why fisheries advisory systems in well-developed regions only make limited use of observational and experiential data, information and knowledge from SIRC and our exploration of ways forward, we found the exchange of experiences between different regions in our regional workshops to be incredibly insightful. Some regions had already developed solutions for challenges experienced in others or were experiencing positive or negative impacts from changes. A problem or solution in one region does not of course have to play out similarly in other regions in view of contextual, cultural and institutional differences. But looking at issues from different angles is very helpful. As part of ways forward in integrating voluntary industry contributions in regional scientific advisory systems, we therefore recommend organizing regional exchanges of experiences.

Final reflections and perspectives

We believe the growing momentum for using voluntary industry contributions in science is linked to a generational change where scientists who embrace more inclusive and transdisciplinary ways of thinking about science are now at the point in their careers where they can make a difference. Well-meaning efforts to enable the use of 'best available information' are, however, confronted with legitimate concerns regarding perceived and real risks that it might be detrimental to the credibility of scientific advice – particularly when science evidence becomes an object of negotiation in management decisions (Winter and Hutchings, 2020). Safeguarding against this requires transparent quality assurances systems for the processes intended to deliver 'best available information', as well as objective evaluation of the performance of the information for its intended purpose. To differing degrees across the world, achieving this will involve adaptations to current fisheries governance frameworks toward new cultures of cooperation. Proposals for possible avenues have been suggested in a number of recent publications (Gómez and Köpsel 2023; Bradley et al., 2019; Holm et al., 2020a; Fulton, 2021; Hart, 2021; Macher et al., 2021; Stephenson et al., 2021; Su et al., 2021; Strand et al., 2022). Better definition of industry's role in contributing to science will improve credibility and legitimacy of the scientific process, and of resulting management. As part of progressing towards integration of voluntary industry contributions into science for advice, further analysis of the receiving systems that have been more receptive of fishers' and other sources of knowledge is needed. Carrying out a performance evaluation of fisheries managed on the basis of fisheries-dependent data or voluntary industry contributions versus fisheries managed (mostly) on the basis of fisheries-independent data, may help rationalize the debate about the utility of voluntary industry contributions. The best evidence for utility of industry data, after all, lies in its performance.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

NAS, SM, SCM, MP and RLS conceived of the idea for this manuscript, collated the initial evidence document and prepared the regional workshops. MB, KB and JAM chaired the regional workshops and prepared their reports. All authors participated in the regional workshops and subsequent analysis. NAS prepared the manuscript with significant contributions from all other authors. Authorship is in alphabetical order after considering the aforementioned types of contributions. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author SCM is employed by MRAG Ltd. All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.954959/full#supplementary-material

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EDITED BY
Matthew R. Baker,
North Pacific Research Board,
United States

REVIEWED BY
Erin Carruthers,
Fish, Food and Allied Workers Union,
Canada
Emma McKinley,
Cardiff University, United Kingdom

*CORRESPONDENCE
Julia Calderwood
Julia.calderwood@marine.ie

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Reflecting on the importance of open communication and social capital for the co-creation of knowledge in Irish fisheries

Julia Calderwood*, Debbi Pedreschi, Macdara Ó Cuaig and David G. Reid

Fisheries Ecosystems Advisory Services, Marine Institute, County Galway, Ireland

Fishing industry stakeholders have unique and important contributions to make to fisheries research. Co-operative and collaborative research approaches between science and industry are important to facilitate the documentation of fishers' knowledge and the co-creation of common understandings. Successful collaborations require open communication, trust and social capital, but numerous barriers exist to establishing these effective partnerships. This paper takes a narrative approach to reflect on the authors' experiences of engaging and collaborating with Irish fishers in the quest for the co-creation of knowledge, while considering how data from industry can best be used and integrated into scientific processes. This includes reflecting on barriers faced, in addition to motives and opportunities that have enabled this work to progress. Through case study examples, we reflect on issues surrounding misunderstandings regarding the roles of scientists and the scientific process, a lack of transparency, a lack of trust, historical/legacy issues, and contemporary pressures including the COVID-19 pandemic and impacts of Brexit. Building trust and active communication are identified as key elements to effectively co-create knowledge and common understanding. Trust is often developed in an informal setting, but more formalized processes, increased transparency and opportunities to engage, and institutional supports may further facilitate effective knowledge co-creation in fisheries.

KEYWORDS

social capital, trust, industry-science partnerships, stakeholders, fishers' experiential knowledge

1 Introduction

Fisheries science is an interdisciplinary field and industry stakeholders, along with academics and, government employees, have unique and valuable contributions to make to this domain (Stephenson et al., 2016; Thompson et al., 2019). While opportunities for fishers to contribute knowledge to fisheries science may have previously been limited, the involvement of stakeholders is increasingly seen as a key aspect of good governance and is recognized as an important component of ecosystem based fisheries management (EBFM) throughout the world (Silvano and Valbo-Jørgensen, 2008; Fischer et al., 2015; United Nations, 2015; Mackinson and Holm, 2020; Mackinson, 2022). Fisheries represent complex systems occurring in dynamic environments and all additional information is likely to help ensure successful management (Dörner et al., 2015). Multiple sources of information are therefore required to achieve the aims of EBFM, and gain a fuller understanding of fisheries and their associated ecosystems, with fishers representing one important source of such knowledge (Thompson et al., 2019).

Fishers' knowledge includes more than just fisheries information and can include ecological and socio-economic data in addition to knowledge of gear technology and development and experience of various fisheries management schemes (Stead et al., 2006; Stephenson et al., 2016; Feekings et al., 2019), all of which are important to improve fisheries knowledge and to help address complex management requirements (Thompson et al., 2019). Fishers can impart knowledge through fisheries-dependent data collection in addition to sharing their own experiential knowledge (referred to as Fishers' Experiential Knowledge or FEK throughout this paper). In some fisheries there are long legacies of such data collection including; the Norwegian reference fleet (Nedreaas et al., 2006), self-sampling in fisheries in the Netherlands (Kraan et al., 2013) and the Northeast Fisheries Science Centre study fleet in the United States (Blackburn, 2017). There are also increasing examples of the documentation and application of FEK including a re-evaluation of Redfish catches in Canadian east coast fisheries (Duplisea, 2018) and of using fisher's knowledge to co-create indicators of food web structure in the Irish sea (Bentley et al., 2019a).

Collaboration, co-operative research and the co-creation of knowledge between science and industry are important in facilitating the documentation of fishers' knowledge and subsequently including FEK in science, research and advice. There is a spectrum upon which fishers can be involved in scientific research and as to how FEK is subsequently used. This ranges from fisher's acting as 'data collectors' and FEK being documented in a standardised manner to fit in with conventional fisheries monitoring data, through to fully participatory research where fishers are full time partners on projects and contribute to the development of research questions, hypotheses, design and execution of research (Stanley and Rice, 2017). While the outcomes of different science-industry partnerships may vary, such partnerships can result in both an increase in data collection and increased communication, transparency, capacity building, and trust between fishers and scientists (Kraan et al., 2013). Indeed, the objectives of many science-industry partnerships are to improve trust while delivering comprehensive, cost effective methods of data collection and data documentation that can strengthen the societal relevance of fisheries research (De Boois et al., 2021). Integrated research is also important, with scientists from a range of disciplines (including natural and social sciences), varied stakeholders, and decision-makers collaborating from the initial planning and design of research projects through to their completion. This helps to ensure transparency, mutual consent and understanding of research topics, management of expectations, tailoring of outputs, and critically, that data is used appropriately to support advice and management, and to enable fishers to understand and contribute to strengthening the scientific knowledge base (Mauser et al., 2013; Dörner et al., 2015; De Boois et al., 2021).

While partnerships between fishers and scientists are regarded as being an essential part of both fisheries science and management, these collaborations often require social capital to be successful (Armstrong et al., 2013). Social capital describes the social norms, networks, and bonds that facilitate co-operation, exchange, and reciprocity among and between groups of individuals, and is important to promote trust and improve cooperation among fishers (Pretty and Ward, 2001; Grafton, 2005; Barnes-Mauthe et al., 2015). Social capital among stakeholders is particularly important in socio-ecological systems which involve a diversity of actors and individuals (Barnes-Mauthe et al., 2015). A lack of trust and support between industry, scientists, and managers frequently leads to low participation in collaborative efforts, limiting the impact of industry data and knowledge on current science and management practices (Mangi et al., 2018).

Numerous challenges exist to building effective partnerships for co-creating knowledge in fisheries. The level of social capital required is also likely to vary depending on the exact role of fishers within a science-industry partnership. While advances are being made in the use of FEK in fisheries science there is no 'one size fits all' approach to overcome these and succeed in co-creating knowledge with stakeholders. In this paper we reflect on experiences in Irish fisheries in this pursuit. Taking a narrative approach, we reflect on engaging and working with Irish fishers in a quest for the co-creation of knowledge through a number of different initiatives. Barriers to such collaboration are highlighted while also considering the motives and opportunities that have allowed these initiatives to progress. Through a series of case study examples we identify key elements required for the co-creation of knowledge in Irish fisheries and how open communication, trust, and social capital were built in these examples. This provides insight that could aid the development of future collaborations, co-operative research projects and management efforts.

2 Case studies

2.1 Irish industry interviews: DiscardLess and RTI

Nineteen semi-structured interviews and small group discussions, documenting opinions and experiences from 21 fishers and industry stakeholders working in the demersal fishing industry, were conducted between July 2016 and September 2017 (Calderwood et al., 2021a). Interviews followed a set of questions which were originally designed to open up discussion around issues surrounding the introduction of the EU's Landing Obligation (DiscardLess project 2015-2020; Calderwood et al., 2021a) in addition to views regarding the potential adoption of Real Time Incentives (RTI) in Irish fisheries (Calderwood et al., 2021a; Pedreschi et al., 2021). By using open-ended questions and adopting a flexible approach (Ritchie et al., 2003; Longhurst, 2010) interviews were not restricted to these topics, however, and opinions were elicited in relation to current management systems, selectivity measures in fisheries and individual's experiences of optimizing catches in line with available quotas, issues and obstacles faced by individuals, and opportunities for improvement within Irish fisheries (Pedreschi et al., 2021). By taking part in these interviews, participating fishers provided a supporting role to the DiscardLess and RTI projects, sharing experiences, opinions and insights that later shaped the direction of research within these two projects and contributing to project outcomes.

Contact with interviewees were made through a number of approaches including *via* producer organizations, though snowball sampling methods (Naderifar et al., 2017) and by directly approaching individuals at harbours around Ireland. Interviews were conducted at locations most convenient to interviewees, which included offices, bars, hotels, homes, and the quayside (Calderwood et al., 2021a). Interview protocols were explained to all participants prior to interviews with corresponding signed consent forms collected. Where permission was given, interviews were audio recorded and later transcribed in full. Where interviewees chose to take part in interviews but not to be recorded notes were taken by hand during the interview. All interviews were anonymized but interviewees represented shore-based managers, co-op managers, officials from fisher representative bodies, and ex-fishers, although the majority were active skippers and vessel owner-operators. All but one individual were male. Vessels represented by the interviewees ranged from between 7 and 38 m in length with the majority of these vessels (77%) being members of the general polyvalent fleet segment. The Irish polyvalent fleet includes multi-purpose vessels of all sizes, including small inshore netters and potters through to medium and large offshore vessels, targeting demersal fish, pelagic fish, crustaceans, and bivalve molluscs.

Interviews were coded for conventional content analysis (Hsieh and Shannon, 2005) using the online software Dedoose (2018: Version 8.0.35) (Dedoose, 2018). Coding was carried out by a single coder (DP) to minimize variability in code application, with coding being reviewed by a second person (JC) to ensure consistency. Codes were assigned under general themes relating to the topics brought up during the interviews (Ryan and Bernard, 2003). Interviews and original associated codes (as detailed in (Pedreschi et al., 2021), were re-examined to identify topics related to trust, communication and fishers contributing their experiential knowledge to the scientific process. Additionally, interviews were examined to determine how fishers view the role of scientists and the scientific process within fisheries management. Outputs from this work were reported back to the fishing industry *via* project websites and publications in industry magazines (Calderwood, 2020).

2.2 At sea commercial catch sampling

Since 1993 the Marine Institute has been working with the Irish fishing industry in the collection of catch data at sea, aboard commercial vessels, under the At Sea Sampling Program. The fishers bring trained samplers to sea for the duration of the fishing trip and facilitate the sampling of the catch by providing a safe working environment to allow the sampler to collect the data according to internationally agreed standard operating procedures (Borges et al., 2004). The fishers do not get financially compensated for having the sampler aboard, as it is seen as the industry's contribution to the collection of scientific data. In the wake of the Covid-19 restrictions many nations suspended their Sampler At-Sea Programs. In Ireland the industry and the Marine Institute fisheries scientists worked together to mitigate for the resulting reduction of scientific data collected at sea by developing an At-Sea Self-Sampling Program. On inception the standard operating procedure (SOP) and associated datasheets and sampling pack were developed by MI Scientists in conjunction with active fishers. Prior to a full roll out of the scheme the At Sea Self-Sampling SOP and sampling pack was trialled by a participating vessel with feedback incorporated into further development prior to official roll out.

The At Sea Self-Sampling Program asks participating skippers and crews to collect data and samples from a subset of the hauls and bring the material ashore where Marine Institute fisheries scientists measure and record the associated data. Each vessel is contacted individually in advance of a possible trip following the statistically sound sampling protocol employed in Ireland since 2016 (Marine Institute, 2017). Once agreed, the participating skipper is trained remotely and supplied with a sampling pack pre-sailing. Participating skippers record haul start & stop positions, date and time, estimate the bulk catch and record the wanted catch by kg per species. One random box of unwanted catch is taken from the same haul for measurement ashore by Marine Institute scientists. Observations on bird, mammal and reptile interactions are also recorded by the skipper. While at sea the participating skipper maintains contact with the Marine Institute's Fisheries Liaison Team Lead and quality assurance (QA) checks are performed during the trip *via* WhatsApp. The skippers provide *in situ* photographs of the datasheets with collected data and act as appropriate following clarification of the scientific QA feedback. Within this initiative skippers play an essential and active role, collecting and providing important data and samples to the Marine Institute regarding their catches.

2.3 WKIRISH

WKIRISH was a series of ICES sponsored benchmark workshops to examine why key stocks in the Irish Sea (e.g. cod, haddock and whiting) had failed to recover despite specific management plans and a substantial reduction in fishing effort. The initial driver for these workshops came from the North Western Waters Advisory Council (NWWAC). The Advisory Councils were set up by the European Commission (EC) to include both industry and eNGO stakeholders. Their role was to advise the EC on fisheries related issues. NWWAC asked ICES if it could investigate why there had been no recovery, and what could be done about it. The analysis included the construction of an ecosystem model (Ecopath with Ecosim – EwE) to explore the role of fishery and ecosystem drivers in the observed stock changes. Some of the data needed came from existing fishery and ecosystem data held by the Marine Institute. However, the base year for the EwE model was 1975, and data for elements such as fish diets for that year, and effort trajectories before 2003 were not available. These data were then reconstructed on the basis of the FEK from the industry participants and used in the model (as detailed in (ICES, 2016; Bentley et al., 2019a; Bentley et al., 2019b)). The model fit to the empirical data was substantially improved by this approach, as was the predictive power. Subsequently, the model was used to explore options for management with the active engagement of the stakeholders. Their confidence in the value of the model was substantially improved by their role in its construction, and then the questions asked of it. As a consequence, the stakeholders supported the conclusions, and actively and positively engaged with the management solutions that were proposed (Bentley, 2020; Bentley et al., 2021).

2.4 IFISH project

The IFISH (Irish Fisheries Information Sharing Network Development) project began in 2020 (running until 2024) with the aims of investigating how new technologies and mobile phone apps could be used to share real-time information to help skippers avoid unwanted catches and reduce discards (IFISH, 2021). The objectives of this project include improving understanding of fisher's bycatch avoidance strategies and adopting a stakeholder driven approach to develop peer-to-peer information sharing so that hotspots of juvenile and non-quota species can be identified in near real time. Documenting and utilizing FEK is crucial to the success of the project, to ensure any tools and apps developed meet industry needs and properly address issues and problems faced in daily fishing operations. To meet its objectives, the project aimed to first use semi-structured interviews and discrete choice experiments to determine how fishers value and target different components of the catch. Further, a co-design approach is central to the project, to collectively develop novel information sharing tools alongside stakeholders. Utilizing open dialogue and fostering two-way relationships with industry to co-design an information sharing app is key to the project's success. While this project was designed by scientists, it was developed based on conversations with industry regarding the need for more up to date information to make static fisheries hotspot maps more useful to them (Calderwood et al., 2019). Close collaboration with industry organisations including producer organisations and seafood advisory companies has been key to developing this work with representatives from such organisations having a significant role in the development of the project work with regard to developing information sharing initiatives with fishers

2.5 Mission Atlantic project

Mission Atlantic (missionatlantic.eu) is an EU-funded project, running from 2020 until 2025, that aims to map and assess the present and future status of Atlantic marine ecosystems under the influence of climate change and anthropogenic exploitation. Through seven regional case studies, one of which is the Celtic Sea case study, along with a whole Atlantic assessment, Mission Atlantic is developing and progressing integrated ecosystem assessments (IEAs) (Levin et al., 2014). IEA consists of a series of steps, the first and most critical of which is scoping with stakeholders. This process allows the identification of key current and emerging issues of concern and regional relevance, and directs and prioritises research, advice production, and management efforts.

Originally stakeholder engagement for Mission Atlantic was planned as a series of in-person interactive workshops to carry out the scoping, co-develop the risk assessment exercises, specify modelling scenarios, and enhance understanding of the socio-ecological system. Due to the COVID-19 pandemic, these initial plans had to be adapted to an online forum, and methodologies and planned interactions changed to accommodate this. Stakeholders within Mission Atlantic Celtic Sea cases study (to date) range from fishing industry representatives to eNGO and conserveation agencies, management bodies, and scientific research and advice agencies. Stakeholders from Ireland, UK, France and Spain have participated in the meetings. Stakeholders are consulted throughout the project, contributing knowledge on active sectors and pressures within the region, ground-truthing results, contributing to conceptual models, and identifying key questions and scenarios for investigation. In this way the stakeholders contribute knowledge and understanding, and also act as the 'clients' of the IEA work, directing effort to ensure relevance and applicability.

2.6 Irish fisheries science research partnership

The Irish Fisheries Science Research Partnership (IFSRP) was first established in 2008 to help build and support collaborative industry-science partnerships and provide a platform for open communication and dialogue between fishing industry representatives and scientists at Ireland's Marine Institute and BIM (Bord Iascaigh Mhara - the Irish seafood development agency) (Marine Institute, 2020). At these meetings research projects, assessment results, research priorities, gear technology and gear development and industry concerns are actively discussed. A key aim of the group is to promote collaborative stakeholder engagement, which is deemed a cornerstone of the Ecosystem Approach to Fisheries Management.

3 Barriers to knowledge co-creation and subsequent mitigation

3.1 Institutional and legislative complexity

There are numerous bodies operating within Ireland involved in assessing fisheries, fisheries management and in enforcing rules and regulations.

Table 1 details individual bodies and government departments in Ireland that are responsible for the management, regulation and research of sea fisheries in Ireland. Much of the management and regulation of sea fisheries is directed by the requirements of the EU's Common Fisheries Policy (European Commission, 2021). In addition, there are the statutory responsibilities for the protection of the marine environment. The primary EU instrument for this is the Marine Strategy Framework Directive (MSFD: European Commission, 2008), whose implementation falls to Department of Housing, Local Government and Heritage. The science and research supporting MSFD reporting comes from a range of national sources. The EU Maritime Spatial Planning Directive (MSPD: European Union, 2014) is responsible for planning spatial use of the sea, and falls under the competency of the Department of Housing, Local Government and Heritage (DHLGH). While these two directives may not directly impact upon fishers' day-to-day work (unlike the CFP), they are relevant to their interests, and add to the complexity of the marine institutional structure within Ireland. Several additional departments are also involved in MSFD & MSPD including the Department of Transport, and the Department of Tourism, Culture, Arts, Gaeltacht, Sport and Media. The Department of the Environment, Climate and Communications (DECC) is also relevant, particularly under the changing landscape due to climate change and the current expansion of offshore renewable energy (ORE). While MARA (Maritime Area Regulatory Authority), a newly established authority for Maritime Area Consent, is also in the legislative landscape in relation to offshore renewable energy (ORE) (Semple, 2021).

With these various bodies operating in the same space it can lead to confusion as to who is responsible for what (Figure 1), especially with regard to how fisheries scientists fit in within this landscape. Regarding the Marine Institute specifically, one interviewee explained '*A lot of the problem is fishermen don't know what the Marine Institute is doing*'. When any of the marine management authorities were brought up in interviews with fishers there were a number of examples where they were lumped together, misidentified or regarded as one and the same with various themes related to 'complexity', 'simplicity', 'legislation' and 'regulation' being identified in interviews. One fisher, for example, was explaining the amount of regulations and paper work required day to day to operate a fishing vessel and said '*The hassle, the food hygiene, the SFPA stuff, the Marine Institute … The Navy … And then you have BIM*'. While some fishers indicated that they understood the scientific role of the Marine Institute in terms of the survey work, data collection and stock assessments performed by its' staff, its links with DAFM often remained the over-riding factor, with a fisher explaining, '*Look, whether you like it or not, right, you guys are with the Marine Institute, they [DAFM] are still your bosses*'. This can further result in distrust with one fisher explaining '*the likes of the distrust that we've been talking about, not necessarily between individual fishermen, but between fishermen and the scientists, and the scientists and the department, and the department and the fishermen*'. The problem of conflation between the science and management bodies is a perceived loss of independence which means that a dissatisfaction with management processes can directly affect an individual's willingness to engage in scientific research if they believe they are one and the same, or mistake them for one another. It has also been recognized that if scientists wear too many hats or take on too many roles it can create confusion regarding their roles, undermining trust from industry (Mackinson et al., 2011). Certainly the work of scientists at the Marine Institute feeds into policy and advice, which likely contributes to the blurred understanding of their roles. This misunderstanding of roles and distrust of scientists has created barriers that need to be broken down prior to working and collaborating effectively with industry (see Section 3.2). Institutional and legislative complexity have also been identified as key barriers to the implementation of the Ecosystems Approach to Fisheries Management (EAFM)

TABLE 1 Bodies and departments within Ireland that have responsibilities in relation to Irish fisheries.

Body	Relation to other bodies	Responsibility
DAFM (Department of Agriculture, Food and the Marine)	Irish government department	- The Sea Fisheries Policy and Management Division within the Department of Agriculture, Food and the Marine (DAFM) is responsible for fisheries management in Ireland (Brennan, 2022) -Manages Ireland's licensing and quota in line with the EU's common fisheries policy (CFP) (DAFM, 2016; Calderwood and Reid, 2019)
SFPA (Sea-Fisheries Protection Authority)	Independent statutory body	-Responsible for regulation of sea fisheries -Responsible for protecting and conserving fisheries resources for long-term use -Promotes compliance with sea fisheries legislation (including CFP) -Verify and enforce compliance where necessary -Monitors and enforces seafood safety
Irish Navy		-Collects VMS data for use by the SFPA -Conduct on-board inspections of fishing vessels in Irish waters
Marine Institute	State agency	-Provides scientific and technical advice to the government to help inform policy and to support the sustainable development of Ireland's marine resources - conducts fisheries surveys and collects fisheries data to provide advice that underpins the fisheries management framework - Scientists at the Marine Institute also conduct research to support an ecosystem based approach to fisheries management
Bord Iascaigh Mhara (BIM)	State agency	- responsible for developing the Irish Seafood Industry -BIM leads on industry training, collection of economic data, seafood processing and marketing, sustainability training and certification, gear technology, and administration of grant-aid and project funding directly to the fisheries and aquaculture sector
Inland fisheries Ireland (IFI)	State agency	- protects, manages and conserves Ireland's inland fisheries and sea angling resources, which includes the 12 mile coastal jurisdiction - research and management of diadromous species
Marine Survey Office (MSO)	A body within the Irish Maritime Administration, Housed within the Irish government's Department of Transport	-responsible for the implementation of all national and international legislation in relation to safety of shipping and the prevention of pollution of the marine environment from ship-based source - regulates the living and working conditions of all Irish ships and crews and foreign flagged ships and crews in Irish ports and the security of Irish ports -grants initial approval of designs and drawings for new vessels or modifications to existing vessels - provides surveys for certification of modified vessels
Mercantile Marine Office (MMO)	A body within the Irish Maritime Administration, Housed within the Irish government's Department of Transport	- maintains a General Register of Shipping -assists vessel owners with all aspects of Ship Registration and activities such as surveys and issuing of Ship Radio Licenses and maintaining the Seafarers Information System and website, assisting seafarers with all aspects of applications for certification

(Young, 1998; Ramírez-Monsalve et al., 2016), a stated goal of the European Commission (European Commission, 2008; European Commission, 2013). It is essential that institutional structures allow for interaction and facilitate stakeholder involvement, a key aspect of EAFM, and of ecosystem-based management (EBM) of socio-ecological systems (Stringer et al., 2006; Mackinson et al., 2011). Complexity can be overwhelming and act as a barrier to such interactions, and while as fisheries scientists we have limited ability to reduce institutional and legislative complexity we can increase trust and social capital between ourselves and fishers by better explaining and communicating our work and role to industry stakeholders.

Many fishers that had a more complete understanding of the work and role of the Marine Institute often had experience of working alongside its' staff, either during sampling work or research projects, illustrating the importance of direct engagement and experiential learning. Reaching a wider audience and finding more opportunities for fishers to work with marine scientists, through research projects as well as schemes such as At Sea Self-Sampling, are therefore increasingly important to build further trust and understanding between scientists and fishers. Fora such as IFSRP also provide industry with insight into the role of the Marine Institute, highlighting the research scientists at the organization are involved in and gives fishers an opportunity to guide the Marine Institute and BIM toward further research to benefit the industry. It is critically important however, for this knowledge to be spread beyond the few industry representatives present at these meetings if a fuller understanding of the work and role of Marine Institute scientists is to spread across the fishing industry. Avenues to reach fishers who are not members of Producer Organisations (POs), co-operatives, RIFFs (Regional

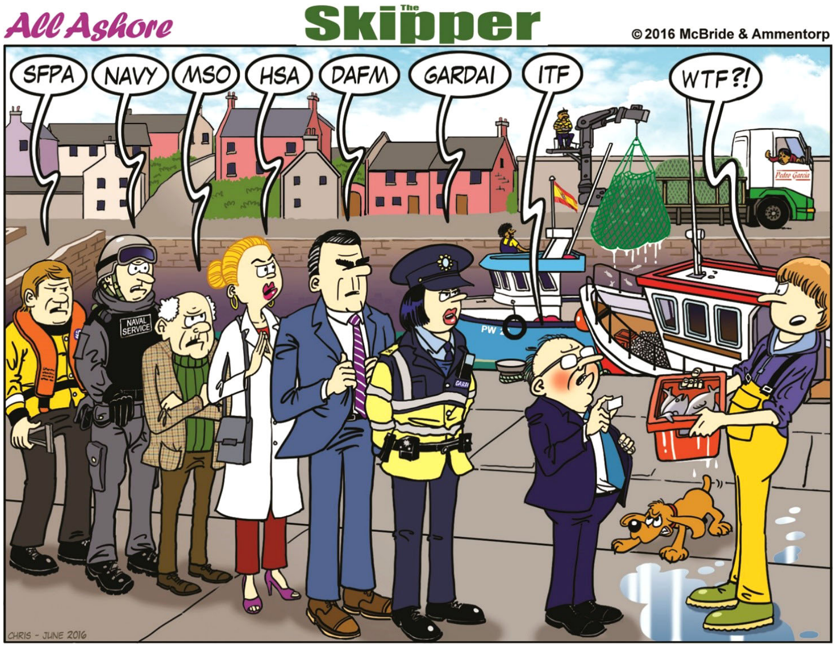

FIGURE 1
Cartoon taken from The Skipper, a leading journal for the Irish and UK fishing industries, reflecting industry confusion over the number of different agencies they are required to interact with. (Image provided courtesy of The Skipper - https://theskipper.ie/).

Inshore Fisheries Forums) and the NIFF (National Inshore Fisheries Forum) also need to be developed and maintained, as within Ireland it is not mandatory for fishers to be members of representative bodies such as PO's.

3.2 Misunderstanding and mistrust of scientific sampling methods and the stock assessment process

A lack of understanding of scientific sampling methods and, particularly, the stock assessment process represent further barriers to building the trust and social capital required to facilitate knowledge co-creation in Irish fisheries (Pálsson, 1995). Fishers can often see the broad importance of fisheries science, with one telling us '*I think there is a lot of people realize that the science arm of things is very important and you need [to] cooperate and all that*'. Yet there is less understanding and support of the science that supports stock assessments. This is unsurprising given their technical nature. Even though there have been large improvements in recent years in making the stock assessments more transparent, they remain a specialist subject. Indeed, transparency can, in some cases, contribute to eroding trust, when observers note some of the assumptions that are included in even the most simple of models. 'Trust' was a theme identified in interviews, relating to numerous relationships including those between fishers, with scientists and with managers but simply, we have often been told that '*I don't trust the science*'. This lack of trust is related to a number of different elements.

Firstly, there is a lack of trust in the sampling stratification of fisheries surveys carried out on research vessels. While fishers target activity where they know they are likely to encounter fish, scientific surveys are designed to find information about the fish population as a whole in an area and survey both where there are and there are not concentrations of species, tracking changes in distributions. These different perspectives often result in differing opinions with regard to the status of fish stocks, which can ultimately erode relationships between fishers and scientists (Mackinson and van der Kooij, 2006). Essentially the scientific sampling methodology is often seen by industry stakeholders as wrong. Comments are often made regarding surveys taking place at times or in locations where there aren't any fish, and how fishers could show scientists where to catch various species. This includes comments such as '*what's the point in doing the science later in the year when all the fish has spawned and moved on*', '*They're scientists, I'm a fisherman, but I can see all the juveniles on the ground when we haul pots and stuff. They tell me they're not there*' and '*it took them 5 years to realise the herring is here. Like it comes out of the Bristol Channel or in The Smalls. They are still doing surveys down in the north of The Trench down towards the top of the Labadie Bank where there hasn't been herrings in 6 years*'. While this highlights the tension between FEK and scientific knowledge, it also shows the strong potential for FEK and industry data to complement and contribute to the scientific data. To achieve this, we need to improve understanding of why, as scientists, we adopt the survey methods that we use. Explaining sampling using simple analogies such as '*you wouldn't estimate the population of Ireland by counting people in the City Centre in Dublin and scaling up from there*' can be useful to communicate such ideas. The possibility of incorporating a small module on fisheries science and associated sampling methods into BIM's Skipper Full Certificate of Competency training course (BIM, 2022) could also be of real benefit to further communicate this message. This would build on individual presentations delivered by Marine Institute staff (entitled 'Fishing for Science – From Deck to Desk and Back) which have been delivered to skippers in training in Ireland.

Even with a fuller understanding of sampling and stock assessment methods, when scientific advice and quotas do not match with what fishers are seeing in their nets this can lead to further frustration and a disincentive to contribute their own data to the scientific process. Interviewees raised a number of specific examples where they were seeing more fish on the ground than was represented by available quota. Even when there is an understanding that the provision of more information could improve stock assessments there can be a reluctance to contribute if the outcomes aren't likely to be favorable to fishers. This is highlighted by the following quote, *'it's just the way the scientists look at the information … we could improve it and get more information, but it almost always has a negative impact on the industry, that's the perception*'. This opinion represents a fear of data, with data provided by fishers being taken out of context or being used where it could have a negative impact on the fishing industry (Ebel et al., 2018). This also links to confusion between TAC, which is determined based on stock abundance and closely related to the science, which then leads to national quota, which is in turn allocated to individual vessels subject to policy decisions. While science gives advice on the state of the stocks and possible TAC, politics sets the actual TAC and policy sets the quota, but fishers relate the quotas they have available to them back to the science and this can lead to challenges when building effective working relationships, as detailed more in section 3.3.

Secondly, some fishing stakeholders don't realise that their logbook and VMS data contribute directly to the stock assessments. Prior to the full implementation of the Landing Obligation one interviewee frankly stated: '*your model will be rubbish if based on logged catch data'*. This is an extremely important disconnect, as when fishers perceive their reporting as contributing only to their monitoring and enforcement, it provides perverse incentives for misreporting (Gallic and Cox, 2006; Hentati-Sundberg et al., 2014). More work is required, therefore, to build trust and understanding so that fishers do not feel that they will be penalized by providing accurate catch information, but instead that they can actively contribute to the scientific process, more accurate stock assessments and successful EBFM. An example that could benefit from more reporting of catches from fishers is that of the North East Atlantic stock of spurdog (*Squalus acanthias*). This stock has been assessed as being historically low and has been subject to zero TAC throughout EU waters since 2010 (European Commission, 2015; Fox, 2015). While fishers have anecdotally reported increases in spurdog in recent years a lack of fleet-based data and reliable catch information since 2010 have been recognized as weaknesses in recent stock assessments (ICES, 2021) Due to their zero TAC status any spurdog caught in Irish fisheries should be recorded in logbooks as discards before being released in case of survival. However, active avoidance of this species is encouraged and some fishers have explained that they know where they could catch spurdog but they avoid these areas so have no records to submit that could aid benchmark assessments for this species. Others, who incidentally catch spurdog may not log it as a discard for fear of fishing grounds being closed as a result. Without more accurate catch information, however, it is difficult to fully assess the fishers' claims that spurdog numbers are increasing. A recent benchmark and subsequent ICES assessment in 2022 has shown an increase in the stock size which may lead to a non zero TAC (ICES, 2021; Institute, M. 2022).

One way to break down barriers and foster trust in the science is to improve understanding of the work and role of scientists (Dedual et al., 2013). The use of direct experience has previously been shown to help build social capital (Bailey et al., 2017), with a lack of trust often being more evident when there is limited contact between fishers and scientists (Glenn et al., 2012). A lack of opportunities for fishers to engage in the scientific process and gain positive reinforcement regarding this have been noted however, especially within European fisheries (Mackinson et al., 2011). The Irish At Sea Self-Sampling Program is, however, one such example which has proven to be a great vehicle to educate a wider distribution of fishers of the scientific process of gathering and collating raw data. As stated a common complaint of fishers is that the "*science is way behind what we see on the ground*". The At Sea Self-Sampling Program allows fishers to feed in their knowledge in a format that can be directly used in the scientific process. The fact that the At Sea Self-Sampling Program samples a subset of what a Sampler At Sea might collect also highlights the utility of taking trained scientists to sea. WKIRISH also provides an example of fishers and fishing industry representatives working alongside scientists to help improve understanding of the scientific process from the industry point of view while utilizing fishers' knowledge to improve our understanding of marine ecosystem functioning (Bentley et al., 2019a). In this instance the initiative began following requests from the fishing industry to provide a benchmark for the Irish Sea, after poor recovery of whitefish stocks in the area were noted. From a request from industry grew a collaborative endeavor that has certainly built trust and social capital, with industry valuing efforts from scientists to address and answer their concerns, while building understanding from different perspectives for all those involved in the process.

Inviting fishers to work alongside scientists during the planning and implementation of surveys can also be a useful way to build understanding of scientific sampling methods. In the mid 2000's there was a perception that the Celtic Sea Herring assessment was wrong, as the fishers felt that the survey was not being conducted in a manner that made sense, given recent changes in distribution etc … To help the fishers get a better understanding of the scientific process a representative fisher (nominated by the fleet) sailed on the scientific survey as an observer with specialist FEK to report back to the industry on the survey. The feedback from the "observer fisher" reported that the fisheries scientists had adapted the survey to reflect recent spatial changes but had done this in a manner that did not compromise on the scientific integrity of the survey time series. A radical change as expected by some fishers would have severely compromised the survey time series. An appreciation of this fact from survey participation led to a greater understanding which the observer fisher was able to communicate to fellow fishers on return. Collaborative experiences, outside of directly working together on surveys and research vessels, can also help improve understanding of the scientific process, including individual knowledge and experience sharing (e.g. IFISH, RTI, DiscardLess), and *via* participation in group workshops and discussion fora (e.g. Mission Atlantic, IFSRP). This improved understanding has been demonstrated where stakeholders that have repeatedly engaged in research fora feel empowered and comfortable to speak knowledgably about ecosystem-based fisheries management (EBFM) in other fora (e.g. in discussions about ORE). From our experiences those individuals who have been engaged in research previously, having gained an understanding of the science and scientific process, are more likely to engage in further scientific research. This may be in part because these individuals are naturally more inclined to engage with scientists due to their own curiosity, enjoyment of the experience, a desire to have more of a say in research and research outcomes, or to stay abreast of the latest developments in research. Working alongside scientists, either supporting survey work, attending science-industry partnership meetings, or being directly involved in research activities, may in itself not be sufficient in providing a full understanding of what fisheries scientists do. One fisher involved in research trips and tagging studies explained '*I don't find the results of it and like there has never been any follow up cod tagging programmes*'. A number of cod tagging programmes have been run by the Marine Institute in close collaboration with industry. These include an industry led initiative around the Greencastle codling fishery, which led to the closure of a winter fishery for juvenile cod (Ó Cuaig and Officer, 2007; Lordan et al., 2011), a Celtic Sea cod tagging programme which provided valuable insight into migration patterns of juvenile cod (Lordan et al., 2011) and a cod tagging study in the Irish Sea to determine mortality sources on cod in this sea area (Lundy, M et al., 2022). In these instances, follow up tagging programmes were not deemed necessary at the time as study objectives were met, so the lack of follow up referred to by the fisher could relate to a lack of accessible results or lack of feedback of results back to industry, as well as the fisher having different expectations of the outcome of the work they were involved in compared to the scientists. It is acknowledged in these cod tagging studies that the enthusiastic response of participating skippers was key to their success and furtive information exchange was achieved (Lordan et al., 2011). But it remains important for all partners to have a full understanding of involvement in research if social capital is to be maintained and not eroded. Indeed, levels of good quality communication are shown to relate to trust between fishers and scientists (Glenn et al., 2012). Thus, there remains a need for improving communication and engagement between scientists and industry to develop understanding and solidify existing collaborations. This has been achieved on a project level (e.g. RTI and DiscardLess) through the use of email newsletter updates. The Marine Institute also has an open access repository of all the research outputs from its' scientists. Resources such as the Stock Book, an annual publication providing advice on commercially exploited fish stocks in Ireland in an easily accessible format is freely available and accessible on-line in pdf and shiny app format (shiny.marine.ie/stockbook) along with a digital interactive shiny app also providing results from Irelands annual ground fish survey in an interactive format (shiny.marine.ie/igfs). Further education and marketing may be required to better point to the information and resources available for fishers to freely access, as well as ensuring results are sent directly to any study participants. Again, a forum such as the IFSRP can be used to highlight recent publications and new on-line resources but effort needs to be made to ensure all fishers are aware of what is available on-line.

3.3 Legacy and contextual challenges

Even after making efforts to overcome issues regarding understanding of our roles as scientists and the scientific process, to build social capital between scientific and fishing communities, there are further concerns often outside of our control as fisheries scientists that can impact upon these working relationships. These include legacy issues, which may have a long rooted history before many of us started our scientific careers. But also current issues and contextual challenges that can affect the willingness of stakeholders to engage with scientists. Regardless of when pressures on fishers emerged, those that are currently impacting upon an individual's fishing operations or are of current concern will significantly impact upon co-operation, even if they have nothing to do with the management, science or the questions we are asking.

Legacy issues that are frequently mentioned when conversing with fishers, and are recurrent themes in interviews, include those surrounding relative stability, quotas and the operations of foreign vessels within the Irish economic exclusion zone (EEZ), and the management of these issues. Relative stability describes the distribution of fisheries resources between EU member fleets, with each member state receiving the same proportion of the available TAC year on year, based on historic fishing records (Symes, 1997; Morin, 2000; European Union, 2013). Prior to Brexit the Irish EEZ constitutes 10% of the EU EEZ with Irish vessels accounting for 42% of landings by weight and 36% of the average value of landings from this area (Department of Food Agriculture and the Marine, 2018). Some members of the Irish fishing industry feel the division of quotas for Irish vessels within their own EEZ is unfair, especially when they have limited quota for fishing in the waters of other jurisdictions. Fishers have described the situation in the Irish fleet as '*fighting over crumbs*'. These issues then came to the fore with the introduction of the EU's Landing Obligation and the risk of choke species (Schorpe, 2010; Catchpole et al., 2017; Calderwood et al., 2021b). Fishers complained that once their monthly quota allowance was used up in any month (Calderwood and Reid, 2019), and they faced a choke situation in any management area, other countries not subject to the same monthly quotas or choke would benefit, '*all the Irish boats will leave there and the Spanish and UK boats will be work away there you know*'.

These feelings of the unjust nature of quota allocations are further conflated by the perception that foreign vessels operating in Irish waters are not subject to the same levels of scrutiny from inspection agencies as Irish vessels. One fisher explained that they felt SFPA officers could only check that legal gear is being used on foreign vessels, but not check catch levels are in line with quota as they do for Irish vessels because '*the Irish authorities don't know what their quotas are because they can swap them*'. This also links to issues many in the industry had with the introduction of electronic logbooks for vessels greater than 12 meters in length (European Commission, 2011). Ireland was one of the first countries in the EU to implement the new legislation and have Irish vessels adopt e-logbooks, as opposed to the use of paper records. Fishers were encouraged to adopt the new system with promises of '*the Spanish will have to go through our hub and we'll know exactly what everybody has*'. But instead fishers have explained that '*soon as they put them in, we were the first boats to put them in, well actually the Spaniards and all the foreign boats don't go through our hub, we don't know what they're landing, they go straight to their own national hubs*'. This again leads to feelings that Irish vessels are disadvantaged fishing in their own waters compared to foreign vessels.

These issues are further linked to a belief that quotas do not reflect the reality observed on the ground (Pedreschi et al., 2021), as touched on in section 3.2. Frustrations arise when quotas are limited and fishers are not only seeing fish on the ground but see other nations catching them when they are not able to. Again this links to any one country or vessels' quota not necessarily reflecting the overall TAC for an area. Yet despite TACs being informed more by the science rather than policy, further distrust and frustration in the system arises with the specification and allocation of Total Allowable Catch (TAC) by the European Commission (EC) at the annual December Council, a historically political process. Years of setting TACs above the recommended scientific advice (Proelss and Houghton, 2012; Carpenter et al., 2016; Borges, 2018; Borges, 2021) has eroded trust in the system, including the science. All of these issues relating to relative stability, the perception that foreign vessels are faring better in Irish waters than the Irish fleet and a general mistrust of the TAC allocation system are entwined. As such they can be described as 'wicked problems' that pose a constant challenge and are difficult to delineate from other issues (Jentoft and Chuenpagdee, 2009). These problems can have long lasting effects on trust and also provide a disincentive to collaborate with scientists, as it is unlikely that results from scientific research can do much to address such legacy issues.

There are often more pressing issues, linked to management, socio-economics, politics and culture, that can also affect the willingness of stakeholders to engage. The impacts of Brexit on Irish fisheries have also been of particular concern in recent years and the uncertainty of the impacts this might have on the Irish fleet. Concerns of reduced quotas as the UK leaves the EU indeed led to Irish fishers protesting in both Cork and Dublin in 2021 (Burns, 2021; Halpin and Kilcoyne, 2021). For some industry representatives the expansions of offshore renewables is expected to have a greater detrimental effect on the fishing industry compared to Brexit (Duffy, 2022). Concerns stem from multiple stakeholders wanting to use the same marine areas with fishers feeling increasingly squeezed. Increasing fuel prices, which were exacerbated by the Russian invasion of Ukraine, are also having a significant impact on the fishing industry with the processing sector seeing knock-on impacts and costs increasing by 200% to 350% compared to the previous year (Forsythe, 2022). These larger, often international issues add to day-to-day challenges including the need for de-watering and weighing catches on the pier (Fagan, 2021), navigating penalty point systems (McCurry, 2021) and finding crew for fishing vessels.

Without immediate or obvious benefit from collaborating with scientists, in terms of addressing legacy and equity issues and contextual challenges, it can be hard to build trust and persuade fishers that there are benefits to contributing FEK and assist with research projects. It is critical that, prior to engagement with stakeholders, effort is made to understand what is affecting them, i.e. to understanding the context in which they are operating. While it may be difficult to enact change to address issues of concern, at the least as scientists we should take the time to listen to the concerns of the fishing industry. While we may have little influence on the things of most concern to fishers, having a full understanding of the challenges and concerns of industry can shape and influence the direction of research and improve our understanding of fishing operations and the motivations of fishers. Taking such time to engage with fishers and build relationships is an essential step in our research programmes, even if not directly addressing research objectives, as open dialogue can be a way of documenting important FEK and putting our research into better context. When working with industry it is also important for scientists to acknowledge things we deem as important may not be as important to industry. While we should continue to pursue science that does have some industry support, it is important to understand this process may take longer than planned, especially when other issues and concerns come more to the forefront. It is critically important to discuss, explain and manage the expectations of all parties involved.

3.4 COVID-19 pandemic

Once such major contextual challenge was the unprecedented effects of the COVID-19 pandemic. COVID-19 has been recognized as having a significant impact on the fishing and aquaculture industries throughout the world (Ray, 2019; White et al., 2021; Alam et al., 2022). The requirements for social distancing in addition to both international and domestic travel restrictions (Kennelly et al., 2020) also impacted on the working patterns of fishers and fisheries scientists within Ireland. This included restricting the ability for at sea samplers to join fishing vessels to sample catches, and for research staff to visit ports to collect catch samples as part of our national sampling program, thus affecting the scientific data collected.

The temporary suspension of the At Sea Sampling program due to Covid-19 restrictions resulted in the development of the At Sea Self-Sampling Program as described above (Section 2.2). While the program resulted in less complete data than before Covid-19, it was still important. The alternative of zero At Sea data on catch composition, would have been seriously detrimental to the assessment process. The At Sea Self Sampling Program ensured that communication lines remained open even in times of limited mobility. The success of the program was due to the participants wish "to do it right" and the strong interaction between the associated scientists and fishers in the inception, development and implementation of the program. Further the effects of Covid-19 restrictions on shore based sampling was minimized by the facilitation of out of hours sampling by the processors and Marine Institute staff. Co-operation from industry to facilitate this sampling was important as the availability of fish to sample was affected by the knock on market pressures that the fleet experienced during Covid-19. In the example of the At Sea Self-Sampling Program the challenges of Covid-19 have actually provided opportunity to open up new avenues of working with industry to collect catch information. The success of the scheme, as seen from both Marine Institute and industry perspectives, has led to it continuing. The Marine Institute now incorporates the initiative into the national data collection program to augment the data collected by scientific samplers at sea under the original At Sea Sampling program. The combination of the dual data streams is expected to increase the number of observations at sea in an efficient and scientific manner, whilst also allowing vessels previously restricted due to accommodation limitations to participate in at sea sampling. Having such a positive result come out of a period of uncertainty for the fishing industry is a great achievement and an example of a successful collaboration between scientists and industry.

As well as impacting sampling, COVID-19 has also had an impact on the engagement of stakeholders with research projects (Köpsel et al., 2021). Travel restrictions and requirements for social distancing in Ireland in the first year of the COVID-19 pandemic impacted on a number of research projects running at the Marine Institute, including IFISH and Mission Atlantic (Sections 2.3 and 2.4). The initial plan for the IFISH project was to travel around Ireland to the main ports, engage with fishers and raise awareness of this new project, as well as conduct interviews to gauge understanding of how fishers value different components of their catches. For Mission Atlantic, in-person stakeholder meetings were planned for the Celtic Sea case study, which would involve participants from Ireland, France, and the UK. Within the first year of the pandemic Ireland's response included restriction on non-essential travel, with individuals being restricted to travel within 2km and then 5km from home, before being extended to 20km, and then county wide travel (Kennelly et al., 2020). During this time much international travel was also restricted, with individual organisations placing restrictions on employees in regards to 'unnecessary travel'. Even once country wide travel was allowed many indoor venues such as cafes and hotels, where we may have previously arranged to meet to chat to stakeholders, were closed. This made face-to-face meetings virtually impossible for many months, impinging on collaborative efforts. This unanticipated situation required adoption of different strategies to maintain engagement with relevant stakeholders. In addition to the obstacles presented by travel restrictions and social distancing measures, Ireland's seafood economy declined by 12% in 2020 compared to 2019, driven primarily by an 18% reduction in domestic consumption, due to the closure of many businesses in the hospitality industry, and an 8% decline in exports (Afloat, 2021; BIM, 2021). The pressures faced by industry during this time led to some fisheries representatives calling on the Irish government to provide supports for a temporary tie-up scheme to assist in dealing with the turmoil in the markets at this time (Mainnín, 2020). Such hardships meant that willingness to engage in research projects was reduced as it was not seen as an immediate priority or as essential (Köpsel et al., 2021).

The IFISH project was just commencing at the outset of the pandemic but every effort was made to maintain open communication channels at this time to try and continue the research and preserve relationships with fishers. The project was advertised *via* social media and industry contacts were invited to participate *via* e-mail. Some interviews were conducted *via* phone and online video call services. While such approaches did aid in overcoming social distancing and travel restrictions, they didn't allow the time and environment to allow conversations to develop as had previously been experienced when conducting face to face interviews. The importance of pre-existing relationships was illustrated as approaching and engaging fishers we had previously worked with was more successful than trying to contact and arrange meetings with fishers we had not previously met in person. While progress was slower than anticipated due to the restrictions, and additional pressures facing the fishing industry, engagement was possible using on-line solutions. As restrictions began to lift, IFISH progressed from on-line meetings to planning in-person events to begin to facilitate focus group discussions on how app technology could be potentially be used to facilitate information sharing between vessels to reduce unwanted bycatch. However, at the time of writing these planned discussions have been postponed as fishers struggle to deal with the recent rises in fuel prices, general inflation, running costs, and crew shortages making it hard for some boats to get to sea and make a living (Moore, 2022). Despite these delays, industry representatives remain keen to pursue this work when the time is right.

For Mission Atlantic planned in-person stakeholder meetings had to be abandoned and replaced with online virtual meetings. This directly impacted the project as it dramatically reduced the time available, and the tasks that could be carried out. Initial plans involved a risk assessment exercise to be carried out with stakeholders. Previous experience had indicated that was a complex exercise, requiring active participation and discussion, with multiple facilitators, in a workshop carried out over a 2-3 days. Critical to its success is the downtime, and building of common understanding as well as group cohesiveness, which cannot be achieved to the same degree online. Furthermore, body language is impossible to read, and so it is more difficult to judge responses when seeking consensus, especially when participants may have their cameras turned off. We were also highly cognizant of the 'screen fatigue' and digital burnout that many were (and are) feeling throughout this period (Bennett et al., 2021; Pandya and Lodha, 2021; Sharma et al., 2021). As a result, we changed the initial exercise from an in-person co-production exercise to an on-line presentation of results and 'sanity-check' approach. In an attempt to avoid some of the common pitfalls of online meetings we encouraged contributions through a range of methods. Participants were free to ask questions at any time verbally or to write in the chat which was monitored by a meeting facilitator. The meeting was carried out under 'Chatham House Rules' where participants are free to use the information received during a meeting outside of the meeting, but not to identity the individual or the affiliation of the people that said it. This encourages some participants to speak more freely. Additionally, we created an online collaborative note-taking Google document with live-note taking by meeting facilitators, to which participants were also encouraged to contribute if they wished. In 2021 a full-day meeting was held where the risk assessment results were presented to stakeholders and discussed in detail. Stakeholders were made aware that this was an iterative process and they were free to suggest changes to the assessment. When the initial results were reviewed and discussed, an additional moderated discussion identified common stakeholder research questions relevant to the case study area. These questions and discussions are being used to direct research efforts in the Celtic Sea case study. In 2022, the same format was applied, except we broke the full day meeting into two half days to avoid information overload and provide time for reflection between sessions. During this meeting the focus was on providing updates, including presenting the modelling framework, defining scenarios that the stakeholders wish to be investigated, and carrying out an online group conceptual modelling exercise. Despite an in-person meeting still being the preferred approach for these meetings for the reasons outlined above, there was good engagement online, with valuable outputs created. With no travel costs and a reduced time commitment without additional travel requirements options for online attendance may have also increased opportunities for attendance. So far we have managed to mitigate against any major project delays through our adaptive and reflective approach.

Each project has been affected by the pandemic to different degrees. This may have been influenced by the type of stakeholder targeted. For Mission Atlantic, although in-person meetings were no longer possible, most of the stakeholders engaged were industry or eNGO representatives, or working for national agencies, and therefore had moved most of their work online. Conversely, the IFISH project is largely targeting individual fishers, whose livelihoods are more directly impacted by the difficulties imposed by the COVID-19 pandemic and rising inflation. As such, it is perhaps not surprising that it has been more difficult to progress the IFISH work under the current circumstances. Additionally, while online meetings do have the benefit of accessibility in theory, consideration must be given to the digital literacy of those you are engaging with, ensuring flexible and simple approaches for effective on-line engagement (Köpsel et al., 2021).

4 Discussion

It is widely acknowledged that fishing industry stakeholders have important and unique contributions to make to fisheries research. Despite advances being made in recognizing the importance of FEK within science and management, and in developing participatory research approaches, a number of barriers exist within Irish fisheries for successful co-creation of knowledge and integration of FEK into the science and management processes. Despite this, efforts by both scientists and fishery stakeholders continue to be made to overcome these barriers, build strong working relationships and foster these relationships for the co-creation of knowledge to advance research and further understanding of Irish fisheries.

Reflecting on our experiences of working together with fishers in Irish fisheries to co-create knowledge we have highlighted the importance of providing opportunities for fishers to work together with scientists to improve understanding of scientific processes and build trust in these. We also highlight the importance of scientists working with and learning from fishers to better inform our science and scientific practices. Two key elements when working together are maintaining regular open communication and allowing time for building trust and subsequently achieving desired outcomes from working together with industry. While the process of collaborating with industry might require time and patience, maintaining momentum and creating opportunities can also be key when establishing participatory research (Mackinson et al., 2011). The importance of social networks has been recognized as being important in the determination of social capital (Grafton, 2005). Strong ties between groups of fishers are often linked to trust and co-operation, but as scientists we need to improve 'linking' social capital, the connections that exist across disparate groups (Grafton, 2005). The networks we have already established, through previous outreach, sampling and survey work, and the case studies outlined herein, provide a solid foundation for continued and future work with industry. Working with those with whom we have already built trust and social capital is an important avenue to maintain momentum. While working with early adopters presents a classic approach to building social capital, we must also ensure that we don't overlook fishers who we haven't previously worked with, or who have fewer links to the Marine Institute, such as those who are not members of Producer Organizations. We must also consider the roles fishers want to take on within science-industry partnerships and how this may impact upon adoption. Many of the examples presented in this paper look at ways in which avenues are provided for fishers to contribute their knowledge once research programmes and initiatives have already been developed. If there were more opportunities to involve fishers from the outset of projects from question formation, hypothesis building and design there may be higher levels of satisfaction and pride in their participation, which then leads to higher social capital that could potentially encourage further participation. The legacy from the WKIRISH process certainly demonstrates how positive relationships can be built with industry when scientists take the time to listen to their concerns and look at how they can be resolved together.

One important element of social capital is trust and trustworthiness (Grafton, 2005). A lack of trust or understanding of the scientific process can reduce the likelihood of fishers contributing their knowledge to the scientific process. While it may seem like a chicken and egg situation, it is evident that it is important for fishers to be involved in the scientific process to build understanding and trust, and further encourage participation. The At Sea Self-Sampling Program provides a successful example of this, highlighting to fishers how they can input data directly into the scientific process whilst at the same time helping them to understand scientific sampling methods. From a potential period of crisis during Covid-19 restrictions came an opportunity for learning and development for both fishers and scientists on how industry can be more involved in national data collection. Certainly social capital was built during this process, resulting in a legacy of the ongoing at sea self-sampling programme. While placing trust in fishers to collect and provide information and data to scientists can be particularly important in building social capital, having fishers aboard scientific surveys can also be beneficial. Working alongside scientists also has been shown to help build trust and provide fishers with an understanding of why scientists operate the way they do in order to minimize potential bias.

Working alongside industry can also help in building trust from the scientists' point of view. It has been recognized that some believe that contributions of knowledge do not hold up to the quality standards or consistency that should be expected from scientific data (Steins et al., 2022). Using appropriate training, data collection methods and remuneration it is however possible for fishers to collect and contribute reliable and useful data (Neis et al., 1999; Kindt-Larsen et al., 2011; Kraan et al., 2013; Mangi et al., 2018; Bentley et al., 2019a; Steins et al., 2022). To have more confidence in the use of such data it may be beneficial for scientists to work alongside those fishers contributing their knowledge, to build working relationships and trust in the information being received. This supports the identification that building positive relationships can be one of the key steps in enabling participatory research (Mackinson et al., 2011). Progress has been made to demonstrate how FEK can be used within quantitative stock assessment processes (Neis et al., 1999; Hutchings and Ferguson, 2000) and food web modelling (Bentley et al., 2019a), which presents a large step forward for EAFM. However, there remains a lack of examples where FEK is regularly fed into stock assessments and more progress is needed to improve the integration of the fishing industry knowledge into fish stock assessment and ecosystem science (Steins et al., 2022). Trust needs to be built so that fishers feel able to provide accurate catch information without possible negative implications and so that scientists feel confident in using FEXK in their work. Certainly opportunities to work with fishers in the field, on-board research vessels or fishing vessels provide opportunities for scientists to learn from fishers. Equally, conversing and collaborating with fishers through projects that involve interviews, focus groups and workshops provide opportunities to learn from fishers and develop a greater understanding of the industry perspectives on current and legacy issues. The two-way nature of information and knowledge exchange must be recognized when working with industry, on whatever platform and within whatever environment, to continue to build trust and fruitful working relationships.

Consideration on how best to engage with and work alongside fishers is also important. Opportunities for improving the understanding and trust required for co-creation through the engagement style and methods used should be taken seriously. If done half-heartedly, engagement can do more harm than good. It is essential that enough time is given to allow consensus to form through understanding and dialogue (Richards et al., 2007). Engagement must be thoughtful, using the tools and methods of engagement appropriate to the message and process, treat all participants fairly, use the best available scientific evidence, and present real opportunities to contribute to and influence decisions (Rowe and Frewer, 2000; Reed, 2008; Pita et al., 2010). Together these help to combat the most common frustrations associated with stakeholder fatigue (Richards et al., 2007). This paper highlights a range of ways to engage with and work alongside fisheries stakeholders, from having fora such as the IFRSP, establishing self-sampling at sea, conducting interviews and questionnaires with fishers, and developing focus groups and workshops. For those leading stakeholder events, engagement, and exercises, a basic understanding of facilitation methods, power dynamics, and social science tools can greatly help to improve the interaction. Better still, is to engage social scientists directly in the process, creating multi-disciplinary teams with more holistic knowledge and approaches that can help to improve interactions and maximize outputs. Again consideration should also be given to the point during a research project or scientific imitative as to when fishers become involved. Significant benefits can be gained from not just viewing fishers as data sources or data collectors but by developing true participatory research approaches that allow all involved to participate in the research process from the development of ideas and questions through to the design and execution (Stanley and Rice, 2017). Appropriate supports are required, however, if all involved stakeholders are to contribute to projects as equal research partners (Stanley and Rice, 2017) and additional resources may need to be found to support such efforts.

Effective communication has also been identified as being essential in order to facilitate stakeholder engagement in research and decision-making processes (Mackinson et al., 2011). A lack of trust between stakeholders, coupled with a lack of involvement in decision-making have been cited as contributing to difficulties experienced in implementing the CFP and undermining its legitimacy in the past, with improved communication outlined as a priority for the European Commission (EC) (European Commission, 2009; Pita et al., 2010; Mackinson et al., 2011). Communication has been identified as the best way to improve outcomes in social dilemmas, with face-to-face communication facilitating consistent, strong, and replicable increases in cooperation and trust (Ostrom, 1998). Our experiences show it is important to ensure fisheries stakeholders are regularly updated on and involved in scientific research throughout its lifespan, from the conception of ideas through to the delivery of results. Communicating results and outcomes from research, that has involved fishers, back to the fishing industry is essential to demonstrate the importance of fishers' contributions, but also to build social capital and ensure fishers feel valued and useful. As scientists, who regularly search for information, we may overlook how best to guide industry stakeholders to data repositories and resultant information produced by research, but this is something that can be easily overcome with a little marketing and education, and improvements in direct communication/feedback. Being realistic about expectations and changes that scientific research can deliver from the outset is also a critically important part of this communication strategy. Results from collaborating with scientists might not provide the quick solutions that some fishers may seek and this should be made clear prior to and during engagement so as not to further erode trust and social capital.

Context will always be evolving, thus it is critically important for scientists to understand the socio-ecological context in which we, the fishers, and fisheries we research operate. Scientists must acknowledge that the things we deem as important may not be as important to industry, and while we should continue to pursue collaborative science and solicit industry support, we must recognize that this process may take longer than planned when other issues and concerns move to the forefront for stakeholders (e.g. Covid-19 or Brexit). For this reason, we would urge for such considerations to be embedded in national research and policy frameworks, so that important engagement fora and the benefits of collaborative activities can continue beyond the lifespan of short-term funded directed research projects.

The many examples presented in this paper demonstrate FEK and collaborative research strengthening our scientific knowledge base. Building social capital and trust to achieve such work collaborations has potential for significant contributions to fisheries science, providing more balanced views of issues facing fisheries and adding to important fisheries data sources. It is also possible to build from these experiences, and improved understanding from both fishers and scientists point of view to develop more truly participatory and collaborative approaches. The examples we have presented, however, represent much of the ground work that has been required to build trust between science and industry and slowly build successful working relationships between these parties.

5 Conclusion

Previous top-down management approaches, a suite of legacy and equity issues that impact upon fishers, and research that has not included stakeholders or has failed to maintain relationships with stakeholders may have eroded social capital between the fishing industry and scientific community (Grafton, 2005). The examples in this paper illustrate in stark detail the complexity of the fisheries landscape in Ireland, ranging from poor understanding, to trust issues that stem from a mistrust of the science but also from legacy issues effecting the fishing industry, to an overwhelming list of current priorities. This complexity is mirrored in many other nations and similar low levels of trust in all governing bodies in UK fisheries has also been found (Ford and Stewart, 2021). Fisheries ecology and management is complex in and of itself and inherently associated with wicked problems. It may be possible for us as scientists to work with fishers despite the legacy issues, but remaining aware of these and the pressures they have created. We must be cognizant, however, that when we attempt to regain trust and build social capital to co-manage, co-build, co-create, and collaborate with stakeholders in any form, we are asking for something; time. Very often we do not even cover the costs of participating. As such, other, more immediate factors, will always significantly impact on cooperation, even if they are nothing to do with management, science, or the questions we are asking. Given the complexity outlined herein, on the surface stakeholders really have very little reason to want to collaborate, when there is simply too much else going on. Consideration should be given to provide remuneration to fishers where possible and appropriate. This again helps to overcome issues related to the quality of FEK in relation to ensuring industry have the capacity consistently to collaborate with the scientific community and are equal parties in collaborative efforts (Steins et al., 2022) . The benefits of contributing knowledge to scientific research also need to be better considered and communicated.

Overall, while there can be numerous challenges to building trust and social capital with fishers, so that their experiential knowledge can be documented and used in fisheries science, the results from working together with industry can be significant. Despite challenges, creating opportunities to work with and alongside fishers builds the social capital and momentum to keep fostering these relationships. We have reflected on challenges unique to Irish fisheries when engaging with industry with the aim of co-producing knowledge. Many of the lessons learned and ways to progress working with the fishing industry are more widely applicable, especially within EU fisheries. Overall, however, there is no one-size-fits-all solution and time needs to be taken to understand individual fisheries and fishers, the avenues they are interested in contributing their knowledge to and the time available to them to do so.

Data availability statement

Anonymised raw data supporting the conclusions of this article will be made available upon request to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Marine Institute Research Committee Ethics Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JC conceptualized the original idea for the paper, conducted industry interviews and contributed to the writing and editing of the paper. DP conducted industry interviews and contributed to the development, writing and editing of the paper. MC contributed to the development, writing and editing of the paper. DR contributed to the development, writing and editing of the paper. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Robert Stephenson,
Fisheries and Oceans Canada
(DFO), Canada

REVIEWED BY
Graham Sherwood,
Gulf of Maine Research
Institute, Portland
Brian R. MacKenzie,
Technical University of
Denmark, Denmark

*CORRESPONDENCE
Laura M. Bliss
blissl@myumanitoba.ca

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Using fishers' knowledge to determine the spatial extent of deep-water spawning of capelin (*Mallotus villosus*) in Newfoundland, Canada

Laura M. Bliss[1]*, Natalya Dawe[2], Erin H. Carruthers[2], Hannah M. Murphy[3] and Gail K. Davoren[1]

[1]Department of Biological Sciences, University of Manitoba, Winnipeg, MB, Canada, [2]Fish, Food and Allied Workers Union, St. John's, NL, Canada, [3]Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, St. John's, NL, Canada

Introduction: On the Newfoundland-Labrador Shelf, Canada, capelin (*Mallotus villosus*) is a key forage fish that migrates annually from offshore to spawn within coastal embayments. Although capelin are thought to primarily spawn on beaches in this region, they also spawn subtidally in deeper water (5–40 m), where their eggs remain throughout incubation. The spatial extent of subtidal (i.e. "deep-water") spawning habitat in coastal Newfoundland is unknown and is a research priority for fishers and management.

Methods: We collaborated with capelin fishers to identify putative deep-water spawning sites as a first step in determining the contribution of deep-water spawning to capelin recruitment. Given limited fine-scale coastal bathymetry and seabed habitat type data, which impeded spatial modeling to determine suitable capelin spawning habitat, this science-industry research collaboration was key to addressing this knowledge gap.

Results: Through two years of multi-bay fisher interviews, 84% of interviewed fishers (56 interviewees) reported having observed deep-water spawning and identified a broad distribution of putative spawning sites throughout coastal Newfoundland. The majority of fishers indicated inter-annual variation in beach and deep-water spawning habitat use, and most interviewees linked this variation to temperature and capelin abundance. Further collaborations with fishers during boat-based surveys, we sampled 136 unique sites within 12 search areas in eastern Placentia Bay and 26 unique sites within six search areas in Bonavista Bay. Underwater video surveys combined with sediment sampling revealed seven previously undocumented deep-water spawning sites.

Conclusion: The deep-water spawning areas derived from these fisher interviews can now be used to build a time series for monitoring capelin spawning habitat use alongside citizen-based beach monitoring data, as a general capelin stock health indicator in a weight of evidence approach for the science advisory process.

KEYWORDS

fishers' knowledge research, collaborative research, Newfoundland (Canada), Capelin (*Mallotus villosus*), knowledge co-creation, fishers' knowledge

Introduction

Many marine systems are described as wasp-waist, whereby energy flow to the higher trophic level is funneled through one or a few forage species at the intermediate trophic level (Bakun, 2006). Thus, alterations in the distributional and density patterns of these forage species can affect marine food webs in unpredictable ways (Coll et al., 2008; Pikitch et al., 2012). Capelin (*Mallotus villosus*) is a key forage fish species in the Northwest Atlantic that functions as the primary wasp-waist species, or link, between lower and higher trophic levels (Lavigne, 1996; Carscadden and Vilhjalmsson, 2002). In coastal Newfoundland, spawning capelin abundance and distribution directly impact the density and distributional patterns of marine mammals (Whitehead and Carscadden, 1985; Johnson and Davoren, 2021), Atlantic cod (*Gadus morhua*; Rose and O'Driscoll, 2002), and seabirds (Carscadden et al., 2002; Davoren and Montevecchi, 2003; Davoren, 2013a). However, in the early 1990s, the capelin population on the Newfoundland Shelf (Northwest Atlantic Fisheries Organization [NAFO] Divisions 2J3KL) crashed from a high of 2–6 million tons (Mt) pre-1991 to 0.03–1.0 Mt for the subsequent three decades, reaching an all-time low in 2010 at ~1% of pre-1991 levels (Buren et al., 2014; DFO, 2015). Further, since 1991 there have been minimal signs of recovery (Buren et al., 2019).

Maturing capelin undergo an annual migration from offshore waters to spawn within coastal embayments of Newfoundland and southern Labrador, with beaches considered the primary spawning habitat in coastal regions (Nakashima and Wheeler, 2002). There are, however, historical reports in this region of capelin spawning at subtidal sites in deeper water (< 50 m; hereafter referred to as 'deep-water sites' Templeman, 1948). These early records included reports of capelin spawn on traps, trawls and nets from other fisheries and on anchors from 5–45 m depth (Templeman, 1948). Since the early 2000s, deep-water spawning sites have been located and scientifically monitored on an annual basis in Trinity Bay (Nakashima and Wheeler, 2002) and Notre Dame Bay (Davoren et al., 2008) and researchers have studied a variety of topics, including spawning habitat selection (Davoren, 2013b; Crook et al., 2017), genetic divergence between beach and deep-water spawners (Penton et al., 2014; Kenchington et al., 2015), and connectivity between spawning habitats (Davoren and Halden, 2014; Davoren et al., 2015), as well as among embayments (Tripp et al., 2020). In particular, recent studies have shown temperature-dependent shifts between subtidal and intertidal habitats, which results in high inter-annual variation in spawning site use within regions (Davoren, 2013b; Crook et al., 2017). These findings support Templeman's (1948) hypothesis that capelin select between these two spawning habitats based on water temperature, occupying warmer beach habitat in years of cooler water and shifting to deep-water habitat in warmer years. Based on observations of abnormal egg development and low larval emergence at deep-water spawning sites in Trinity Bay, Nakashima and Wheeler (2002) inferred that larval production from this habitat would be limited. More recent studies, however, have shown that both spawning habitats have similar egg densities, temperature-dependent egg development (Penton et al., 2012) and produce larvae in good condition (Penton and Davoren, 2008). Although fishers have reported that deep-water spawning has become more prevalent since 1994 (Nakashima and Clark, 1999) and persistently urge fisheries scientists to quantify the productivity of this habitat (Dawe and Carruthers, 2019), little is currently known about the relative contribution of deep-water and beach habitats to population-level capelin recruitment (Davoren et al., 2008), partly because the province-wide spatial extent of these coastal deep-water spawning sites is unknown.

As capelin typically spawn subtidally in small patches of suitable sediment (0.5–25 mm; Templeman, 1948; Nakashima and Wheeler, 2002; Davoren et al., 2008; Penton et al., 2012; Penton and Davoren, 2013) within a limited temperature range (2–12°C; Carscadden et al., 1989; Davoren, 2013b; Crook et al., 2017), modeling the spatial extent of this habitat in coastal Newfoundland requires both fine-scale (< 100 m) bathymetry and seabed habitat information within the 50 m contour, which is typically within suitable temperature ranges for capelin spawning (Davoren et al., 2006). Unfortunately, both data types have limited spatial coverage within coastal Newfoundland. Therefore, we aimed to collaborate with capelin fishers to identify potential deep-water spawning areas. Fishers' knowledge (FK) research and, more broadly, Local and Traditional Ecological Knowledge (LEK & TEK), can provide information on species beyond the scope of ongoing scientific observations (e.g., Neis et al., 1999; Silvano et al., 2006; Martinez-Levasseur et al., 2017). In coastal Newfoundland, a long-standing commercial capelin roe fishery occurs during their spawning season with a 100% utilization of both male and female fish since 2006, so fishers collect pre-season samples to determine sex ratios of the schools, female size and roe content (DFO, 2022a). The focus on roe results in an intensive observation window by fishers during spawning which leads to extensive LEK on the location, timing, and duration of beach and deep-water spawning. Additionally, capelin deep-water spawning may overlap with traditional fishing grounds for other species such as cod. Incorporating such fishers' knowledge has increased our understanding of capelin stock dynamics and ecology in the past (DFO, 1997; Neis and Morris, 2002). In support, FK of other fish stocks has challenged the results/conclusions of stock assessments (e.g., Neis et al., 1999; Hutchings and Ferguson, 2000) and has documented spawning components (e.g., Ames, 2004; DeCelles et al., 2017) as well as fish migration and feeding patterns (e.g., Fraser et al., 2006; Silvano et al., 2006) that either differed from or were not previously documented by fisheries science.

To identify the number and location of deep-water capelin spawning sites throughout the south and east coasts of Newfoundland, we used structured interviews in 2018 and

2019 to document capelin fishers' knowledge of deep-water spawning areas and then, using information recorded during these interviews, we worked with capelin fishers during boat-based surveys to locate deep-water spawning sites during the 2019 spawning season. We focused our boat-based research surveys on only Bonavista and Placentia bays due to previous knowledge on potential deep-water spawning sites (Placentia Bay, Sjare et al., 2003) and encouragement by fishers based on the economic importance of the local capelin fishery (Bonavista Bay, DFO, 2022a). These bays also represent two different capelin stocks (Placentia Bay: 3Ps; Bonavista Bay: 2J3KL), one of which (3Ps) has a paucity of data. Fisher knowledge interviews were also used to assess inter-annual shifts in the use of beach and deep-water spawning sites, as well as to identify factors likely influencing these shifts in habitat use. Our ultimate goal was to map fishers' knowledge of the spatial extent of deep-water spawning sites to serve as an important first step in quantifying the contribution of deep-water spawning habitat to capelin recruitment dynamics and to complement ongoing work examining the productivity of capelin spawning habitats (Penton et al., 2012; Davoren et al., 2015) and regions (Tripp et al., 2020) as well as environmental drivers of capelin recruitment (Murphy et al., 2018; Lewis et al., 2019). The results from our study address a research priority for fishers, thereby strengthening fisher-science advisor relationships, and have the potential to be used in the assessment of the stock alongside a citizen-based beach monitoring time series (Murphy, 2022).

Materials and methods

Interview design

We asked capelin fishers a series of questions during in-person interviews. Researcher (ND) from the Fish, Food and Allied Workers Union (FFAW) conducted interviews during January–February 2019 (26 interviewees) in Conception, Trinity, Bonavista, Notre Dame, and White bays, and researcher (LB) from the University of Manitoba conducted interviews during August 2018 in eastern Placentia Bay, St. Mary's Bay and Southern Avalon (22 interviewees), and July–August 2019 in eastern and western Placentia Bay (19 interviewees). Interview questions were based on an interview template previously used to investigate changes in capelin biology and behavior (Sjare et al., 2003; Table S1). The primary purpose of the interviews was to obtain information on the spatial locations of capelin beach and deep-water spawning activity, while the secondary purpose was to obtain information on the inter-annual changes in use of spawning habitats, as well as factors likely influencing these changes. We identified interviewees by recruitment at the wharf, during which we asked fishers present who in the area had the most experience fishing capelin. Long-time fishers were recommended by their peers as "experts", that is, particularly knowledgeable representatives of their fleet sector and region (e.g. Davis and Wagner, 2003). We identified additional interviewees using snowball sampling (i.e. asking interviewees to recommend other fishers; e.g. Gunderson and Watson, 2007). Other fishers were recommended for interviews based on their length of time in the fishery (range 8–65 years), fleet sector (fixed or mobile), and region.

We asked interviewees if they knew whether capelin spawned on beaches and/or in deep water currently or historically. Deep-water spawning was defined as subtidal spawning that is not contiguous with a beach or a beach spawning site. We also asked interviewees how they knew deep-water spawning occurred (see Table S1 for specific questions). Physical evidence of deep-water spawning included the presence of capelin eggs adhered to fishing gear (e.g., nets, traps, pots) and capelin spawning visually observed on the seabed in < 5 m depth. Supplemental non-physical evidence that fishers stated to aid in identifying deep-water spawning areas included 'heard from others', 'bird and whale activity', and 'aggregations of capelin' including deep-water spawning behavior observed on echosounders (i.e. stationary aggregations of seabed-associated shoals that were confirmed to be capelin during fishing). Finally, we asked interviewees to draw the location(s) of beach and deep-water spawning on a nautical chart and to only provide information on deep-water spawning locations that were based on physical evidence. These areas identified as putative deep-water spawning areas based on physical evidence (hereafter referred to as 'putative areas') were later converted to centroid points for standardization and used to inform boat-based sampling (see below).

As we were also interested in inter-annual changes in the use of beach and deep-water spawning areas, along with fishers' understanding of factors likely influencing changes in habitat use, we also asked questions related to changes in the timing of spawning, area use, and the duration of spawning at known spawning areas (see Table S1 for specific questions).

Boat-based sampling

As there is high inter-annual variation in the timing of the first day of capelin spawning (3–6 weeks; Crook et al., 2017), the timing of spawning from interviews (in previous years) was not used to determine the initiation of boat-based sampling. Instead, prior to boat-based sampling, we regularly monitored citizen-science social media platforms, including Twitter (#CapelinRoll) and www.ecapelin.ca, where beach spawning observations are posted, to ensure that we began boat-based surveys after capelin had begun beach spawning. This minimized the chances of sampling before deep-water spawning had commenced. Additionally, when spawning at beaches was reported on social media, we sampled them and other nearby beach sites at least once to verify capelin had started spawning. Specifically, we carefully examined beach sediment for adherent eggs and, when eggs were present, we placed the sediment/egg sample into a 20 mL glass scintillation vial with Stockard's Solution (50 mL formaldehyde, 37% solution; 40 mL glacial acetic acid; 60 mL glycerin; 850 mL sea water). Samples of 50–100 eggs from each site were then examined under a dissecting microscopic (Olympus SZX7) to quantify the number of eggs within six stages of development (as described in Frank and Leggett, 1981; see methods in Penton et al., 2012). The presence of eggs in early developmental stages (Stage I & II) was used to indicate current and recent spawning activity (i.e. 1–5 days, depending on site-specific temperature), whereas later stages (Stages III–VI) indicated spawning activity many days prior to sampling.

To search for deep-water capelin spawning areas, we chartered local fishers for boat-based sampling during July–August 2019. A standard-sized rectangle (4.6 km by 2.3 km) was drawn around the centroid of each putative deep-water spawning area indicated by capelin fishers during interviews. The standardized rectangle size was based on the largest area indicated by an interviewee. If more than one rectangle overlapped, we replaced the overlapping rectangles with a single rectangle which was arranged to cover the area of highest spatial overlap. As the purpose of the interviews was to identify areas in which to search for capelin deep-water spawning, we called these rectangles 'search areas'. As we did not have fine-scale (< 100 m) bathymetry or seabed habitat type data to refine the search area based on suitable capelin spawning habitat, we used ArcMap 10.3.1 to generate 10 random sites within each search area. The random sites within a search area were at least 500 m apart, based on the size of the sampling vessel (6 m) and expected drift to reduce the risk of resampling another randomly generated site. Other sites (hereafter referred to as 'adaptive sites') were added within a search area or outside a search area if we saw evidence suggesting a nearby capelin spawning site while at sea (i.e., dead male capelin on the seabed; stunned, solitary males in the water column; capelin schools on an echosounder or observed from the surface; abundant foraging seabirds and/or whales). All random and adaptive sites were examined carefully regardless of whether they had suitable spawning sediment (0.5–25 mm, Penton and Davoren, 2012), as capelin are also known to spawn on suitable algal species in areas dominated by bedrock in coastal Newfoundland (Bliss and Davoren, 2021).

At each random and adaptive site, we first deployed underwater video cameras to visually determine the presence/absence of capelin eggs. These surveys were conducted during daylight hours, although capelin spawn in both daylight and dark. Underwater video cameras (GoPro Hero 7) were attached to a metal frame (meshless whelk or crab pot), along with a temperature logger (Hoskin Scientific Limited Waterproof TidbiT v2 temperature logger or Star-Oddi DST) that measured temperature every 5–60 s throughout each deployment. The metal frame was lowered to the seabed and left at the bottom for three minutes ('stationary survey'), during which video footage was continuously recorded. At each site, bottom temperature was characterized by averaging measurements after temperature stabilized at depth. In Placentia Bay only, the metal frame was subsequently lifted ~1 m off the seabed and allowed to drift for up to 250 m ('drift survey') to explore more of the adjacent seabed for the presence of capelin eggs. When eggs were determined to be visually present or when egg presence/absence was uncertain, we sampled the sediment using a 15-cm^2 Ponar Grab system or a dredge, which consisted of a metal pipe (diameter: 11.4 cm; length [top]: 39.4 cm; length [bottom]: 47 cm) with 150-µm mesh at one end. We identified eggs from sediment samples obtained from deep-water sites as capelin eggs based on egg size and colour (Friðgeirsson, 1976), and compared these eggs to reference capelin egg samples collected from active capelin beach spawning sites. Additionally, we quantified the primary stage of egg development from each sample (described above).

Ethical statement

Animal: The care and use of experimental animals complied with Canadian Council of Animal Care animal welfare laws, guidelines and policies as approved by Canadian Council of Animal Care (Protocol: F16-017).

Human: When we contacted fishers, and before each interview, we described project objectives and how the data would be used, thereby providing the information needed for free and informed consent. Additionally, all interviews were randomly assigned a unique alpha-numeric identifier to ensure anonymity (e.g., A1, B6, F15). We adhered to national ethical research guidelines (e.g., TCPS2 2018), ensuring confidentiality and privacy was protected. Interviews lasted 0.5–3 h, and we recorded responses on prepared interview sheets.

Results

Interviews

Over two years (2018, 2019), we interviewed a total of 67 former or current capelin fishers along the southern and eastern Newfoundland coasts (Figure 1). In 2018, interviewees across all regions (22 interviewees) on average had 34 years (range: 8–65 years) of fishing experience, which was similar to 2019 (45 interviewees; average: 40 years; range: 19–60 years). During exploratory analysis, we found fishing experience did not affect the number of capelin spawning areas reported, likely because we targeted community 'experts', and thus, the average interviewee had experience fishing capelin before the stock

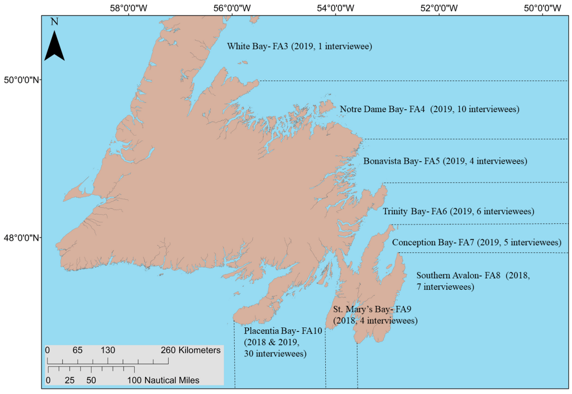

FIGURE 1
Capelin fishing areas (FA; fishing areas delineated by dashed black lines) covered by interviews of capelin fishers, along with the number of interviewees residing in each fishing area and the year interviews were conducted indicated in parentheses.

collapsed (i.e. pre-1991). In 2018, 19/22 interviewees across all regions said that capelin spawn in deep water and 5/19 referred to these areas as “capelin holes” (described as bathymetric depressions); 13/19 indicated one or more deep-water areas on a map. In 2019, the majority of interviewees in all regions (37/45) said that capelin spawn in deep water and 34/37 indicated one or more deep-water areas on a map. Many fishers were not surprised to be asked about the importance of deep-water spawning and clearly had years of experience observing it:

“If they don’t hit the beach [to spawn], they’re offshore [spawning]. Now I believe that’s a common occurrence.” (A1)

The interviewed fishers in 2018 and 2019 that reported capelin spawning in deep water (56/67), noted that this knowledge was based on one or more types of information. Fishers that indicated locations of deep-water spawning areas primarily reported observing capelin eggs adhered to their fishing gear, including on trawl foot gear, cod gillnets, lumpfish nets or on crab and lobster pots or visual observations of capelin eggs on the seabed. This physical evidence was often supplemented by non-physical evidence based on observations: the location of capelin spawning behavior as observed on echosounders (8 interviewees; see quotes A2, J7, and F2 below), occurrence of post-spawning capelin and/or capelin eggs in cod stomachs (4), persistent aggregations of whales and gulls during the spawning season (4), and information from other fishers (3). For example:

“When they [capelin] are flat on the bottom, they are spawning and if you put a net there it will be covered by spawn.” (A2)

“See them [capelin] on sounders when they are flat on the bottom. They are spawning. If [you] put a net there [it will be] full of spawn.” (J7)

“[If you] see spawn on the gear [you will] see them on the sounder they stay on the bottom for days.” (F2)

As the capelin spawning migration typically moves northward up the coast of the island, with capelin spawning first in southern bays and subsequently spawn in northern bays as the season progresses (Johnson and Davoren, 2021), many fishers harvest capelin in multiple capelin fishing areas (FA; shown in Figure 1) within a single season. Therefore, our interviewees often identified more than one deep-water spawning location in bays other than their bay of residence. Interviewees identified 101 putative deep-water spawning areas and 193 putative beach spawning areas across eight FAs (see centroids in Figure 2). Due to limited ship time, we focused on 13 putative deep-water spawning areas in eastern Placentia Bay and seven in southern Bonavista Bay. Most search areas in Placentia and Bonavista bays contained a single putative area, with the exception of search areas three (two putative areas) and nine (two putative areas; Figure 3). Therefore, a total of 18 search areas (4.6 km by 2.3 km rectangles) were established for both bays (see rectangle search areas in Figure 3).

In Placentia Bay, the 12 search areas overlapped with all five of the areas previously indicated as important areas for capelin spawning (i.e., St. Lawrence, Marystown/Burin, Swift Current, Placentia, and Cape St. Mary’s; Sjare et al., 2003) based on fisher interviews (see black ellipses in Figure 2B). Out of the 41 interviewees that indicated deep-water spawning areas in Placentia Bay on a map, 10 interviewees identified putative areas < 5 km from Cape St. Mary’s Ecological Reserve as important for capelin deep-water spawning, seven identified areas near Placentia, six identified areas in Marystown/Burin, and three identified areas in St. Lawrence. Only two of the 41 interviewees had knowledge about deep-water capelin spawning in the Swift Current area (Figure 2B). Fishers also identified putative deep-water spawning areas that have been scientifically documented and monitored along the northeast coast (Penton and Davoren, 2012; Figure 2A, red circles) and six of the putative deep-water spawning areas were within 3.5 km of long-term scientifically monitored deep-water spawning sites in Trinity Bay (red circles; Figure 2B; Nakashima and Wheeler, 2002).

In all bays across both years, 31 of the 56 interviewees who said that capelin spawn in deep water also said that capelin shifted between beach and nearby deep-water habitats within bays annually or on a decadal scale. Eighteen of the 31 interviewees identified factors associated with these shifts: 2/18 suggested the abundance of capelin and 17/18 indicated temperature as the primary factor causing the shift between spawning habitats. For example:

“Temperature has all to do with it. Capelin don’t have to come into the land to spawn. If the temperature is right in 20 fathoms of water, they’ll spawn in 20 fathoms of water.” (B1)

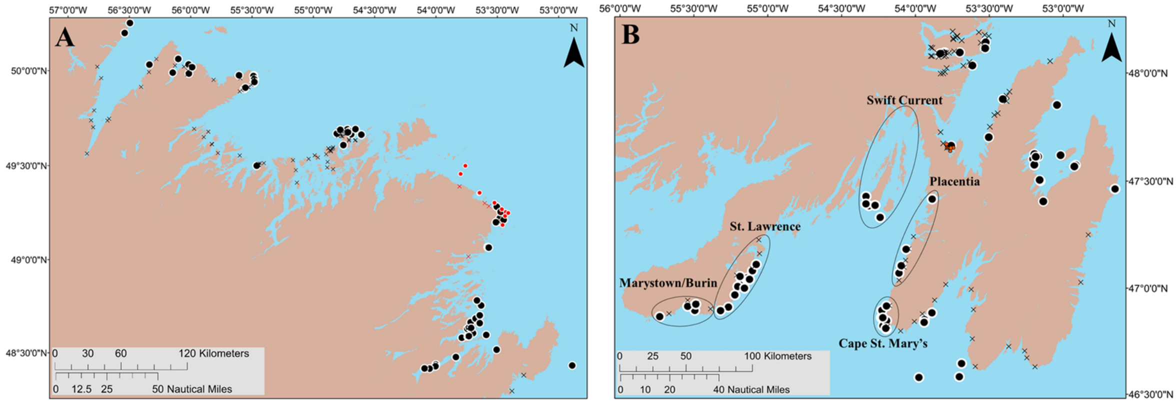

FIGURE 2
The centroids of putative beach (193; black X symbol) and deep-water (101; black circles) spawning areas identified by interviewees, along with areas previously suggested as important for capelin deep-water spawning by archived fisher interviews in Placentia Bay (black ellipses; based on Sjare et al., 2003), other known and scientifically monitored deep-water spawning sites (16 red circles; based on Nakashima and Wheeler, 2002 and Penton and Davoren, (2012) and beach spawning sites (10; red X symbol). Panel **(A)** (left): Capelin fishing areas 3–5; Panel **(B)** (right): Capelin fishing areas 6–10.

"Temperature has to do with everything. When and where they spawn. [If the] temperature [is] not right by the shore – [capelin will] spawn where the temperature is right." (B2)

"More capelin spawn in the water now than on beaches. [Capelin] spawned more on beaches in the 1980s. Has to do with the water temperature." (B3)

Fishers were interviewed along the northeast coast in early 2019, following the 2018 capelin spawning season, which was earlier and more broadly distributed than 2016 and 2017 (DFO, 2021). Among interviewed fishers on the northeast coast who compared 2018 spawning activity to recent years, almost all (17/18) reported an increase in the amount of spawning capelin and/or the number of spawning locations during 2018 relative to recent years.

Boat-based sampling

To confirm capelin were actively spawning prior to or during boat-based sampling during July 2019, we sampled beach sites for capelin spawning in Placentia Bay (three sites), Bonavista Bay (five sites), and nearby beaches along the coast of the Southern Avalon Peninsula (five sites) of Newfoundland (Table 1). In three out of the five initial beach sediment samples from sites in Bonavista Bay, the presence of capelin eggs in later developmental stages (i.e. Stage III–VI; Table 1) indicated that capelin had begun spawning prior to the initial egg sampling date. Similarly, both of the initial beach egg samples in western and eastern Placentia Bay were primarily in later developmental stages, while eggs in early developmental stages (i.e. Stage I–II) in later egg samples from the beaches indicated continued spawning or a second spawning run (Table 1).

After confirming the presence of spawning capelin in the bays of interest, we sampled for capelin eggs at putative deep-water spawning areas using an underwater camera and/or a bottom grab/dredge at a total of 136 unique sites within 12 search areas in eastern Placentia Bay (Jul 16, 20, 21, 23, 25, 27 and Aug 6, 7, 9, 10, 11, 15) and 26 unique sites within six search areas in Bonavista Bay (Aug 9, 10, 11, 14, 19, 20). These sites included randomly-generated sites (141 sites) and adaptive sites based on evidence of capelin spawning while at sea (21 sites; see methods). We found seven deep-water capelin spawning sites within two search areas (search area 6 in Bonavista Bay; search area 17 in Placentia Bay; Figure 3). These sites were identified from underwater footage based on the presence of dense mats of yellowish fish eggs adhered to gravel/sand, pebbles, or algae (Bliss and Davoren, 2021) which were later confirmed to be capelin eggs. Although dead and live capelin were observed at some of these sites, capelin in the act of spawning were not seen on the video footage. Even though spawning behavior was not directly observed during these surveys, a thorough search of areas adjacent to where capelin eggs were found did not reveal any other egg patches at nearby subtidal or beach sites (Bliss and Davoren, 2021). Overall, we sampled eggs from two of the three deep-water spawning sites located in Placentia Bay and each of the four sites located in Bonavista Bay (Table 2). All seven of these deep-water sites were non-contiguous with the beach, with site-specific depths ranging from 6.1–13.9 m and temperatures ranging from 3.0–15.6°C at the time of egg sampling (Table 2). We measured temperature at the Placentia Bay deep-water spawning sites three times from 20 July to 11 August and the temperature increased at both sites by a maximum of 6.6°C (Table 2).

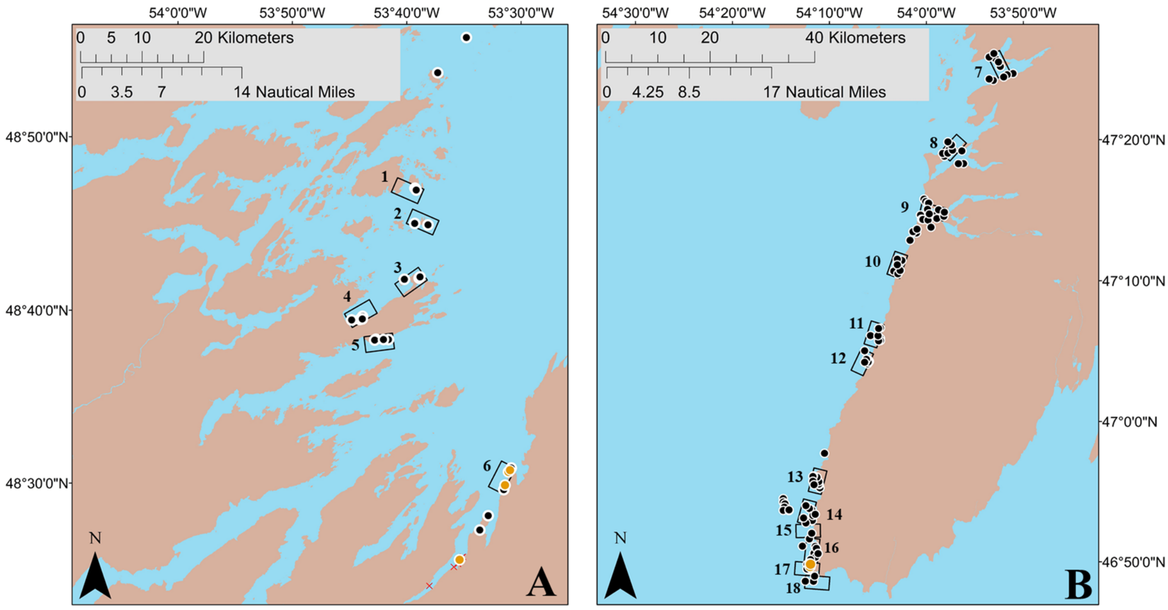

FIGURE 3
Boat-based search areas (18 areas; rectangles) based on putative deep-water spawning areas identified by interviewees, along with random and adaptive sites (162; black circles), where underwater camera surveys and sediment sampling for capelin spawning (i.e. presence of capelin eggs) were conducted during July–August 2019. Beach sites (21; red X symbol) and deep-water sites where capelin eggs were found (7; orange circles) during July 2019 are also indicated. Panel **(A)** (left): Bonavista Bay, capelin fishing area 5. Panel **(B)** (right): Placentia Bay, capelin fishing area 10.

Discussion

During two years of capelin fisher interviews in multiple bays, we found that 84% of interviewed fishers reported knowledge of deep-water spawning, and interviewed fishers identified a broad distribution of putative beach and deep-water spawning sites throughout coastal Newfoundland. Fifty-five percent of fishers indicated inter-annual variation in spawning habitat use; most linked this variation to temperature and some to capelin abundance. By comparing our fisher interview results with similar archived interviews from Placentia Bay in the 1990s (Sjare et al., 2003), fishers identified many of the same deep-water spawning locations in 2018–2019 as in the 1990s. Although the spatial scope of the knowledge of 67 fishers on deep-water and beach spawning spanned across eight bays and two stocks (3Ps, 2J3KL) in coastal Newfoundland, other ecological areas of interest were not covered by our interviews (e.g., Fogo island) and/or boat-based sampling (e.g., Swift Current). We recommend that these areas are considered a priority for further investigation *via* interviews and boat-based surveys. Based on the high proportion of fishers that identified deep-water spawning areas in this study (56/67) and previous research (Templeman, 1948; Sjare et al., 2003), we conclude that future research may find that deep-water spawning of capelin is widespread throughout coastal Newfoundland.

Although multiple deep-water spawning sites were located that were not previously scientifically documented, we identified active spawning sites during boat-based surveys in only 2 out of the 18 surveyed fisher-interview-based search areas. This result may indicate a disadvantage to using fisher knowledge contributions to inform the location of deep-water spawning sites; however, the low proportion of search areas with active spawning sites may have been due to a number of other reasons. First, as suitable habitat for deep-water spawning can be patchily distributed and suitable patches may be small (Davoren et al., 2008; Penton and Davoren, 2012; Davoren, 2013a; Bliss and Davoren, 2021), active sites may have simply been missed during our boat-based surveys. Second, suitable sediment may be ephemeral at flat sites among years (Penton and Davoren, 2012) and, thus, interviewees may have outlined areas that are no longer suitable for spawning capelin. In contrast, annually persistent deep-water capelin spawning sites are typically found in bathymetric depressions, referred to as "capelin holes" by fishers in this study, where suitable sediment is retained (Penton and Davoren, 2012). Third, the timing of our boat-based surveys began after the start of capelin spawning in both bays. As high abundances of seabirds and whales aggregate at capelin spawning sites during spawning (i.e. multi-species biological hotspots; Davoren, 2013a), they are more easily identified from observations at the ocean surface. If spawning was complete in an area before we began our boat-based surveys, reduced predator activity would make capelin spawning sites more difficult to locate.

Another explanation for the low proportion of active deep-water spawning sites within search areas may be related to inter-

TABLE 1 Beach capelin egg sampling in Newfoundland during July and August 2019 indicating the sampling location, date and the percentage of capelin eggs in early developmental stages (i.e. Stages I–II) and late developmental stages (i.e. Stages III–VI).

Region	Location	Latitude (N)	Longitude (W)	Date of Egg Sample	Percent of Eggs at Stages I–II	Percent of Eggs at Stages III–VI
Placentia Bay (West)	Little Lawn	47.390	53.137	Jul 09	25	75
		47.390	53.137	Jul 19	100	0
Placentia Bay (East)	Patrick's Cove	46.882	53.947	Jul 18	34	66
		47.276	52.830	Jul 29	6	94
	St. Bride's	46.920	54.175	Jul 15	11	89
		46.920	54.175	Jul 19	6	94
St. Mary's Bay	Branch	46.882	53.947	Jul 10	19	81
		47.039	54.118	Jul 18	0	100
Conception Bay	Holyrood	46.929	55.483	Jul 11	80	20
		47.039	54.118	Jul 22	22	78
		46.929	55.483	Jul 29	0	100
Southern Avalon	Burnt Cove	47.197	52.849	Jul 11	73	27
	Tors Cove	47.390	53.137	Jul 22	0	100
	Witless Bay	47.213	52.845	Jul 22	42	58
Bonavista Bay	Princeton Beach (Site 1)	48.426	53.590	Aug 14	35	65
	Princeton Beach (Site 2)	48.428	53.586	Aug 14	97	3
	North Princeton Beach	48.419	53.598	Aug 14	59	41
	Sandy Point Beach, Charleston	48.401	53.634	Aug 19	20	80
	North of Breen Point	48.429	53.585	Aug 19	47	53

Total percent of eggs is the number of eggs per category divided by the total number of live eggs. Region names are the same as those listed in Figure 1.

annual shifts in beach and deep-water spawning habitat use (Nakashima and Wheeler, 2002; Davoren, 2013b; Penton and Davoren, 2013; Crook et al., 2017). Indeed, habitat suitability and, thus, shifts in the use of habitats and sites (i.e. beach vs. deep-water) and site location within habitats among years appear to be driven by variation in habitat- and site-specific temperature that results in departures from the optimal temperature range for offspring survival (2–12°C; Davoren, 2013b; Penton and Davoren, 2013; Crook et al., 2017). This is supported by the results of our interviews, thereby indicating agreement in fisher-based and science-based knowledge. Indeed, 55% of interviewees that shared knowledge about deep-water spawning also noted shifts between beach and deep-water habitat use among years and 94% of these interviewees stated temperature was the primary factor causing these shifts. However, as water temperatures were similar during 2018 and 2019, and were warmer relative to the local long-term average (Cyr and Galbraith, 2021; DFO, 2021), we would expect extensive use of deep-water spawning sites because beaches may have been too warm (≥ 12°C) later in the summer. Therefore, temperature was likely not a limiting factor for detecting deep-water spawning sites in our study. Inter-annual variation in site-specific temperature, however, may have resulted in some putative spawning areas being unused during our surveys. In support, seabed temperature where *D. viridis* was found with adhered capelin eggs in Placentia Bay were on average cooler (4.3–4.9°C) than sites without capelin eggs (9.2 ± 3.9°C), indicating that unused sites were at or near the upper temperature threshold for spawning (≥ 12°C). Additionally, it is possible that in warmer years, such as those encountered in 2018 and 2019, capelin may move further offshore into unsurveyed areas where bottom temperature was

TABLE 2 Capelin eggs sampled at six of the seven newly found deep-water spawning sites in Placentia Bay and Bonavista Bay during July–August, 2019.

Region	Search Area	Location	Latitude (N)	Longitude (W)	Depth (m)	Temperature at Bottom (°C)	Date of Egg Sample	Percent of Eggs at Stages I–II	Percent of Eggs at Stages III–VI
Bonavista Bay	6	Ladder Rock Cove	48.498	53.523	6.1	15.6	19-Aug	0	100
	6	Plate Cove Head (Site 1)	48.511	53.518	7.7	14	19-Aug	39	61
	6	Plate Cove Head (Site 2)	48.512	53.516	13.9	7.9	19-Aug	21	79
	Southwest of 6	Long Beach Bight	48.426	53.590	15	3.0	19-Aug	66	34
Placentia Bay (East)	17	Near Cape St. Mary's (Site 1)	46.828	54.200	10	4.3	20-Jul	57	43
					10	–	1-Aug	0	100
	17	Near Cape St. Mary's* (Site 2–3)	46.830–46.831	54.199–54.200	9.5	4.6	20-Jul	17	83

*Asterix represents one egg sample for two sites that were 123 meters apart.
Total percent of eggs is the number of eggs per category divided by the total number of live eggs. No abnormally formed or dead eggs were observed in any of these samples. Note Near Cape St. Mary's (Site 1) was sampled two times, 20 Jul and 1 Aug 2019.
Location of search areas indicated on Figure 3.

more suitable for spawning. Monitoring changes in capelin spawning distribution in relation to inter-annual variation in temperature would be an excellent opportunity for further collaboration with fishers.

Inter-annual variation in capelin abundance may also explain the low proportion of detected active deep-water spawning areas. Indeed, density-dependent habitat use (e.g., Basin Model; MacCall, 1990) would result in fewer spawning sites occupied during years of lower capelin abundance, which was found in a recent capelin study (Crook et al., 2017). In support, four interviewees specifically noted the use of fewer sites in both beach and deep-water habitats when capelin abundance is lower. Interestingly, fisher interviews were conducted during two fishing seasons with different perceptions of the state of the capelin stock, with 2018 considered a higher capelin biomass year than both 2017 and 2019 based on spring acoustic surveys of offshore abundance (DFO, 2022b); however, the 2018 capelin biomass was only ~5.5% of pre-1991 levels (DFO, 2021). Ongoing communications with fishers in Bonavista Bay indicated that in 2018 capelin spawned at both beach and deep-water sites where they had not been observed spawning for the past 20 years, whereas in 2019 spawning capelin abundance and distribution was perceived to be more restricted and, thus, more in line with recent, post-collapse years. In support, a citizen science program (www.ecapelin.ca) indicated that the abundance of beach spawning sites was higher with a broader distribution during 2018 than 2019; however, another citizen science program (DFO spawning diaries) found similar use of beach sites in both years. This difference, however, may be due to the methodologies of the two citizen science programs. Both programs aim to capture the spatial and temporal extent of beach spawning, but the former relies on volunteer participation across the island of Newfoundland, whereas the latter is a long-term collaborative monitoring program with a core number of beach sites in NAFO Division 3KLP monitored each year by paid citizen scientists, so does not capture sporadic beach use outside the core area (Murphy, 2022). Overall, lower capelin abundance in 2019 combined with fewer beach spawning sites used suggests that fewer deep-water spawning sites may have been used, thereby resulting in fewer active spawning sites within some search areas.

Given the lack of fine-scale bathymetry and seabed habitat classification in coastal Newfoundland, fishers' knowledge in this study resulted in the identification of many previously undocumented putative capelin deep-water spawning areas in an otherwise expansive area. Similar to other studies where fishers' knowledge increased understanding of fish ecology (e.g., Fraser et al., 2006; Silvano et al., 2006; Johannes et al., 2008; Paterson et al., 2018), we found that fishers' knowledge of capelin spawning behavior in coastal Newfoundland spanned a different temporal, spatial, and behavioral observational lens in comparison to traditional scientific studies. Indeed, interviewed fishers' 8–65 years of observations in multiple bays was a vast resource of ecological information without which the baseline map of putative deep-water spawning sites herein would not have been possible. Our study illustrates that the long history of fishing capelin for food, bait, roe, and fertilizer in Newfoundland (DFO, 2022a) and the ongoing commercial fisheries for capelin during the spawning period have resulted in extensive LEK of the locations and timing of capelin spawning in coastal Newfoundland along with considerable knowledge of capelin life history (i.e., spawning, migration, survival). Although the Canadian Department of Fisheries and Oceans (DFO) has a longstanding history of collecting this knowledge along with data from citizen scientists on the timing of capelin beach spawning (i.e. spawning diary program; Murphy et al., 2021; DFO, 2022a; Murphy, 2022), we recommend further fisher collaborations to ensure the incorporation of this knowledge in future capelin stock assessments.

In conclusion, by combining fisher interviews and collaborative boat-based sampling, where fishers were directly involved in data collection and choosing non-random adaptive survey sites based on experiential and ecological knowledge of capelin spawning, we generated a baseline map of many putative capelin spawning areas to target for future investigation. Through the integration of fishers' knowledge and scientific knowledge, we aimed to resolve conflicts between capelin fishers and science advisors and improve stock assessment and management, as shown in previous studies (e.g., Stanley and Rice, 2007; Carruthers and Neis, 2011; Duplisea, 2018). In particular, fishers have reported increasing use of deep-water spawning habitat (Nakashima and Clark, 1999) and have advocated for more scientific studies to incorporate productivity data from this habitat into the Newfoundland capelin stock assessment (Dawe and Carruthers, 2019). The Newfoundland capelin stock assessment already integrates data from a beach spawning diary program, which is used as a general indicator of stock health in a weight of evidence approach to provide scientific advice on stock status. For example, a high number of spawning sites used and earlier spawning are predicted to produce stronger year classes (DFO, 2021; Murphy et al., 2021). The baseline map of deep-water spawning sites generated in this study could similarly be used to build a time series for monitoring deep-water spawning habitat use and shifts between beach and deep-water spawning habitats, providing additional insight into the health of both 3Ps and 2J3KL capelin stocks. As monitoring deep-water spawning sites will be more difficult compared to beach spawning sites, and as monitoring these sites requires vessels, sampling equipment, and expert fisher knowledge, building this time series will require a network of fishers to participate annually. Although this program may be costly, fishers already fishing nearby putative sites during spawning presents an excellent opportunity for further science-industry research collaboration, building on our strong, multi-year collaborative relationships established during this research. To illustrate, through the collaborations and professional relationships established during this study, a fisher volunteered to monitor the deep-water sites near Cape St. Mary's throughout the COVID-19 pandemic during other fishing activities. Overall, knowledge of capelin spawning habitat, especially persistently used deep-water spawning sites, are key to identifying highly productive coastal areas for capelin. As this is recognized as an important gap in our knowledge on capelin stock dynamics, identifying these key capelin spawning areas will have management implications for the timing and location of the capelin fishery (i.e., which bays are open and when), as well as applications for marine spatial planning and marine conservation efforts.

As climate projections forecast an increase in SST of 0.4°–2.2°C within the next 50 years on the Newfoundland Shelf (Han et al., 2015), if capelin remain in their current range, they are predicted to shift from warm, beach spawning habitat to cooler deep-water habitat to ensure offspring survival (Nakashima and Wheeler, 2002; Davoren, 2013b; Penton and Davoren, 2013; Crook et al., 2017). Although warming conditions might be expected to result in earlier capelin spawning (Buren et al., 2014), the lack of return to pre-collapse timing of spawning (June) relative to post-collapse timing (July) despite the return to pre-collapse oceanographic conditions (Murphy et al., 2021) suggests that capelin phenology might not shift considerably in response to future climate change. In combination with a warming climate, the abrupt and persistent delay in the timing of spawning when the stock collapsed in 1991 may further promote the use of deep-water spawning sites as capelin are now predominately spawning in mid-July when the beaches may be too warm (> 12°C; Crook et al., 2017; Murphy et al., 2021). Therefore, determining the relative contribution of beach and deep-water spawning to capelin recruitment is an important research question. Fishers support these research avenues, whereby 19/56 mentioned the need for increased monitoring and stewardship of beach and deep-water spawning sites and three of these 19 fishers mentioned this need unprompted. Specifically, two fishers requested research on the survivability of larvae at deep-water sites in Bonavista Bay and another requested increased sampling at deep-water sites in Conception Bay. The next step to understanding the contribution of deep-water spawning habitat to capelin recruitment is to continue to examine the spatial extent of deep-water spawning sites, possibly using different technologies (e.g. acoustic-based seabed classification), combined with quantitative estimates of site-specific larval production, as larval production is tightly linked to recruitment (i.e. age-two recruits; Murphy et al., 2018).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by The University of Manitoba Research Ethics Board Protocol Number: HS21718 (J2018:021). The patients/participants provided their written informed consent to participate in this study. The animal study was reviewed and approved by Canadian Council of Animal Care (Protocol: F16-017).

Author contributions

LB was responsible for data generation, survey design, project design, data analysis, fieldwork, and manuscript preparation. Further, LB acquired additional funding from the University of Manitoba. ND aided in survey design and fieldwork such as interviews in northern bays of Newfoundland. HM provided edits and feedback on the project, and contributed to the development of the manuscript and provided expertise on government stock assessments and spawning diaries programs in Newfoundland. EC and GD contributed to project design, acquired the majority of the funding from Fisheries and Oceans Canada through the Coastal Environmental Baseline Program, and provided edits and feedback on the project as it developed and established the original idea for the project. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor RS declared a shared affiliation with the author HM at the time of review.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1061689/full#supplementary-material

SUPPLEMENTARY TABLE 1
Interview questions.

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Steven Mackinson,
Scottish Pelagic Fishermen's Association,
United Kingdom

REVIEWED BY
Tiago Veiga-Malta,
Technical University of Denmark, Denmark
Alain Henri
Fonteneau, Saint Malo, France

*CORRESPONDENCE
Jefferson Murua
jmurua@azti.es

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Improving sustainable practices in tuna purse seine fish aggregating device (FAD) fisheries worldwide through continued collaboration with fishers

Jefferson Murua[1*], Gala Moreno[2], Laurent Dagorn[3], David Itano[4], Martin Hall[5], Hilario Murua[2] and Victor Restrepo[2]

[1]Sustainable Fisheries Management Tuna Department, AZTI-Tecnalia, Sukarrieta, Spain, [2]International Seafood Sustainability Foundation, Pittsburgh, PA, United States, [3]Marine Biodiversity, Exploitation and Conservation (MARBEC), University of Montpellier, Centre National de la Recherche Scientifique (CNRS), Ifremer, Institut de Recherche pour le Développement (IRD), Sète, France, [4]Opah Consulting, Honolulu, Hawaii, HI, United States, [5]RedCID Red para el estudio de capturas incidentales y Descartes, San Diego, CA, United States

More than a decade of bottom-up collaborative workshops and research with fishers from the principal tropical tuna purse seine fleets to reduce ecological impacts associated with the use of fish aggregating devices (FADs) has yielded novel improved sustainable fishing practices in all oceans. This integrative effort is founded on participatory knowledge-exchange workshops organized by the International Seafood Sustainability Foundation (ISSF), referred to as "ISSF Skippers Workshops", where scientists, fishers, and key stakeholders examine and develop together ways and tools to minimize fishery impacts. Workshops organized since 2010 have reached fleet members in 23 countries across Asia, Africa, the Americas, Europe, and Oceania, with over 4,000 attendances, mostly skippers and crew, operating in the Indian, Atlantic, and Pacific oceans. Structured and continued open transparent discussions on ocean-specific options to minimize FAD associated bycatch, ghost fishing and marine pollution have produced an array of novel co-constructed solutions and a better understanding of ecosystem and fishery dynamics. Dedicated at sea research cruises in commercial purse seiners have enabled testing some of the ideas proposed in workshops. Results obtained were then communicated back to fishers for a double loop learning system resulting in solution refinement and/or adoption. Furthermore, fishers' increased trust and stewardship have stimulated unprecedented large-scale science-industry research projects across oceans, such as multi-fleet biodegradable FAD trials, the adoption and widespread use of non-entangling FADs, and the development and adoption of best practices for the safe handling and release of vulnerable bycatch. This model of collaborative research is broadly applicable to other natural resource conservation fields. Support for long-term inclusive programs enabling harvesters to proactively collaborate in impact mitigation research contributes to improved scientific advice, voluntary compliance, and adaptive management for lasting sustainability trajectories.

KEYWORDS

participatory approach, fishers ecological knowledge, tuna fisheries, bycatch mitigation, fish aggregated devices (FADs), co-management, elasmobranch conservation, purse seiners

1 Introduction

Marine ecosystems worldwide are affected by fishery impacts including overfishing, bycatch, marine pollution, and ghost fishing (Kelleher, 2005; Dagorn et al., 2012; Hall et al., 2013; Komoroske and Lewison, 2015; Pauly and Zeller, 2016; Stelfox et al., 2016; Strain et al., 2022). Minimizing these fishery impacts has long been a primary focus on fisheries management, but conservation measures have frequently failed to deliver expected outcomes (Chapin et al., 2009; Gilman et al., 2014). Many attribute this shortfall to bottlenecks arising from poor understanding of fishery system complexities, particularly fishers' dynamic behaviours and strategies towards resource exploitation and regulatory frameworks (Hilborn, 1985; Nielsen and Vedsmand, 1999; Salas and Gaertner, 2004; Leslie and McLeod, 2007; Iwane et al., 2021). As McGrath and Castello (2015) pointed out, it is increasingly apparent that fisheries management is not about managing fish but fishers and understanding the social and economic circumstances driving their behaviours. Highly centralized management approaches have been criticized for institutionalised inertia and stakeholder exclusion leading to polarization and poor compliance associated with illegitimacy perceptions by fishers (Nielsen and Holm, 2007; Rohe et al., 2017; Oyanedel et al., 2020; Guirkinger et al., 2021). Therefore, designing technically sound conservation management measures does not ensure effective implementation as, if these are considered unfair by fishers, they will find ways to circumvent such measures (e.g., "fishing the line"), especially in the absence of strong monitoring, control and surveillance systems (Horta e Costa et al., 2013; Guirkinger et al., 2021).

While top-down fisheries management remains the prevalent *status quo*, in recent years several national and international fisheries bodies have attempted greater stakeholder integration (e.g., Canada's Pacific Integrated Commercial Fisheries Initiative, European Union's Long Distance Fleet Advisory Council, etc.) (Stephenson et al., 2016; Holm et al., 2020). However, most inclusive research and cooperative management initiatives have been based on small-scale artisanal fisheries, possibly due to their simpler stakeholder structure and reduced geographical scope facilitating co-management approaches (Carr and Heyman, 2012; Trimble and Berkes, 2013; Saavedra-Diaz et al., 2015; Karr et al., 2017; Chuenpagdee and Jentoft, 2018; d'Armengol et al., 2018; Garza-Gil et al., 2020). In large-scale transoceanic fisheries, achieving representative fisher participation is substantially more challenging due to their widespread distribution, long periods at sea and multiple fleet nationalities and strategies with competing objectives (Torres-Irineo et al., 2014; Tickler et al., 2018). In general, international governance bodies employ industry associations to make participation numbers manageable and facilitate consensus reaching (Mackinson et al., 2020). For example, in tuna regional fisheries management organizations (tRFMOs), which oversee multiple fleet nationalities and various fishing gears (e.g., longline, pole and line, purse seine, handline, driftnets, recreational, etc.), it is often centralised ship-owner associations who represent industry and interact with policymakers. However, tuna fishers' views and interests are wide-ranging and can often differ from other industry stakeholders such as ship-owners, producers, or retailers (Sampedro et al., 2017; Airaud et al., 2020). Thus, so-called bottom-up approaches in fishery governance would be better defined as "middle-up" processes, due to the absence of direct fisher involvement (e.g., captains, navigators, deck crew). This widespread exclusion of fishers from decision-making processes generates a profound sense of disempowerment and mistrust towards fisheries managers and scientists and potentially foments lower compliance of regulations from which they feel disconnected (Dorner et al., 2015; Linke et al., 2020). Conservation measures are only as effective as their correct day-to-day implementation at sea, which ultimately rests in the hands of fishers. Developing long-lasting conservation solutions requires well thought mitigation strategies, but perhaps more importantly a more inclusive decision-making process which prevents conflict between players and increases voluntary compliance through a sense of fairness and stewardship (Mackinson et al., 2011; Hansen, 2014; Chapin et al., 2015; Aswani et al., 2018; Mackinson and Middleton, 2018; West et al., 2018; Mathevet et al., 2018; Rudolph et al., 2020).

In addition, the exchange of knowledge between fishers and scientists is known to significantly contribute to a deeper understanding of complex and dynamic fishery-ecosystem interactions (Johannes et al., 2000; Branch et al., 2006; Field et al., 2013; Giareta et al., 2021; Leduc et al., 2021). Fishers' inputs can provide timely and accurate fleet dynamics explanations to alterations in catch rates to inform stock status, including adoption of new fishing technologies and strategies in reaction to competitors and regulations (Moreno et al., 2007a; Moreno et al., 2007b; Carruthers and Neis (2011); Lopez et al., 2014; Torres-Irineo et al., 2014; Jaiteh et al., 2016; Sampedro et al., 2017). Furthermore, experienced fishers have valuable empirical knowledge on historical species distribution and abundances, and fishing technology evolution, which can help better characterize long and short-term population changes and effort creep, respectively. This non-official source of information is not only very useful in poorly monitored small scale artisanal fisheries

(Johannes, 1998; Saldana-Ruiz et al., 2017; Alfaro-Shigueto et al., 2018; Berkstrom et al., 2019; Hunnam et al., 2021), but also in data-rich industrial fisheries with rapid technological shifts and complex fleet tactics (Moreno et al., 2007a; Moreno et al., 2007b; Carruthers and Neis, 2011; Lopez et al., 2014; Macusi et al., 2017; Torres-Irineo et al., 2017). Furthermore, fishers' deep practical understanding of how fishing gear works and interacts with different species, gained through years of conducting fishing operations under varying conditions, is extremely valuable to improve selective fishing gear and practices (Hall, 2007; Jenkins, 2010; Poisson et al., 2014; Da Veiga Malta et al., 2019). This in-depth technical knowledge of gear and fishing strategy is often difficult to find among researchers, as most current scientific disciplines focus on other aspects (e.g., fish biology, population dynamics, oceanography). Even studies by fisheries technologists on industrial purse seine fishing gear are scarce and mostly theoretical (Kim and Park, 2009; Zhou et al., 2019), which warrants more cooperative work with fishers for access to at-sea gear trials. These exchanges of knowledge from fishers to scientists and vice versa are also an excellent way of establishing mutual respect, by highlighting the additive value of connecting both kinds of expertise (Mackinson, 2001; Wedemeyer-Strombel et al., 2019; Pereyra et al., 2021).

In past decades, the few cooperative approaches involving direct fisher participation in tuna industrial-scale fisheries were often a last-resource reaction to crisis events (Joseph, 1994; Roheim and Sutinen, 2006). For example, in the 1970s after strong public pressure to reduce dolphin mortality in the Eastern Pacific Ocean purse seine tuna fishery, fishers engaged with the Inter American Tropical Tuna Commission (IATTC) scientists in participatory workshops to co-create novel dolphin-safe gear (e.g., the Medina panel, named after the inventor captain Harold Medina) and release techniques (e.g., backdown procedure) (Hall, 1998; Hall, 2007). Since 1992 the Agreement of the International Dolphin Conservation Program (AIDCP) ensures that every new skipper in the IATTC intending to perform sets on dolphin-tuna aggregations completes training in best dolphin-safe practices to ensure the application of correct mitigation procedures, backed up by a penalty system for vessels exceeding dolphin mortality limits (Hall, 1998). Today dolphin mortality has been dramatically reduced in the fishery (Hall, 2007; Ballance et al., 2021). Despite the remarkable success of this sustained collaborative approach, surprisingly the AIDCP remains the only tuna RFMO that integrates a long-term program with captains and crew for best practice training.

In tropical tuna fisheries around 5 million tonnes were caught in 2020, of which 66 percent of the total catch is made by purse seiners with 36 percent deriving from sets on fish aggregating devices (FADs), 27 percent from unassociated sets and 3 percent from dolphin sets, which are only observed in the Eastern Pacific (ISSF, 2022). Both artisanal and industrial tuna fisheries have employed for decades FADs because they attract diverse species of fish, including tunas (Taquet et al., 2007), but their numbers and catches have rapidly increased in recent decades (Fonteneau et al., 2013; Hall and Roman, 2013; Maufroy et al., 2016; Dupaix et al., 2021). Initially these FADs were fixed in space i.e., anchored FADs (aFADs), but with the advent of radio tracking buoys and later GPS-geolocating buoys, enabling fishers to accurately track FAD position, man-made drifting FADs (dFADs) grew in number and efficiency (Lopez et al., 2014; Wain et al., 2021). Traditionally dFADs were built with durable and cheap reused materials such as plastic net corks for floatation and old purse seine net panels hanging under the water's surface to slow down drift and provide shade, both characteristics considered by fishers helpful to encourage tuna aggregation (Itano et al., 2004; Moreno et al., 2022). Because FAD fishing has been associated with several ecological impacts such as increases in juvenile tuna catch, vulnerable species bycatch, marine pollution and potential ecological traps (Marsac et al., 2000; Hallier and Gaertner, 2008; Dagorn et al., 2012), pressure by environmental non-government organizations (ENGOs) grew to advocate for improved FADs management in recent years. In addition to a greater number of RFMO conservation measures to limit FAD effects (e.g., FAD closures, FAD limits), this elicited a reactive response by the tuna retailers and industry to reduce FAD fishery impacts. Science-industry partnerships, such as the International Seafood Sustainability Foundation (ISSF), were borne around this time to address these and other sustainability concerns in tuna fisheries (e.g., IUU fishing, overcapacity, etc.) through the support of high-quality research and direct collaboration with tuna fleets to provide science-based solutions. In 2010 ISSF launched the Bycatch Project to develop best practices in tuna purse seine fisheries operating with FADs to mitigate ecosystem impacts. This was articulated through cooperative research actions with fishers, with the hope of reaching practical and effective solutions quickly. Also, measures developed jointly by fishers and scientists would presumably improve their implementation. At the base of this scientific research was a series of participatory workshops, referred to as "ISSF Skippers Workshops", in which tuna purse seine fishers and other key fishery stakeholders engaged with scientists and contributed their knowledge and perspectives to find corrective protocols and technology to reduce unwanted ecological impacts. The workshops were viewed as a scientist-fisher integrative global effort that reached the principal tropical tuna regions and international purse seine fleets. In this paper, we describe the process, lessons learned, and progress made in tuna fisheries to improve sustainable practices through this multi-ocean international collaborative research action program with fishers started in 2010 and still ongoing as of 2022.

2 Methods

2.1 ISSF bycatch project

The ISSF Bycatch Project is based on three interconnected pillars: (1) a Bycatch Committee (BC) formed by a team of experienced fisheries scientists with transdisciplinary expertise (i.e., ecology, animal behaviour, fishing technology, stock assessment, fish biology, etc.), (2) bycatch mitigation workshops with fishers and other stakeholders (i.e., ISSF Skippers Workshops), and (3) scientific research cruises onboard vessels to test impact mitigation ideas proposed by BC members and fishers.

Interactions between these three elements yielded a number of positive outcomes (Figure 1). Initially, impact mitigation research options favoured by the BC were presented to fishers in the workshops and their acceptance level recorded. Mitigatory options were categorized by scientists according to species group and time of

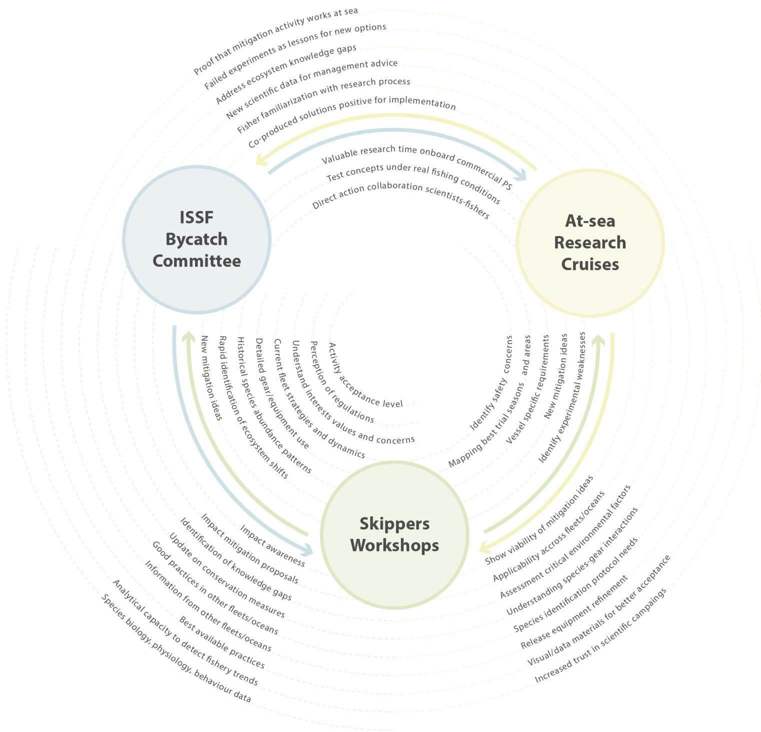

FIGURE 1
Flow chart between the three elements of the ISSF Bycatch Project: (1) Scientific Bycatch Committee, (2) Skippers Workshops, and (3) research cruises.

execution during the purse seine fishing operation (e.g., before, during or after the set) (Table 1). Fishers could propose improvements to these proposals or suggest new options to be tested. After the fishers' feedback, BC scientists regrouped and decided which mitigation actions to test in the research cruises. At sea mitigation activity trial results were communicated back to fishers in subsequent workshops to propose their adoption if successful, refine solutions if needed, or discard if clearly ineffective.

2.2 ISSF skippers workshops

The participatory workshops covered information on global tuna fisheries statistics and management, biology of species and a range of fishery mitigation topics including endangered, threatened, and protected (ETP) species bycatch mitigation, juvenile yellowfin and bigeye tuna catch reduction, FAD ghost fishing prevention, and marine pollution reduction. In addition, related RFMO conservation measures and their alignment with current fishing strategies were discussed, including opinions on the efficiency of regulations such as FAD closures and limits. Also, some bycatch related conservation measure infractions were mentioned in the workshops (e.g., the illegality and penalties for shark finning). However, in general, the workshops were not about dealing with IUU practices (e.g., transhipment issues, seeding FADs in unauthorized EEZs), as otherwise fishers could misunderstand the purpose of the meeting and become highly defensive. These matters are better left to monitoring and management agencies who can track these illegal practices through observer reports or dFAD buoy data and apply the corresponding penalties. Additionally, the growing market demand for sustainable fish sources (e.g., eco-certified fisheries) was discussed at workshops to raise fisher awareness on this subject.

A presentation helped guide the meetings, in which technical scientific jargon was avoided, instead focusing on clear language and visual user-friendly materials (e.g., maps, photos, illustrations, videos) showing examples of best practices and trial results. Presentations were regularly updated, including the latest findings from ISSF's own research cruises, other scientific groups elsewhere, the peer-reviewed literature and good practices learned during exchanges with fishers from different fleets.

Invitation to the workshops was often coordinated with help of the different local purse seine associations and tried to target locations and times favourable for higher fisher presence. This included workshops during unloading peak seasons at major tuna fishing ports such as Majuro (Republic of the Marshall Islands), Pohnpei (Federated States of Micronesia), Tema (Ghana), Jakarta (Indonesia) or Port Victoria (Seychelles), and in well-known purse seine fishers' hometowns during FAD fishery closures when many returned home, including Bermeo (Spain), Concarneau (France), Manta (Ecuador), Busan (South Korea), Shanghai (Peoples Republic of China), Madeira (Portugal) or Zadar (Croatia). Note that Portugal and Croatia do not have a tropical tuna purse seine fleet *per se*, but many fishers from these countries have been working on vessels of the Pacific Ocean since the 1960s. Meanwhile countries like Peru are rebuilding their tuna fishery (i.e., 14 purse seiners as of 2022) and raising bycatch mitigation awareness in this fleet is especially critical due to their rich waters being among the most important hotspots for sharks and rays worldwide (Lezama-Ochoa et al., 2019; Gonzalez-Pestana et al., 2021). Additional to the ISSF Skipper Workshops other parallel sustainability initiatives (e.g.,

TABLE 1 ISSF Skippers Workshops 2010- 2019 by location and participant number by work occupational group.

Continent	Location	No. WS	Skippers	Crew	Ship-owners	Fleet Mangs.	Fleet Reps	Gov. Mangs.	Scientists	Total participations
Africa	Ghana (Accra, Tema)	9	108	95	25	43	131	33	9	444
	Mauritius (Port Louis)	1	5	3	0	0	1	0	0	9
	Senegal (Dakar)	1	4	3	0	3	3	3	2	18
	Seychelles (Mahe)	1	6	2	0	0	0	1	0	9
Europe	Croatia (Zadar)	1	8	0	0	0	0	0	1	9
	France (Concarneau)	4	67	16	0	8	8	0	8	107
	Portugal (Madeira)	1	4	19	0	0	2	0	1	26
	Spain (Sukarrieta, Bermeo, Cangas, Vigo)	15	587	238	10	14	45	2	19	915
America	Ecuador (Manta, Posorja)	12	546	292	10	24	42	4	14	932
	Mexico (Mazatlan, Manzanillo)	3	110	71	1	3	5	8	2	200
	Panama (Panama City)	3	14	6	3	1	9	6	14	53
	Peru (Lima)	4	41	18	3	5	49	15	40	171
	USA (San Diego)	3	21	1	5	5	9	1	1	43
Asia	Indonesia (Bitung, Kendari, Benoa Jakarta, Sibolga, Banda Aceh, Prigi, Pekalongan, Makasar, Manado,Ambon)	24	512	145	4	20	30	92	42	845
	Japan (Yaizu)	1	1	0	0	0	17	0	11	29
	Philippines (General Santos)	3	58	13	2	5	15	4	24	121
	People's Republic of China (Shangai, Zhousan)	2	18	1	0	10	13	0	9	51
	South Korea (Busan)	2	16	9	0	2	18	5	37	87
	Taiwan (Kaoshioung)	1	1	0	0	6	12	0	0	19
	Vietnam (Quy Nohn)	1	42	0	0	0	13	0	3	58
Oceania	American Samoa (Pago Pago)	3	13	3	2	1	11	3	5	38
	Federated States of Micronesia (Ponphei)	2	10	5	1	0	4	0	0	20
	Republic of the Marshall Islands (Majuro)	4	27	11	0	3	7	2	1	51
Total		101	2219	951	66	153	444	179	243	4255

observer training programs, deck crew trainings, biodegradable FAD projects) coordinated by other scientific teams have complemented mitigation training needs in several regions.

Workshop duration was usually 4-5 hours maximum, as fishers are not used to long meetings and have busy schedules. Workshop organization was usually coordinated with help from ship owners, purse seine fleet associations and other key industry contacts. In some workshops interpreters were hired for translation. While the primary target audience was fishers including captains, navigators, chief engineers, officers, deck bosses and deck crew, the workshops were also open, free of charge, to all fishery stakeholders such as ship-owners, fleet managers, local fisheries scientists, fisheries managers, conservation group members, etc who voluntarily participated. The workshops have been financially supported up to now by ISSF and various funders (see Acknowledgments).

Most workshops were presented by two tuna fisheries scientists, one being an expert in a particular region (e.g., Indian, Atlantic, Eastern Pacific or Western and Central Pacific Oceans), the other being the workshop program coordinator, who was present in practically all workshops worldwide. The scientific coordinator figure ensured workshop harmonization across regions and direct collection and transference of knowledge gained between the different workshops. Importantly, fishers in a given region would always interact with the same two scientists (i.e., regional expert and workshop coordinator), year-after-year, thus gradually building a relationship of trust and mutual understanding.

During each fleet's workshops, the degree of acceptance level of proposed impact mitigation activities was recorded. Acceptance levels were usually based on participants' perceptions of the probability of success at sea and on how they viewed these approaches affecting their daily fishing routines (i.e., efficiency and practicality) and catches. For example, if an activity could result in a significant detriment to fishers, such as high risk of target catch loss or physical danger to crew, it would usually receive poor acceptance even if it was technically efficient at reducing an environmental impact. Categories of acceptance were scored as low, mid, and high, or a combination of these, based on the comments and feedback by workshop participants. For example, when most fishers in a workshop supported an activity (i.e., > 70%), it was considered high acceptance, but if many fishers provided negative comments, it was scored as low acceptance (i.e., < 50%). When only part of the fishers in the workshops viewed an activity as positive (i.e., 50-70%) or thought that more work was necessary to better develop a practice, then a medium acceptance score was assigned. This may not necessarily represent all opinions across a given fleet but served as a useful indicator to guide scientists on which activities would be easier to find support from fishers to test cooperatively, versus other options which would encounter strong industry opposition and be less likely voluntarily adopted. After each workshop, scientists produced a standardized report for the BC describing key points and acceptance levels by each fleet.

During the workshop, a voluntary anonymous multiple-choice questionnaire with different options around fishery practices covering a range of mitigation subjects was completed by participants. Questions were regularly reviewed and updated to collect useful information on topics of interest (e.g., adoption of best release practices, characteristics of FADs used, evolving fishing strategies, echo-sounder buoys employed, etc.). The questionnaire allowed quantifying fishers' responses and provided them a chance to contribute with their knowledge and perspectives, especially for those fishers that due to their character were more reserved during plenary discussions.

In addition to the standard ISSF Skippers Workshops, ISSF has also organized participatory workshops with purse seine fishers but focusing on a particular topic of interest such as FAD retrieval, biodegradable FADs, etc. at locations including Spain, Philippines, Federated States of Micronesia, and Papua New Guinea (Moreno et al., 2016; Moreno et al., 2018). These workshops are not counted in the results section because they did not cover the full range of impact mitigation subjects of the standard workshops.

For those tuna fishers not able to attend particular workshops, ISSF has produced free online training tools. ISSF provides fishers with easily accessible downloadable best practice guidebooks (http://www.issfguidebooks.org/) and pre-recorded workshop videos in English and with subtitles in various languages (https://www.youtube.com/watch?v=hXlgHWhIAeQ). In addition, ISSF websites offer free access to other instructional materials, such as research reports, guides on species identification, etc.

2.3 Train-the-trainer programs

Some tuna fleets in developing countries despite being primarily composed of artisanal purse seiners, due to the sheer number of vessels and rich fishing grounds, represent a significant portion of global catches. For example, Indonesia provides over 15 percent of the world's tuna supply, being the top tuna producing country in the world. These fleets are often widely distributed across numerous small ports. Reaching a representative proportion of fishers to raise awareness is logistically very challenging. Furthermore, many of these fishers may be affected by illiteracy and lower access to online training tools.

To address these training difficulties a train-the-trainer program was set up in the Indonesian archipelago, in which a group of experienced tuna scientists from the Indonesian Centre for Fisheries Research and Development (CFRD) were trained to conduct workshops with fishers during their regular trips to many fishing ports. This helped reach a larger number of fishers through in-person workshops during opportunistic and planned port visits.

Recently, ISSF started expanding their train-the-trainer program to other tuna fishing gears such as longline. Again, longline fishers are difficult to reach at one given time and location. To increase chances of engagement with longline fishers, in-port stationed personnel from several fishing companies have been trained by scientists to show fishers best mitigation practices and collect feedback opportunistically when vessels arrive to unload the fish. These workshops are not computed in the results section as they began in 2020.

2.4 In port vessel visits

For workshops taking place at key ports, typically ISSF scientists made visits to available vessels. During ISSF Skippers Workshops contact was made with ship-owners and fishers who had vessels in port to arrange visits to their vessels. Those visits helped scientists to learn first-hand about the fishing technology on the bridge, types of FADs, and the equipment employed on the deck. This was especially helpful in semi-industrial fleets, like the Indonesian or Vietnamese, for which detailed vessel technology and FAD design is sparce. Also, those visits allowed for a more personalised and informal interaction with fishers to review the topics addressed during the workshop (Figure 2). Visits also show fishers that scientists are interested in learning about the vessels they work in and particular circumstances that might affect the application of mitigation options.

2.5 ISSF research cruises

At sea trials were conducted to examine the viability of several mitigation actions proposed by fishers and scientists. The majority of research cruises involved testing the efficacy of novel developments in technology or operational protocols in large-scale purse seiners (e.g., 800-2500 GT). In particular instances, field work was also carried out on smaller scale research vessels. Both purse seine and small vessel research cruises were either fully chartered for dedicated ISSF Bycatch Project research or alternatively scientists embarked opportunistically. For opportunistic research on commercial purse seine fishing trips, ISSF arranged several meetings to pre-establish and agree with ship-owners and fishers the mitigation activities to be tested and under which conditions. Those meetings were key to solve concerns and make sure that everyone understood the work to be done onboard. This was often reflected in contracts signed between the parties involved.

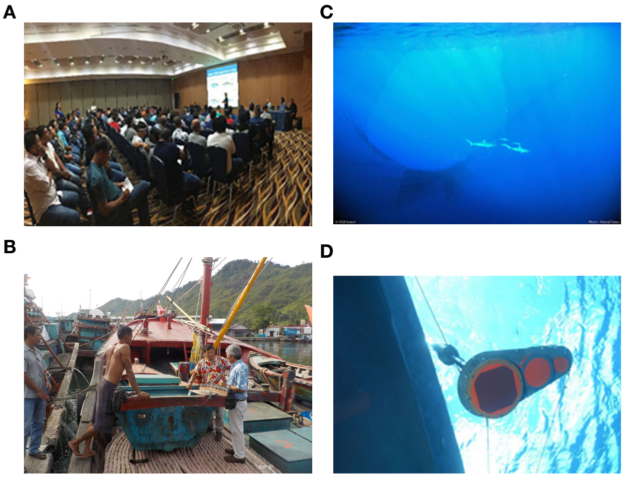

FIGURE 2
ISSF scientists and fishers **(A)** in a large-scale workshop at Manta (Ecuador), **(B)** during a visit to a small-scale purse seiner in Sibolga (Indonesia), **(C)** trials with shark escape windows in the net in the Western Pacific Ocean, and **(D)** multi-frequency echosounder transducers to improve tuna species discrimination in FADs tested during research cruises.

From the outset, the plan was to conduct research cruises in different types of vessels and in fishing areas to cross-examine the efficacy and implementability of mitigation activities in different oceanic regions. Also, fishers of the different flags involved in opportunistic research cruises contributed fleet- and ocean-specific knowledge to improve the studies. For some of the activities in recent years, especially non-entangling and biodegradable FAD trials, voluntary opportunistic research scaled up from work on single vessels to whole fishing company or even fleet level.

Complimentary to the research on vessels, a series of experimental works were undertaken in controlled scenarios such as laboratories, in offshore fish cages or marine protected coastal areas, to investigate parameters of interest such as characterizing the rate of erosion of biodegradable FAD materials or determining the acoustic signature of different tuna species and sizes to study acoustic discrimination.

2.6 Proactive vessel register

In 2012, ISSF created the Proactive Vessel Register (PVR) which enabled tuna vessel owners to identify themselves as active participants in meaningful sustainability efforts, such as implementing specific best practices. Participating vessels are regularly audited by independent accredited consultants (e.g., MRAG-Americas) to verify these sustainable actions. Tuna purchasers and other stakeholders can easily check the freely available online PVR information on hundreds of vessels worldwide (https://iss-foundation.org/knowledge-tools/databases/proactive-vessel-register/) and make informed decisions for sustainable tuna sourcing. For example, tuna traders and processor members of the International Seafood Sustainability Association (ISSA) committed to purchasing tuna only from vessels that comply with certain ISSF Conservation Measures and the PVR is a platform that tracks whether vessels are complying with them. Thus, adhering to sustainability requirements should favor market accessibility for PVR members. As of the 24th August 2022, 1,410 tuna vessels are registered, of which 489 are large-scale tropical tuna purse seiners, representing three-quarters of the large-scale tuna purse seiners worldwide (Justel-Rubio and Recio, 2022).

One of the sustainability actions reflected in the PVR is having the skippers of purse seine listed vessels trained in best mitigation practices. Skippers can become certified in best practices by attending in-person ISSF Skippers Workshops or completing the online Skipper Guidebooks. Skippers benefit from having the PVR certification as many fishing companies request it when recruiting personnel.

3 Results

3.1 ISSF Skippers workshop locations and participation

Participatory workshops have been attended by members of the principal tropical tuna purse seine fleets operating in the Indian, Atlantic, Eastern Pacific and Western and Central Pacific Oceans. Between 2009-2019 a total of 101 ISSF Skippers Workshops were conducted in 23 countries, reaching a total of 4,255 participations (Table 1). In some instances, certain fishers would repeat participation in workshops for a given location over the years. By continent, Asia was the region with more workshops (34%), mostly due to the strong effort in the Indonesian aFAD fishery with the train-the-trainer program delivering 24 workshops. North and South America yielded 25% of the global workshops, in which Ecuador, with 12 workshops, was the primary country due to its importance as the largest tuna purse seiner fleet in the Eastern Pacific Ocean. About 20% of workshops were conducted in Europe, mostly in Spain (15), as its associated vessels operate in all tropical tuna RMFO regions and amount 10% of global catches, followed by France with 4 workshops. In the African continent 12 workshops were organized, most taking place in Ghana (9) due to the importance of this fleet in the Eastern

Atlantic Ocean. Finally, 9 workshops were conducted in Oceania, targeting key island nation ports like Pago Pago (American Samoa), Majuro (Republic of the Marshall Islands) and Pohnpei (Federated States of Micronesia) where a variety of domestic or domestically based and distant water fishing (DWF) fleets operate year-round.

Overall, workshop composition by working occupation was dominated by fishers, skippers being the largest group of attendants (53%), followed by fishers occupying other crew positions (e.g., deck bosses, deck crew, chief engineers, officers) (22%). In the non-fisher professions, the largest group was fleet representatives (e.g., fleet managers, vessel inspectors, operations managers, assistant managers) (14%), followed by fisheries scientists (6%), governmental agency fisheries managers (4%), and ship-owners (1%). Note that some fishers and other stakeholders have participated in several workshops over the years, thus the total number of unique participants would be lower than the number of participations. Nevertheless, given the workshops' geographical scope and continued interactions over time significant portions of fishers in various fleets were reached. This is especially true in locations such as Ecuador (932 participations), Spain (915), Indonesia (845), or Ghana (444), where workshops were held almost yearly.

3.2 Acceptance level for impact mitigation activities

Several mitigatory activities for different animal groups were openly talked about with fishers in the workshops (Table 2). Due to the short duration of the workshops not all actions were presented in each workshop, but usually the principal topics were discussed (e.g., non-entangling and biodegradable FADs, vulnerable species best

TABLE 2 ISSF Bycatch Project mitigation activities discussed between scientist and fishers during the ISSF Skippers Workshops, by species groups and time in the fishing operation (1) before, (2) during and (3) after the set.

Species Group	Activity	Description
Sharks & Rays	(1) Shift effort from FADs to free schools	In most regions sharks are found in higher numbers in FAD sets compared to free school sets
	(1) Set time on FADs	Find times of the day to set when sharks move away from FADs and tunas are still aggregated
	(1) FAD designs to reduce entanglement	Modification of FAD construction and design to minimize opportunity of accidental entanglement
	(1) Time/area closures	Examine area and season hotspots for specific elasmobranch species and temporarily restrict sets
	(1) Attracting sharks away from FADs	Attract sharks with chum or other positive stimuli away from the FAD before the set or use double FADs moving away one FAD with the sharks and setting on the other FAD with the tuna.
	(2) Release sharks from net	Using shark release windows in the net, fishing sharks with hook and line and releasing outside of net, backdown maneuver for sharks, or release maneuver over the net's corkline with whale sharks
	(3) Live release from deck	Develop best practices to release sharks and rays once arriving on deck, including bycatch release devices to assist with safer manipulation
	(3) Prohibiting finning	Minimize incentive for fishers to carry out shark finning though penalty systems for vessels involved
Turtles	(1) FAD designs to reduce entanglement	Modification of FAD construction and design to minimize opportunity of accidental entanglement
	(1) Biodegradable FAD designs	Utilization of biodegradable materials so that if FADs accidentally end up beaching in turtle habitats, the structure will quickly degrade
	(3) Live release from deck	Develop best practices to release turtles once arriving on deck, including protocols to avoid accidental injuries
Undesired catches of yellowfin and bigeye tuna	(1) Shift some effort to free schools or reduce number of FAD sets	In some regions BET and/or YFT need to be protected due to their stocks being overfished. The juvenile sizes of these species appear mostly in floating object sets
	(1) Setting catch limits by gear and enforcing them	Set TACs for the different gears that catch juvenile yellowfin and bigeye tuna.
	(1) Selective fishing using acoustics	Use echo-sounders from vessels and buoys to discriminate tuna species and select FADs with fewer proportion of undesired tuna species.
	(1) Time/area closures	Examine area and season hotspots for undesired catches of small yellowfin or bigeye tuna and temporarily restrict sets
	(1) Set time	Find times of day when species of tunas that need to be protected are less aggregated to FADs
	(1) Net depth and FAD depth	In areas where yellowfin and bigeye tuna are deeper in the water column than skipjack, by using shallower purse seine nets and FADs, their catches could be reduced
Bony fish	(3) Live release from deck	Develop methods and tools to ensure fast release of live finfish from deck
	(3) Retention and utilization	Already requested by the four tuna RFMOs to avoid wasteful discards
Impact on coastal and benthic ecosystems	(1) Biodegradable FAD designs	Utilization of biodegradable materials so that when FADs are abandoned or lost the structure will quickly degrade

release methods, acoustic discrimination). Also, each topic presented was dynamic, changing over time as new experimental results emerged in the research cruises and fleet level trials (e.g., designs of non-entangling FADs have been evolving from simple modifications of traditional FADs with purse seine net tied in bundles to FADs with no net material nowadays).

A pattern emerged during fleet consultations in workshops in which activities that were strongly rejected initially by fishers, continued to be consistently dismissed in following years (Tables 3A, B). Fishers considered these options presented by scientists as operationally unviable or poorly aligned with the reality of their fishing strategies (e.g., shark escape panels in the purse seine net, avoidance of small FAD sets to reduce bycatch rates, or trying to catch skipjack when schools move away from the FAD). Instead, other activities which initially received mid to high range scores, gradually increased to highest acceptance levels in following years (Tables 3C–F). This well-received category included activities such as moving to non-entangling and biodegradable FADs, development of protocols and tools for best practices on safe deck release for vulnerable bycatch and advances in acoustic discrimination of tuna species found at FADs to increase selectivity. Other topics were also consulted in the meetings or questionnaires, such as the potential of FADs to act as ecological traps (i.e., changing tuna movement patterns, reducing feeding and condition factors, etc.). However, fishers generally either did not believe or due to lack of conclusive evidence were unsure whether such FAD-derived phenomenon was taking place. This is in line with the prevailing current scientific view that there is inadequate scientific information to conclude if deployments of dFADs function as ecological traps for tunas. Also, fishers were questioned in some workshops about further limiting the number of FADs as an alternative to reduce impacts. This option received good to mid-level acceptances in fleets with lower reliance on FAD sets (e.g., some Western and Central Pacific Ocean fleets with higher free school set rates) but was poorly valued by other fleets with stronger FAD use (e.g., some fleets in the Indian, Atlantic and Eastern Pacific Oceans). Such lower acceptance by the latter sector was to be expected as their competitive catch performance relies on more intensive FAD exploitation strategies.

The general tendency of acceptance levels was similar among most fleets, but in some cases certain fleets showed different patterns for particular measures. These divergences were associated with different fishers' perspectives (e.g., more traditional, less open to new practices), or particular circumstances in those fleets. For example, while most fleets showed mid-high acceptance for non-entangling and biodegradable FADs, the Chinese showed low-mid acceptance. This might be related to fishers in this fleet being very attached to their traditional FADs, having low expectations for alternative FAD designs working properly and/or other factors such as the higher costs of biodegradable materials and the difficulty of accessing high-quality biodegradable materials in their region.

3.3 At sea research cruises

Most research activities at sea focused on how to minimize FAD related impacts (e.g., shark bycatch reduction, lowering FAD structure impacts, juvenile tuna avoidance). In the early stages of the ISSF Bycatch Project the plan was to fully charter large-scale purse seiners for research work, with scientists having a high degree of control over when and how to perform fishing activities for experimental purposes. For example, during a set scientists could choose to delay the fishing operation for several hours so that they could dive in the net or introduce remotely operated vehicle (ROV) to observe and film the behavior of tunas and bycatch species. However, given the exceedingly high costs of renting these large-scale vessels for a one-month trip (e.g., over 1 million USD per trip), the strategy quickly shifted to conducting opportunistic work on purse seiners, which involved a small team of scientists onboard (e.g., 2-4 persons) focusing on a number of pre-agreed and selected activities with the ship-owner and skipper.

The ISSF Bycatch Project aimed at organizing at least two research cruises per year, spreading out trials in a balanced way between the various regions of the Indian, Atlantic and Pacific Oceans to check if proposed mitigation options could be generally applied or only in zones with certain environmental conditions (e.g., high underwater visibility, slow currents, certain water temperature, calm waters, deep thermoclines, etc.). For example, the Western Pacific offers potential for mitigation options taking advantage of the spatial separation between sharks and tunas inside the net thanks to the deep thermocline. However, such options are less viable in shallow thermocline regions like the Eastern Atlantic Ocean where species groups are closer in the net. Between four and five at sea research trials were conducted in each ocean (Table 4), in collaboration with vessels from different fleets (e.g., Ecuador, Spain, Ghana, USA, France, etc.). This enabled cross examination of mitigation activity performance under different fishing strategies and vessel types. For example, in the Ghanaian vessels limited acoustic equipment prevented high-tech species discrimination trials or the USA fleet vessels worked with bycatch release devices on deck (e.g., hoppers) while other fleets do not.

In some instances, trials were conducted at multi-vessel level, with all purse seine vessels in particular companies or fleets cooperating in a research study. This was the case for example with non-entangling biodegradable FADs projects in the Indian Ocean (European Union fleet BIOFAD project, Murua et al., 2023), the Ghanaian fleet in the Atlantic or the Ecuadorian fleet in the Eastern Pacific (IATTC project). Due to the high proportion of FAD loss or change of hands, a high number of experimental FADs was necessary to obtain meaningful statistical results. By sharing experimental trial efforts among all vessels in a fleet, this strategy requires that each vessel only deploys a small number of experimental FADs (e.g., < 5% of its annual FAD limit), thus reducing the risk of negative economic impacts per purse seiner if prototypes perform poorly (e.g., degrade too quickly or are inefficient at attracting tuna).

In some instances, for particular activities such as tuna and bycatch species´ tagging at FADs for behavioural studies, smaller scale research vessels were employed. These were either chartered vessels or again opportunistic work on other experimental vessels (e.g., Secretariat of the Pacific Community's Tuna Tagging Program). In addition, other complementary experimental activities have been conducted in near-shore facilities to monitor performance of biodegradable materials and tuna acoustic identification developments under controlled marine conditions (Table 5).

TABLE 3 Evolution of ISSF Skippers Workshop impact mitigation activity acceptance by fishers for (A) avoidance of small FAD sets, (B) shark escape panel, (C) non-entangling FADs, (D) biodegradable FADs, (E) best bycatch release practices from deck, and (F) echo-sounder buoy selectivity.

FLEET	ACCEPTANCE LEVEL							
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
(A) AVOIDANCE SMALL SETS								
A	–	–	LOW-MID	–	LOW	–	–	–
B	–	–	–	LOW	–	–	–	–
C	–	–	–	–	–	–	–	–
D	–	–	–	–	–	–	–	–
E	–	–	MID-HIGH	LOW	–	–	–	–
F	–	–	LOW	LOW	LOW	–	–	–
G	–	–	LOW	–	–	–	–	–
H	–	–	–	–	–	–	–	–
I	–	–	LOW	–	–	–	–	–
J	LOW	–	–		–	–	–	–
K	–	LOW-MID	LOW	LOW	LOW	–	–	–
L	LOW	LOW	LOW-MID	LOW	LOW	–	–	–
M	–	–	–	–	LOW	–	–	–
N	–	–	–	–	LOW	–	–	–
O	–	–	–	–	LOW	–	–	–
(B) SHARK ESCAPE PANEL								
A	MID	MID	LOW	LOW	LOW-MID	LOW-MID	–	–
B	–	–	–	MID	–	–	–	–
C	–	MID	–	LOW	–	LOW-MID	–	–
D	–	MID	–	–	–	–	–	–
E	LOW-MID	–	MID-HIGH	LOW-MID	–	LOW-MID	–	–
F	–	–	NA	NA	NA	NA	–	–
G	–	–	MID	LOW	–	–	–	–
H	LOW	–	LOW	–	–	–	–	–
I	–	–	MID	–	–	–	–	–
J	–	–	LOW	–	–	LOW-MID	–	–
K	LOW	MID	–	LOW	–	–	–	–
L	LOW	LOW	LOW-MID	LOW-MID	LOW	–	–	–
M	LOW	LOW	LOW	LOW-MID	LOW	–	–	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	LOW	–	–	–
(C) NON-ENTANGLING FADS								
A	MID	MID-HIGH	MID-HIGH	MID-HIGH	HIGH	HIGH	HIGH	HIGH
B	–	–	–	HIGH	–	–	–	–
C	–	MID	–	MID-HIGH	–	HIGH	HIGH	–
D	–	MID-HIGH	–	–	–	–	–	–
E	HIGH	–	MID-HIGH	MID-HIGH	–	LOW-MID	–	–

(Continued)

TABLE 3 Continued

FLEET	ACCEPTANCE LEVEL							
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
F	–	–	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
G	–	–	HIGH	MID-HIGH	–	–	–	–
H	MID-HIGH	–	MID-HIGH	MID-HIGH	–	–	–	–
I	–	–	MID-HIGH	–	–	–	–	–
J	HIGH	–	–	HIGH	–	HIGH	–	HIGH
K	MID-HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
L	LOW-MID	MID	MID	MID-HIGH	MID-HIGH	MID-HIGH	MID-HIGH	–
M	–	–	–	–	HIGH	–	–	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	MID	MID	–	–
(D) BIODEGRADABLE FADS								
A	MID	–	MID	MID-HIGH	MID-HIGH	HIGH	MID-HIGH	HIGH
B	–	–	–	MID	–	–	–	–
C	–	–	MID	MID-HIGH	–	HIGH	MID-HIGH	–
D	MID	–	MID-HIGH	–	–	–	MID-HIGH	–
E	MID	MID	–	–	–	MID	MID-HIGH	–
F	–	MID-HIGH	–	HIGH	HIGH	HIGH	MID-HIGH	MID-HIGH
G	–	–	–	MID-HIGH	–	–	–	–
H	–	–	–	MID-HIGH	–	–	–	MID-HIGH
I	–	–	–	–		MID	MID-HIGH	–
J	LOW-MID	MID	–	–	–	–	–	–
K	–	MID	MID	MID-HIGH	–	HIGH	–	HIGH
L	LOW-MID	MID	LOW-MID	MID	MID-HIGH	HIGH	HIGH	HIGH
M	–	–	–	–	MID	MID-HIGH	HIGH	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	LOW-MID	LOW-MID	–	–
(E) SHARK & RAY BEST RELEASE PRACTICES								
A	MID	MID-HIGH	HIGH	MID-HIGH	HIGH	HIGH	–	HIGH
B	–	–	–	HIGH	–	–	–	–
C	–	MID-HIGH	–	MID-HIGH	–	MID	–	–
D	–	MID-HIGH	–	–	–	–	–	–
E	MID-HIGH	–	MID-HIGH	HIGH	–	MID-HIGH	HIGH	HIGH
F	–	–	LOW	LOW-MID	MID	HIGH	HIGH	–
G	–	–	MID-HIGH	MID-HIGH	–	–	HIGH	–
H	MID	–	MID	–	–	–	–	–
I		–	MID-HIGH	–	–	–	MID-HIGH	–
J	MID	–	–	MID	–	MID	–	–
K	MID	MID-HIGH	HIGH	HIGH	HIGH	MID-HIGH	–	HIGH
L	MID	MID	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

(Continued)

TABLE 3 Continued

FLEET	ACCEPTANCE LEVEL							
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
M	–	–	–	–	HIGH	LOW	–	MID-HIGH
N	–	–	–	–	MID	–	–	–
O	–	–	–	–	LOW-MID	–	–	–
(F) ECHO-SOUNDER SELECTIVITY								
A	MID	MID	HIGH	MID-HIGH	MID-HIGH	HIGH	HIGH	HIGH
B	–	–	–	MID	–	–	–	–
C	–	MID	–	MID	–	–	HIGH	–
D	–	MID	–	–	–	–	–	–
E	MID	–	MID	MID	–	MID-HIGH	–	HIGH
F	–	–	NA	NA	NA	NA	NA	NA
G	–	–	MID	HIGH	–	–	–	–
H	LOW	–	MID	–	MID-HIGH	–	MID-HIGH	–
I	–	–	MID	–	–	HIGH	HIGH	–
J	MID	–	–	–	–	–	–	HIGH
K	MID	MID	MID	HIGH	HIGH	HIGH	HIGH	HIGH
L	LOW	MID	MID	MID	MID	–	–	–
M	–	–	–	–	HIGH	–	–	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	MID	–	–	–

Acceptance levels ranging from low to high for best received options.
NA, Not Applicable.

Describing the extensive series of experimental results obtained during the years in ISSF research trials is beyond the scope of this article, but Restrepo et al. (2018) provide a summary of outcomes of such field-based investigations and references to more detailed documents. Overall, trial results showed that several theoretically possible mitigation actions did not work as predicted in practice (e.g., catching skipjack when moving away from the FAD, shark escape windows, sort tail FADs to attract less bigeye tuna) as suggested by fishers at skipper workshops. Other trials yielded promising results but require further refinement (e.g., fishing sharks in the net, echo-sounder buoys with acoustic discrimination, biodegradable FADs). In general, even experiments that have proven successful such as non-entangling FADs or new bycatch release devices (e.g., hoppers with ramps, mobulid sorting grids), have required trial-and-error processes of several years of adjusting protocols and designs to meet functional requirements that integrate well with the whole fishing operation.

4 Discussion

A decade of collaborative research to mitigate FAD related impacts between scientists and fishers from tropical tuna purse seine fleets across the world is advancing marine conservation practices as demonstrated by the general move to non-entangling FADs and improved bycatch release methods. This truly international network of participatory ISSF Skippers Workshops and research cruises has reduced gaps between tuna fishers and scientists by providing a stable platform where both can express their views, concerns, and develop preferred options to mitigate fishery impacts. This program is an important opportunity to move away from traditional hierarchical decision-making structures, by giving fishers a voice to directly contribute towards improved impact mitigation options. The sense of stewardship gained by fishers through participation in research decisions and actions is promoting the voluntary adoption of best practices. In recent years, many tuna fishing companies have obtained, or are in advanced assessment stages for, Marine Stewardship Council (MSC) eco-certification, where Principle 2 on minimizing environmental impacts is scored. Without recently improved RFMO management measures (e.g., FAD limits, higher observer coverage) and the significant corrective actions developed through science-fisher research cooperation in the last decade, it would have been unlikely for companies using FADs to achieve eco-certification status.

Lessons gained from this multinational tuna purse seine industry inclusive approach are widely transferrable to other fisheries. In fact, ISSF has recently started to conduct ISSF Skippers Workshops with tuna longline fisheries (e.g., Fiji, Taiwan, etc.), with views to expanding this program across key fleets. Similarly, this participatory program model could be easily adapted and exported

TABLE 4 Tuna purse seine fishery ISSF-related research cruises testing mitigation activities between 2011-2020, namely (1) non-entangling FAD designs, (2) deployment and data collection of non-entangling biodegradable FADs, (3) deployment and data collection of shallow vs deep FADs to study effect on bigeye tuna catches, (4) behavior of tunas and other species around FADs, (5) behavior of tunas and other species in the net, (6) improving pre-set estimation of species, sizes and quantities associated to FADs with acoustics, (7) avoiding catch of sharks before setting, (8) releasing sharks and other vulnerable species from the net, (9) releasing undesirable sizes of yellowfin and bigeye tuna from the net, (10) releasing sharks and other vulnerable species from onboard the vessel, (11) post-release survival of vulnerable species, (12) improving monitoring capabilities onboard, (13) fundamental biology research of FAD aggregated species.

Ocean	Vessel	Researched activities	Year
Eastern Pacific Ocean	F/V Yolanda L*	1, 3, 6, 11	2011
	F/V *Via* Simoun*	11	2012
	Nirsa fleet*	3	2015-17
	F/V Ljubica*	8	2016
	Ecuadorian fleet (with IATTC)*	2	2020
Western and Central Pacific Ocean	F/V Cape Finisterre*	4, 5, 6, 8, 9, 11, 12	2012
	F/V Cape Finisterre*	8, 11, 13	2013
	Albatun Tres*	6, 8, 9, 13	2014
	CP-10,11,12 (with SPC)**	4	2014-2016
	CFC fleet*	2	2020
Indian Ocean	MV Maya's Dugong**	3, 7	2011
	F/V Torre Giulia*	1, 4, 6, 7, 8, 11, 13	2012
	Inpesca fleet*	2	2017
	EU/Seychelles/Mauritius fleet (BIOFAD project)*	2	2019-20
Atlantic Ocean	F/V Cap Lopez*	1, 8, 11	2015
	Sea Dragon**	1,4	2015
	F/V Mar de Sergio*	5, 6, 8	2016
	F/V Pacific Star*	8, 10, 11	2018
	Ghana fleet*	2	2020

IATTC, Inter-American Tropical Tuna Commission; SPC, The Pacific Community.
*Large-scale purse seine vessels, **small research vessels.

to many different fishery scales (e.g., local, regional, international) and gears (e.g., static, demersal, pelagic) if the same guiding principles are applied.

4.1 Raising awareness on the need for sustainable fishing

During the first round of ISSF Skippers Workshops in 2010, most fishers, some with over 30-years' experience in the tuna fishery, stated that was their first direct interaction with fisheries scientists. In early workshops fishers had limited awareness on the extent of impacts caused by their fishery (e.g., degree of shark entanglement mortality in FADs, the low survival rate of bycaught elasmobranchs, effects of juvenile tuna catch on stocks). Similarly, many scientists working for decades in tuna fisheries knew few fishers personally prior to these workshops. This illustrates the little direct interaction takes place between fishers and scientists in some fisheries, especially in long-distance fleets where fishers operate very far away from their national scientific institutions.

In general, fishers also had little understanding of the growing importance of consumer demands for sustainable fish and therefore

TABLE 5 ISSF-related FAD impact mitigation research activities conducted in near-shore facilities in collaboration with other scientific institutions.

Location	Experimental Tests	Year
Oahu, Hawaii	Biodegradable FAD materials (with University of Hawaii)	2015
Achotines, Panama	Tropical Tuna species acoustic discrimination (with IATTC)	2016-2022
Maniyafushi, Maldives	Biodegradable FAD materials (with IPNLF)	2016
Barcelona, Spain	Oceanographic biodegradable FAD designs (with ICM-CSIC)	2019-2022

IPNLF, International Pole and Line Foundation; ICM-CSIC, Instituto de Ciencias del Mar.

retailers' necessity of sourcing seafood from environmentally friendly fisheries. Usually, fishers' primary objective is to obtain the highest possible catches because their income and job security depend on it. However, the risk of tuna sale restrictions if their catches are unsustainably harvested, should serve as a motivation for fishing companies to find and implement better practices. It is key that ship-owners reassure fishers about the importance of applying best practices and provide the necessary means, such as biodegradable materials or bycatch release equipment, to enable their application.

In the knowledge exchanges with scientists the fishers learn also about tuna and bycatch species biology, ecology and fishery management which is essential for a better understanding of the functioning of marine ecosystems and conservation (Silva et al., 2021). For example, fishers learning about the slow life histories of sharks and mobulid rays making them more vulnerable to fishing mortality can help raise awareness to apply survival enhancing practices. Fishers must also be aware about the full range of potential negative consequences associated with environmental impacts. For example, impacts on elasmobranch populations could lead to spatio-temporal fishing closures, difficulty to obtain eco-certifications, fines for captains accidentally capturing them, etc. Thus, increased environmental and market awareness, through a deeper understanding of the reasons and consequences associated with applying best practices, plays a critical role in fishers' motivation to voluntarily implement changes.

4.2 Fisher-scientists interaction strategies

Motivation and accountability in purse seiner fleets is also achieved through fisher inclusivity in solution development, especially if involved from the early decision stages. In the first workshop rounds, fishers were somewhat skeptical and reluctant to share their views with unfamiliar scientists. Important to the workshops' dynamics was the strategy of maintaining over the years the same scientific personnel. Facilitating scientists avoided judgmental attitudes, which often contribute towards stereotypical roles and communication blockages. By having the workshops focusing only on technical aspects to reduce fishery impacts, rather than on ideological or political issues, fishers viewed the meeting as more objective and unbiased. An open-minded approach that empathized with fishers' concerns prevailed when trying to discuss impact mitigation options. In this way, over multiple interactions, fishers developed a personal trust relationship with these scientists. This promoted greater exchange of opinions and feedback by fishers, even on the more sensitive topics (e.g., FAD numbers, fishing strategies).

Workshop participant number varied between locations from small (e.g., < 10 participants) to large groups (e.g., >100). In small workshops communication usually was more distended, while in larger workshops often few more outspoken fishers mainly intervened. However, large meetings allowed greater outreach by significantly engaging with a representative section of a fleet. In all workshops fishers completed an anonymous questionnaire on key aspects of the FAD fishery, which allowed all participants to provide their input on mitigation practices. Meanwhile, port visits to speak with fishers onboard their vessels allowed for more informal conversations, and in addition, enabled close examination of fishing equipment and FADs employed. The workshops and vessel visits were a very effective method for scientists to learn the latest fishing strategies and fishing technologies being adopted in each ocean. These tuna fleets have a dynamic behavior, often adapting their strategies to other competitors, new technologies and regulations. Keeping close track of such changes, and understanding the driving forces behind them, is paramount to plan effective conservation measures.

Most fishers engaged in the workshops belonged to fleets with large-scale vessels employing dFADs. However, some key purse seine fleets like the Indonesian, operate with small-scale vessels (e.g., 10-250 GT) on aFADs. Due to the semi-artisanal nature of these vessels, with limited space and fishing technologies (e.g., no modern hauling equipment or echo-sounder buoys), and man-made anchored floating objects (see Murua et al., 2018), their impacts are somewhat different to dFADs and adapted mitigation strategies were necessary. The train-the-trainer program with local scientists resulted in a greater number of workshop trainers and trainees in the local language across the multiple fishing ports. Thanks to this approach Indonesia was the fleet with the most ports visited and highest overall fisher participations in the whole ISSF Skipper Workshop program. Didactic materials (e.g., species ID and best release practice posters) were also widely distributed among purse seine vessels to ensure fishers had access to this information. While this was the most visited fleet, this does not necessarily imply it is the one that has advanced the most in the last 12 years. Many other factors come into play when trying to explain sustainability improvement rates in different fleets, including the baseline level of their practices when the program started, fishers' socio-economic circumstances, resources available to implement better practices, effective science-based management programs, etc. Outreach efforts need to be maintained with the Indonesian and other small-scale vessel fleets in developing nations (e.g., Vietnam, Philippines) due to the large number of fishers requiring training and limited surveillance, monitor and control systems in place to ensure best practices.

The international aspect of the collaborative program played an important role in fishers perceiving with a sense of fairness the adoption of best developed practices, as other competing purse seine fleets had also to comply with the same rules (e.g., PVR conservation measures). Fishers' pretext of "why do we have to carry out these conservation efforts when other fleets are not?" disappears under this overarching global approach. Furthermore, as fishing companies learn about competing industry members taking steps towards sustainable practices, the general reaction has been to improve their standards to avoid being left behind. The strategy of involving purse seiners from various fleets in research not only helped to share the risks and responsibilities associated with the trials, but also the chance to showcase the commitment of fishers from different nationalities towards sustainable fishing.

4.3 Selecting impact mitigation solutions

For true deliberation and innovation processes both scientists and fishers must aim to be honest and willing to reach agreements. For ISSF scientists making fishers aware from the start that research activities are frequently based on slow trial-and-error processes was key. Patience and perseverance are required in many instances when developing novel alternatives, often undergoing failures and numerous iterations before solutions become functional. For example, biodegradable FADs continue to evolve since tested first in the early 2010s, still trying to find better designs and materials to enable their commercial implementation. The workshops provided scientists with a platform to discuss with fishers in detail and face-to-face why some experiments have not performed as expected. Even failed experiments can contribute important new understanding of challenging factors and provide insights into which steps to follow next. Fishers, and scientists, must be prepared to encounter research bottlenecks (e.g., finding ways to deter sharks from FADs) as otherwise they can become frustrated and lose motivation.

The workshops assisted scientists with the identification of fishers showing greater interest for exploring mitigatory solutions. These fishers, referred to by Jenkins (2010) as having a "fisher-inventor profile", due to their problem-solving and experimental attitudes, are a great asset when developing selective technologies and practices. Their positive mindset towards research helps motivate other fishers to join these efforts, having a pronounced positive effect on their local fishery or fleet. Throughout the years of workshops, ISSF scientists have built close alliances with these proactive fishers. For example, when planning research cruises, trying to develop new bycatch release devices, or organizing specialized workshops, ISSF scientists often reach out to these strategic fishers first for collaboration.

Measures poorly aligned with fishers' views, are less likely to be applied unless strong monitoring and enforcement exist, and even then, fishers might try to find ways to circumvent them. Therefore, carefully considering fishers' essential needs when developing new solutions is critical. Fishers often raised practical common-sense concerns, such as requesting that if alternative non-entangling and biodegradable FAD designs were implemented, they should still attract tuna effectively. Similarly, they ask that if they must release dangerous vulnerable bycatch species from deck (e.g., large sharks), the methods proposed should not compromise their personal safety. Conservation activities which result in lower trade-offs for fishers (i.e., minimal loss of target catch or time) are more likely to be successfully adopted. Even easier to implement are win-win activities, in which fishers gain a competitive or safety advantage (e.g., bycatch reduction devices (BRDs) that minimize handling risks of hazardous species like elasmobranchs). Some advances are occurring this way, such as the development of novel or adapted BRDs based on fishers' ideas provided at workshops (Murua et al., 2021a; Murua et al., 2021b). However, BDR prototypes need further testing and refinement to be widely adopted by different fleets. To assess improvements in the application of vulnerable species bycatch release practices, whether manual or BDR-assisted, in recent years high quality observer data should be carefully collected. Preliminary observer data analysis for some fleets seem to indicate improvements in bycatch release times from deck in recent years (Grande et al., 2019), but this can be species or size specific (Maufroy et al., 2020). Therefore, this is still work in progress and multi-ocean fleet trends should be evaluated in more detail. Furthermore, the evolution in the condition at release and survival rates of sharks and mobulids (e.g., using vitality indexes, lactate levels or with pop-up satellite tagging) should be examined by scientists over time to measure the efficiency of different release methods in purse seiners (Filmalter et al., 2015).

Levels of support for some activities were not always equal across the board given the great variety of fleets and their associated beliefs, fishing technology, and strategies. Fishing industry has often been described as a traditional sector and incorporating new practices can be a slow process. Therefore, during initial research stages it made sense to collaborate in actions perceived as more viable or beneficial by fishers, as they will be more willing to participate in trials. The acceptance levels at workshops were not static and fishers' opinions on some activities change over time. Many new mitigation ideas presented by scientists in the early workshop rounds were totally new to fishers. Often repeated interaction with fishers to cross-exchange ideas and get familiarized with novel concepts was necessary. In several activities fishers support increased from medium to high levels consistently across many fleets from the first workshop rounds onwards. Presentation during successive workshop rounds of data and videos from at-sea trials and progress by other fleets demonstrating how some activities were viable in purse seiners like theirs was a powerful tool to increase fishers' acceptance and assist to increase their application in commercial fishing trips.

Fishers' feedback in the workshops yielded important savings in research time at sea and costs by learning about best areas and seasons to target mitigation activities and by identifying ways to avoid experimental protocol caveats. Some activities proposed by scientists in the workshops consistently received low scores over the years, often because fishers thought experimental trials would not work (e.g., catching skipjack away from the FAD, double-FADs) or because required tasks would go against their fishing strategies (e.g., avoidance of small FAD sets). Bycatch scientists did not always follow fishers' recommendations and tried some of the activities with lower acceptance levels (e.g., fishing skipjack away from the FAD, shark escape windows). It is worth pointing out that various activities accepted by scientists and fishers did not fully work (e.g., attracting sharks away from the FAD with bait). Some experiments if tested more thoroughly could have potential for more positive results (e.g., utilization of more attractive bait alternatives for sharks) as underlying mechanisms of the differential sensory capacities (e.g., vision, smell, earing) of FAD associated species like tunas and elasmobranchs are still poorly understood.

4.4 Research cruises to test mitigatory activities

Mitigatory research at sea in open ocean dFAD tuna fisheries, like in many other industrial-scale pelagic fisheries, is incredibly expensive. Hence, many studies in tuna fisheries prior to the ISSF Bycatch Project have been conducted on aFADs closer to shore, in laboratories, or desk-top studies based on logbook and observer data. Initial dedicated chartering of large purse seiners by ISSF for research cruises proved too costly and was not a long-term viable option. Thus, opportunistic scientific work on cooperating commercial purse seiners was adopted as an alternative. While fishing companies can be interested in supporting scientific work, they also want assurances that the experiments performed will not impact negatively on their activity. The considerable time and resources invested in these complex negotiations to reach agreements between both parties are often overlooked in the chronograms and budgets of scientific programs. However, this preparatory process is an essential step for fishers and scientists to fully clarify and understand their respective roles and responsibilities in research campaigns. In some cases, during negotiations scientists had to compromise for less complex or risky trials, to ensure ship-owners approve the experimental protocols to be conducted on their vessels.

From the beginning ISSF scientists understood that the efficiency of impact mitigation options needed testing in multiple fleets across oceans, and preferably also in different areas and seasons within each ocean. For example, due to predominant oceanographic currents non-entangling FAD designs with simple submerged structures worked well in the Indian Ocean (e.g., rope or coiled netting tails) but not in the Pacific and Atlantic, where adjustments were required. Furthermore, tuna purse seiner vessels come in a wide range of sizes (e.g., 10-2500 GT) and equipment configurations. Thus, in most cases newly created best practices, such as bycatch reduction devices (BRDs) or net modifications, were carefully customized to each situation for effective results. During the first years of at sea trials research was predominantly executed at a single vessel level (i.e., one research trip on a particular purse seiner). However, after initial cruises yielding positive results, the rest of the purse seine industry increasingly joined research actions as a form to advance faster towards better practices. Also, tuna companies saw in cooperative research an opportunity to prepare for possible future regulatory measures (e.g., biodegradable FADs) and a way to influence their requirements. This change towards a more proactive vision has led to a rapid increase in collaborations; especially in the last five years, with several voluntary trials of unprecedented scale in terms of numbers of vessels involved. In fact, most of these large-scale FAD research efforts now co-funded by industry and different agencies (e.g., RFMOs, EU, ENGOs) are being conducted by some of the fleets with the highest frequency of workshops (e.g., EU, Ecuador, Ghana) in projects mostly coordinated by those same scientists involved in the workshops. Perhaps not surprisingly, some of the fleets most actively engaged in the ISSF Skippers Workshops have pioneered the voluntary adoption of codes of best practices programs which go beyond RFMO requirements. Meanwhile, several fleets also started to voluntarily share fishing buoy data (e.g., FAD echo-sounder buoy data), as recommended during the ISSF Skipper Workshops, useful for scientists to improve stock assessments and ecosystem monitoring (Moreno et al., 2016; Santiago et al., 2020). These sources of information are of great value for ecosystem-based fisheries management (EBFM) purposes.

Similarly, the wide diversity of workshop locations assisted in characterizing the large variety of fishing strategies employed (e.g., anchored FADs vs drifting FADs; FAD vs free school fishing; company vessels working individually or in groups; vessels unassisted vs vessels aided by supply vessels, helicopters, etc.) and vessel types and equipment (e.g., large industrial vs small scale purse seiners; use of echo-sounder buoys vs non-use; small vs large sized nets) in these fisheries. Tactics employed by fishers are quite dynamic and may change in a relatively short time due to technological advances or in response to legislative measures. Regular meetings with individual fleets helped track up to date fishing strategy changes such as rates of adoption of echo-sounder buoy technology, fishers' shift to working in coordinated company vessel groups, adaptations to FAD closures and limits, and so on. Understanding the motivations driving these behavioral and technical changes is essential for adaptive management policies. For instance, this information is of great interest to scientists and managers to accurately estimate relative abundance indices to inform stock status (e.g., effort creep) and devise effective conservation measures in a timely manner. Furthermore, many fishers attending the workshops had decades of experience in their fishery and have been able to assist with historical and more recent information for scientific studies, including endangered species observation rates over the years or contrast observations on tuna population behavior. Part of this information was obtained through the anonymous questionnaires filled in by participants and covering various topics (e.g., types of FADs used, fishing strategies, vessel and FAD equipment, bycatch release methods, etc.).

4.5 Non entangling FADs case study

One of the most illustrating examples of the fisher-scientists solution development process and voluntary implementation was the shift from entangling to non-entangling FADs. At the beginning of the workshops in 2010 the idea of non-entangling FADs was totally alien to fishers, as they had been working with the traditional entangling FAD designs for over 30 years. However, a study by Filmalter et al. (2013) in the Indian Ocean revealed that the rate of shark entanglement in FADs was much higher than previously thought (Figure 3). Additionally, turtles were sometimes entangled in FADs, especially near or on top of the raft when climbing to rest on them. This information was shared at the workshops, helping raise awareness among fishers about the need to replace traditional FAD designs. Through repeated exposure to the non-entangling FAD concept fleets became familiar to the idea. In addition, it was important to let fishers to provide their input in the non-entangling FAD designs from the beginning of the experimental process and by 2012 some vessels started testing them voluntarily. At times, flexibility and adaptability on both parts were necessary to accommodate demands from each party. Initially scientists wanted to construct non-entangling FADs with zero netting, but this drastic change would have been rejected by fleets as alternative materials were not globally/regionally available. Furthermore, at this early stage of the collaborative process fishers were not mentally prepared for such marked change in FAD configuration. Instead, to accelerate the transition to less entangling designs the use of small mesh and tied up mesh materials (categorized as lower entanglement risk FADs by the ISSF guide, ISSF (2012)) was allowed, as fishers were familiarized with these materials. During this whole development process, the ISSF Skippers Workshops collected updated feedback on the various non-entangling FAD trials in each fleet and served as a transmission channel showing fishers from every region the best materials and designs employed by others. This cross pollination of experiences helped speed up the development in reaching efficient non-entangling FAD designs and encouraged many companies, which had initial doubts about these FAD types (e.g., fear of new FADs yielding lower catches, being lost faster, etc.), to make the transition before their respective RFMOs required them (Murua et al., 2016). Currently there is a push to implement fully non-entangling FADs without netting, with various RFMOs having adopted conservation measures to prohibit any net material in FADs (e.g., IOTC Resolution 19/02;

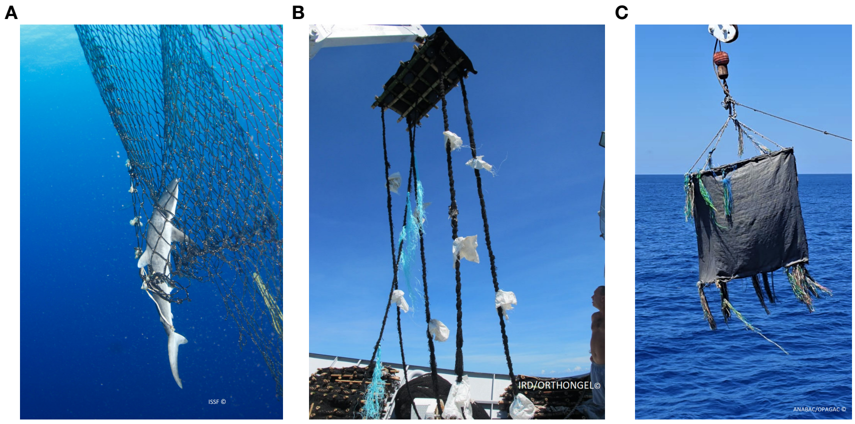

FIGURE 3
Transition process from traditional entangling dFADs to non-entangling dFADs with zero netting, **(A)** Shark entangled in the tail of a traditional high entanglement risk dFAD constructed with large mesh open panels, **(B)** dFAD prototype tested in 2013 by the French fleet with net tied up into bundles to minimize entanglement risk, **(C)** non-entangling dFAD employed in the Indian Ocean built with canvas and biodegradable rope attractors and no netting material.

WCPFC CMM 2021-01) and ISSF requesting the same by January 2024 in its conservation measure 3.7. High level of monitoring will be essential to verify to which degree this transition is being implemented, as some fishers might be reluctant to change if they feel that using small mesh netting is enough to prevent most FAD entanglements. This is an issue in which ship-owners will also need to show commitment, as they are responsible for buying and providing the materials to build FADs.

4.6 Sustained collaboration for long-lasting improvements

To build strong collaborative bridges requires a considerable effort investment which must be sustained overtime, as sporadic interventions with fishers are unlikely to yield desirable long-term benefits. Only when fishers know that their opinion and expertise will be consulted and genuinely considered on a regular basis, in a similar way fisheries management bodies consider systematically scientific committees' recommendations, will they feel part of the process as well. Otherwise, one-off meetings with scientists may not be perceived by fishers as truly collaborative processes and they might even feel used by scientists as mere data providers for academic studies. Scientists have been often criticized for being very active in requesting data from industry for their studies but have frequently failed to report back to fishers on the results and use derived from such data. This non-reciprocal behavior only helps reinforce fishers' mistrust in the scientific process. Full-circle inclusive research processes in which fishers are involved from the initial planning and design stages until the final product is achieved are necessary.

While having workshops at certain locations on an annual or biannual basis may be viewed as low frequency and short duration (e.g., 5 hours), when sustained overtime there is a cumulative long-term effect. From the workshops' experience it seems preferrable to maintain a slow but steady pace of interactions to build stable working relationships rather than putting excessive strain on fishers to collaborate. If scientists request fishers to attend several meetings per year, most likely this will backfire as there would be a burnout effect. This is because, unlike coastal fishers, large-scale tuna vessel fishers spend many months at sea away from their family and when in their free time at home often must attend not only these workshops, but other courses too (e.g., health and safety certifications, fishing technology update courses, etc.). Also, having the workshops on an annual basis, allows time for novel results from the latest experimental trials or lessons learned from other scientific groups or fleets to be incorporated in the presentation (e.g., recent research cruises, improvements in FAD designs, new trials by other fleets). In this way repeating participants can keep up to date with the latest trends in impact mitigation and learn new ways in which scientists and fishers from other fleets are addressing the same issues.

Up to 2019, the ISSF Skippers Workshops have maintained a high level of consistency, aiming at delivering around 8 to 12 workshops per year worldwide. While the program has tried to reach as many fleets as possible, some of the venues became almost fixed every year (e.g., Spain, Ecuador, Indonesia, Ghana) due to the strategic importance of these fleets in their regions and favorable access to fishers at particular times of the year (e.g., during FAD closures, fishers' holidays, etc.). Unfortunately, since 2020 due to the Covid-19 pandemic, workshops were abruptly discontinued, and only in 2022 they are slowly starting again, but this time around with several restrictions in terms of travel access to certain regions and a more limited budget. These circumstances could slow down or even revert the unprecedented high levels of cooperation achieved between tuna purse seine fishers and scientists in the last decade. It would be advisable that regional or international funding bodies (e.g., national fisheries agencies, RMFOs, ENGOs, etc.) set up or support fisher-scientist research programs that enable regular meeting opportunities to keep working on the improvement of harvesting practices. Furthermore, there is an increasing need for fishers, especially newcomers, to be well acquainted with the growing number of conservation regulations, both voluntary (e.g., Codes of Good Practices, ISSF) and obligatory (e.g., RFMOs).

5 Conclusion

The ISSF workshops and associated research cruises provide a bright spot example of how promoting a more integrated approach of fishers and industry from large-scale fisheries in impact mitigation research can yield better technical solutions for adoption of changes and gear modifications at fleet level that support sustainable best practices. Our experience also highlights the importance of building long-term collaborative bridges with fishers based on trust, mutual respect of knowledge, identification of common goals and perseverance to develop effective solutions and a sense of stewardship. In global fisheries, like the tropical tuna purse seine one, involving key fleets from all oceans has been crucial to understand the differences between each region and customize fit-for-purpose sustainable practices that consider fishers' circumstances. While the process here described is still work in progress and we fully acknowledge more actions are needed to further improve marine conservation in tuna fisheries, important advances have been achieved in a relatively short period thanks to an unprecedented scale of cooperation with hundreds of vessels taking part in research to test new FAD constructions and selective fishing protocols. It is recommended that to better assess progress in sustainable practices of these tuna fleets, or any others following cooperative models, a combination of comprehensive scientific studies, observer data, and independent audits should be employed. Collaborative fisher-scientist consultation platforms and action research programs should continue to be supported in the future to consolidate and continue the growth of sustainable fishing practices.

Recommendations

This work presents the broadest fisher-scientist research collaborative initiative ever conducted in tuna fisheries to improve sustainable practices worldwide. During the last decade scientists associated with the International Seafood Sustainability Foundation's Bycatch Project have coordinated over 100 participatory workshops in 23 countries across the Americas, Asia, Europe, Africa, and Oceania with tropical tuna purse seine fishers to address environmental impacts. Additionally, multiple research campaigns onboard large-scale tuna purse seiners in the Indian, Atlantic and Pacific Oceans have tested innovative mitigation alternatives. Research activities favoured by fishers, such as better vulnerable bycatch release methods or minimizing marine pollution, were prioritized. Critical advances including voluntary replacement of highly entangling fish aggregating devices (FADs) with non-entangling designs and improvement in bycatch release equipment, showcase the benefits of bottom-up integrative strategies. Ongoing research continues to refine other solutions such as biodegradable FADs or acoustic selectivity tools with support from industry. Important lessons learned during this process include the need to establish reliable and trustworthy fora for direct open communication with fishers that improve experimental outcomes and promote stewardship conductive to adoption of best practices. For sustainable fishery trajectories to continue advancing into the future, long-term well-funded fisher-inclusive research and awareness programs should be maintained.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials. Further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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EDITED BY
Matthew R. Baker,
North Pacific Research Board,
United States

REVIEWED BY
José Lino Vieira De Oliveira Costa,
University of Lisbon, Portugal
Jocelyn Runnebaum,
The Nature Conservancy,
United States

*CORRESPONDENCE
Thomas Heimann
theimann@cfrfoundation.org

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Mobilizing the fishing industry to address data gaps created by shifting species distribution

Thomas Heimann[1*], Hannah Verkamp[1], Jason McNamee[2] and N. David Bethoney[1]

[1]Commercial Fisheries Research Foundation, South Kingstown, RI, United States, [2]Rhode Island Department of Environmental Management, Bureau of Natural Resources, Providence, RI, United States

Globally, climate change is inducing range shifts and expansions for numerous species. For commercially exploited species, such as those in directed fisheries, this can cause numerous issues with management and jurisdictions as the species shift and expand into areas at levels previously unseen. The black sea bass (*Centropristis striata)* fishery has rapidly expanded in the northern Atlantic. Over the past decade commercial landings have more than doubled in the New England and Mid-Atlantic regions. This increase is related to a northward shift in the species' center of biomass and range expansion. There is a crucial need for increased data in this species' northern range. Oftentimes, large-scale fisheries data collection is limited by available resources and the difficulty of collecting data at-sea. Citizen science, such as fishing industry-based Research Fleets, represent a cost-effective option to help overcome these limitations and allow for the rapid collection of large amounts of data. The Commercial Fisheries Research Foundation and Rhode Island Department of Environmental Management established the Black Sea Bass Research Fleet in 2016. The Research Fleet is composed of fishers representing a variety of gear types who collect fishery-dependent data on black sea bass at-sea on a custom tablet application. In five years, 20 captains participated in the Research Fleet and collected length, visually-identified sex, and disposition data on 40,939 individual black sea bass throughout southern New England and into the Mid-Atlantic Bight. Catch, effort, and basic environmental data from 2,288 sampling sessions have been collected alongside this biological data. We apply the collaborative Research Fleet approach to a finfish for the first time and evaluate its performance over the first five years of sampling through participant engagement, magnitude of data collection, and interest in collected data. Further, we introduce the next steps being undertaken to incorporate the collected data into the management framework. This project illustrates that a science-industry research collaboration such as the Black Sea Bass Research Fleet can consistently collect large amounts of fishery-dependent data on black sea bass, and highlights a mutual interest among fishers, scientists, and managers to expand the collection of reliable data on this important species.

KEYWORDS

fisheries, fishery dependent data, collaborative research, citizen science, New England, black sea bass

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1 Introduction

Worldwide, climate change is impacting the historic distribution of species through both boundary shifts and range expansions due to increased sea temperatures (Perry et al., 2005; Kleisner et al., 2017; Ojea et al., 2020). This phenomenon is dramatically apparent on the United States Northeast Continental Shelf, and specifically the southern New England region, which is expected to warm far above the globally predicted average over the coming years (Kleisner et al., 2017). Sea temperature warming, and the associated species range expansions and shifts, can cause particular concern for exploited species such as those targeted by commercial fisheries due to a plethora of socio-economic issues related to management, jurisdictions, and community resilience and dependence on specific targeted species (Ojea et al., 2020). Sustainable management of a fishery often requires broad data collection across the species range and throughout the gear types which interact with it. The need for this data is confounded when ranges shift and new gear types begin interacting with the species on previously unforeseen scales. Black sea bass (*Centropristis striata*) are a prime example of an important finfish fishery that is currently experiencing these issues on a large scale.

Black sea bass range along the Atlantic coast of the United States from the Gulf of Mexico to the Gulf of Maine (Moser and Shepherd, 2009). Black sea bass is managed as three separate stocks, the north Atlantic, south Atlantic, and Gulf of Mexico, with significant genetic differentiation among stocks (Roy et al., 2012). The majority of the fishery, and landings, are produced by the north Atlantic stock which ranges from Cape Hatteras to Cape Cod and can be divided into two subunits (NEFSC, 2017). The northern subunit of the north Atlantic black sea bass stock (hereafter 'northern subunit') is generally considered to consist of all National Marine Fisheries Service statistical areas north of Hudson Canyon (NEFSC, 2017; ASMFC, 2019a).

Commercial landings from the north Atlantic stock peaked in 1952 at 21.8 million pounds (9,888 metric tons) (ASMFC 2019b). Landings steadily declined in the following decades and reached a low in 1971 at 1.2 million pounds (544 metric tons) (NEFSC, 2017). Throughout the following four decades landings increased slightly but remained relatively steady at around 3 million pounds (1,360 tons) (ASMFC 2019b). In 2000 this stock underwent a rebuilding plan and was declared rebuilt in 2009. Spawning stock biomass has increased substantially across the region since the rebuilding plan was put into effect and after the stock was declared rebuilt; spawning stock biomass was 7,483 metric tons in 2000, 11,125 metric tons in 2009 once declared rebuilt, and most recent updates have spawning stock biomass at 22,199 metric tons in 2018 in the northern subunit (MAFMC, 2013; NEFSC, 2020). Further, there is evidence of a northward shift in the center of biomass, possibly due to climate change and warming waters (Bell et al., 2015). The bulk of black sea bass catch and landings are now coming from the northern subunit; between 2010 and 2017, commercial landings of black sea bass caught in the northern subunit increased by 11% and accounted for 58% of commercial black sea bass landings (ASMFC 2019b). The increase in biomass in the northern range of the species is likely a result of a range expansion, with suitable habitat becoming available for longer periods of time within the year and increased recruitment success in this portion of the range, as has been documented for other species such as Atlantic croaker (*Micropogonias undulatus*) (Hare and Able, 2007). This expansion is supported by the fact that the increased abundance in the northern subunit was not followed by a decrease in the southern subunit, where abundance has instead remained relatively stable (ASMFC 2019b). These changes in stock structure and distribution have created several challenging management issues.

The foremost management issue is the distribution of the black sea bass resource relative to historic fishing communities and the state allocations of commercial quota. Historically, more northern states, such as those in southern New England, had substantially lower allocations relative to states further south (Table 1, ASMFC 2021a). This is because allocations were based on the statewide landings in the black sea bass fishery from 1980-2001, when the fishery operated largely out of the Mid-Atlantic region (ASMFC 2021a). However, given the recent northward expansion in the biomass of black sea bass, fishing communities in the northern range of the species are

TABLE 1 Percent of black sea bass quota allocated to each state in the black sea bass north Atlantic stock.

State	Historic Allocation	New Allocation	Change
Maine	0.50%	0.40%	-0.10%
New Hampshire	0.50%	0.40%	-0.10%
Massachusetts	13.00%	15.44%	2.44%
Rhode Island	11.00%	13.06%	2.06%
Connecticut	1.00%	3.67%	2.67%
New York	7.00%	9.79%	2.79%
New Jersey	20.00%	19.81%	-0.19%
Delaware	5.00%	4.09%	-0.91%
Maryland	11.00%	8.73%	-2.27%
Virginia	20.00%	15.88%	-4.12%
North Carolina	11.00%	8.73%	-2.27%

Historic allocations were set in 2000 and were in place, unchanged, until the new allocations were put in place for 2022.

interacting with the species on an ever-expanding scale (ASMFC 2021a). Fisheries in the northern range have regularly experienced short seasonal openings with high regulatory discards due to the mismatch of historically based allocations and an expanding northward range of black sea bass. This is the result of relatively low daily catch limits, for example 50 pounds per day in Rhode Island, and the magnitude of black sea bass interaction with a wide variety of gear types. Depending on the season, price, and gear type fished, many vessels catch and land black sea bass primarily as bycatch and not necessarily as a main target species. The landing of black sea bass from bycatch is particularly common within the trawl, gillnet, and lobster/crab pot fisheries. The only fisheries to consistently target black sea bass throughout the year are the fish pot and rod and reel fisheries. Recently, the MAFMC and ASMFC voted to change the state quota allocations to attempt to account for these changes in biomass distribution, with many states in the northern stock receiving increases in quota and more southern states receiving decreases (Table 1, ASMFC 2021a).

Management adaptation of the black sea bass stock has been hindered due to significant data gaps for the species, particularly for the north Atlantic stock (Shepherd, 2009; NEFSC, 2017). Discard characterizations, as well as expanded biological data collection within the black sea bass fishery, have been identified as top priorities (Miller et al., 2009; NEFSC, 2017; ACCSP, 2021). Further, the current assessment model for this species only differentiates between the trawl and non-trawl fishery, though several gear types are used to catch black sea bass. Biological characterization of the catch and discards within specific fisheries may help inform biological reference points, reduce the overall uncertainty in the stock assessment, and allow for more representative management of the black sea bass stock. Despite the need for expanded biological data collection and catch and discard characterizations, there have been no regional or coastwide efforts to increase monitoring of the species. One alternative to expand data collection and obtain critically needed data to help fill in these gaps in our knowledge is to engage the fishing community through citizen science.

The application of citizen science has expanded rapidly in recent decades. Across the United States, and globally, there are a multitude of examples of data collected by citizen scientists having direct impacts on the formation or alteration of policy and the advancement of science (Bonney et al., 2009; Dickinson et al., 2012; Aceves-Bueno et al., 2015). The strength of citizen science often lays in the broad reach of data collection, creating a data stream so spatially expansive it would generally be cost-prohibitive from a traditional monitoring survey standpoint (Tulloch et al., 2013; Goldstein et al., 2014; Thiel et al., 2014; Theobald et al., 2015). Citizen science has been applied to track the presence of invasive species, detect range shifts for a variety of species in response to climate change, track movement and migration of species across state and international boundaries, and among many other uses, monitor the spread of diseases (Dickinson et al., 2012).

The confluence of citizen science and fisheries science is less common than between other fields, as the logistics of sampling at-sea are difficult for many who lack a platform and experience with at-sea work (Gawarkiewicz and Malek Mercer, 2019). To address this issue, a variety of citizen science-based models for fishery data collection have been piloted and employed across the United States and globally. One such approach is the Research Fleet model, which was first developed for crustaceans (the Lobster and Jonah Crab Research Fleet was established in 2013; Mercer et al., 2018; Gawarkiewicz and Mercer, 2019). The Research Fleet approach leverages the time on the water of the commercial fishing industry to collect targeted fishery-dependent-data for assessment and management of species in a cost-efficient manner (Mercer et al., 2018). It accomplishes this by using modern technology that enables the efficient collection of data at-sea through a tablet application (Mercer et al., 2018; Gawarkiewicz and Malek Mercer, 2019). Importantly, Research Fleets represent a collaborative, rather than cooperative, approach to data collection (Wendt & Starr 2009). Research Fleet participants retain joint ownership of data and provide input on project development, and this transparency fosters a high level of trust and mutual interest in project results (Mercer et al., 2018). Importantly, Research Fleet participants are compensated for data collection with a monthly sampling stipend. The stipend acknowledges the high opportunity cost of collecting fishery dependent data at-sea as well as the high threshold barrier (permits, crew, vessels, fuel, etc.) to participate in fisheries science.

There is still apprehension about utilizing fishermen as citizen scientists on both the management and industry side. Managers are often hesitant to apply data collected from fishermen due to the potential of a conflict of interest (Bonney et al., 2021). Further, fishermen are often hesitant to collect and self-report data, due to the fear of unintentionally providing data that is used to impose stricter regulations (Ebel et al., 2018). Self-reported discard data is one of the most contentious as fishermen are generally concerned any reported discards will be held against them when setting possession limits and quotas (Bell et al., 2017). However, accurate discard estimations are critical for proper fishery management through informing stock assessments about those portions of the population removals (Punt et al., 2006; Aarts and Poos, 2009). Despite these hesitations, data from the Lobster and Jonah Crab Research Fleet was incorporated into the 2020 American Lobster Stock Assessment (Gawarkiewicz and Malek Mercer, 2019; ASMFC, 2020), and additional data will be utilized in the upcoming Jonah Crab Benchmark Stock Assessment (ASMFC 2021b). In addition, self-reported discard data from the NEFSC Cooperative Research Study Fleet was found to produce similar results when compared to fishery-dependent data collected by scientists, further suggesting that such data could be used to accurately characterize fishery discards and to inform management (Bell et al., 2017).

To collect critically needed black sea bass data from a wide variety of commercial fisheries in the southern New England and Mid-Atlantic Bight regions, a black sea bass Research Fleet (hereafter Research Fleet) was established in 2016 by the Commercial Fisheries Research Foundation (CFRF) and the Rhode Island Department of Environmental Management Division of Marine Fisheries (RIDEM). This Research Fleet aimed to adapt the Research Fleet model to a finfish species for the first time. Data collection by the Research Fleet was targeted to address the needs of management and uncertainty in the assessment to characterize the composition of black sea bass caught by various gear-types that interact with the species. The goal of this paper is distinctly different from the goals of the Research Fleet. The information presented herein is intended to provide an outline of the methods used to establish the Research Fleet as well as provide a vetted framework for implementing a similar citizen science strategy applicable to other climate change induced species management issues. This study will evaluate the effectiveness of the citizen-science based Research Fleet to answer the following questions: 1) Can the Research Fleet model be adapted for the multi-gear black sea bass fishery? 2) Can a fishermen-based citizen science Research Fleet consistently collect biological fishery-dependent data from their black sea bass catch and discards? And 3) Will the self-reported discard data collected by the Research Fleet program be useful for fisheries managers and assessment scientists and what must be done for the data to be incorporated into management decisions?

2 Materials and methods

The first step towards launching the Black Sea Bass Research Fleet and addressing the research questions noted above was the formation of a project steering committee. The project steering committee brought together a group of stakeholders from the fishing industry, management community, and fisheries scientists. The steering committee met numerous times to strategize the role of the Research Fleet and which data sources would be most valuable to the assessment and management process. Managers and fisheries scientists discussed specific data needs in the black sea bass stock assessment and industry members provided input on the feasibility of fishery-dependent data collection while at-sea. Collaboratively, the steering committee settled on what was believed to be the most logistically feasible and scientifically impactful data parameters to be collected by the Research Fleet; catch and discard characterization derived from disposition (retained for sale or discarded), individual total length, and visually identified sex collected in tandem with simple gear -specific effort metrics. At-sea sampling protocols to collect the chosen parameters were then developed alongside the steering committee to ensure the protocols would produce data of the quality envisioned by fisheries scientists and managers that fully utilized the time on the water of at-sea citizen science fishermen. The at-sea sampling protocols were designed to be minimally intrusive on the commercial fishing operations of participating vessels while addressing the data gaps in the stock assessment by collecting gear-specific discard characterizations.

The sampling protocols and associated data parameters can be divided into two components: individual black sea bass, and sampling sessions. It was decided that each individually sampled black sea bass would be measured for total length (cm), visually sexed (male, female, and unknown), and disposition status (retained and discarded) recorded. Alongside this biological data collected per individual black sea bass, catch and effort metrics, as well as basic environmental data, are recorded for each sampling session, which is defined as one discrete gear haul from a unique location in time and space. Due to the unique multi-gear nature of the black sea bass fishery, the Black Sea Bass Research Fleet required adaptation from the original Research Fleet model, as described by Mercer et al., 2018, to include vessels from multiple, rather than a singular, gear types. This required a broader definition of a sampling session relative to the original Research Fleet model and allowed for standardized effort data collection across multiple gear types. As a result, unique effort metrics were identified for each gear type that regularly interacts with black sea bass (Table 2). Data parameters for both individual fish and sampling session data were aligned with the Atlantic Coastal Cooperative Statistics Program (ACCSP), which serves as the federal data repository for fishery data on the east coast of the United States, to allow for streamlined transfer to state and federal managing agencies. To collect the chosen data parameters at-sea, the CFRF followed the original Research Fleet model and developed a tailored tablet application (On Deck Data) for data collection and an online database to allow for wireless data transmission (Mercer et al., 2018).

Prior to commencement of Research Fleet sampling, power analyses were performed to estimate the total number of sampling events and total number of black sea bass to target each sampling event each month to maximize the scientific power of collected data. Analysis was completed using data provided from the RIDEM state trawl and ventless fish pot surveys. The power analyses were run using R statistical software (ver.3.2.4). The function used was power.t.test from the stats package in R. The function was configured by using the calculated standard deviation from each data group, an effect size value (Δ) as defined in the data section above, a significance value (α) = 0.2, a power value = 0.8, and defining the analysis as a one sample test. The default method for the function is to run a two tailed test, so the default was used in these analyses. Based on results from the power analysis, the sampling protocols were modified to request that participants sample 50 discarded black sea bass from commercial catch from three unique sampling sessions per month for up to a total of 150 black sea bass sampled per month to reach the desired statistical power.

With defined at-sea sampling protocols, pre-determined sampling targets, and a data collection tablet application in development, the

TABLE 2 Effort metrics collected for each gear type in the Research Fleet.

Bottom Otter Trawl	Sink Gillnet	Comm. R&R	Charter	Lobster Pot	Fish Pot
Mesh size (in.)	# of panels per string	Time fishing (hours)	Time fishing (hours)	Soak time (days)	Soak time (days)
Tow time (hours.decimal)	Length of net panels (feet)	# of rods fished	# of rods fished	# of traps	# of traps
Sweep length (feet)	Mesh size (in.)	# of hooks used	# of hooks used	Escape vent size (in.)	Escape vent size (in.)
	Soak Time (days)			Escape vent shape	Entrance size (in.)
	Net Height (Feet)				
	Tie Downs (Inches)				

Users have the option to select "other" gear if none of the six above gears were used to catch black sea bass (such as oyster aquaculture gear and commercial whelk pots). Comm. R&R stands for Commercial Rod and Reel.

CFRF and RIDEM announced a public application period for interested Research Fleet participants. The application announcement was advertised among local Rhode Island industry through the CFRF and RIDEM email list-servs for fishing industry members, physical postings at local docks, and by word of mouth. The CFRF reviewed all applications and picked top choice candidates based on establishing a Research Fleet which covered the major fisheries interacting with black sea bass, as a target species or bycatch, in the southern New England and Mid-Atlantic Bight region and number of days fished per year.

All data is collected at-sea from commercial fishing trips by the participating Research Fleet vessel's captain and/or crew using On Deck Data. When gear is hauled from a unique location in time and space, and black sea bass is present in the catch, a sampling session is initiated by a fisherman in On Deck Data. Once the session has begun, the date, time, and latitude and longitude are automatically pulled from the tablet's internal clock and global positioning system. The area fished is described by the associated statistical area used in assessments (NOAA NEFSC, 2020), bottom water depth, and bottom habitat type classification (hard, soft, or structure). Next, the user selects a gear type and records the accompanying gear specific effort metrics (Table 2). If black sea bass are not the target species, then the target species is selected from a preset list or is typed in manually. After this data has been entered, users are brought to the biological sampling screen where Research Fleet members record data for individual black sea bass [total length (cm), visually identified sex (male, female, or unknown), and disposition (kept, discarded)]. After all black sea bass are sampled for the session, users finish the sampling session by entering catch data; members have the option to record the total number of black sea bass retained and the total number of black sea bass discarded for the gear haul or, alternatively, record the total estimated hail weight of the total black sea bass catch. Ideally, Research Fleet members repeat the sampling session steps described above three times per month, recording 50 black sea bass per session to hit the target of 150 black sea bass sampled monthly. While sampling within a sampling session, Research Fleet members first target sampling all black sea bass that will be discarded. Due to the catch rates of some gear types, catching 50 discarded black sea bass per sampling session (as described above) may not be a common occurrence. If there is an insufficient number of discarded black sea bass caught per sampling session, retained black sea bass may be randomly sampled as the fish comes on board during the sampling session until the target of 50 is reached. Further, and to encourage more regular sampling from the Research Fleet, the "other" gear type option was added to On Deck Data. Many of the fishing vessels operating within the Research Fleet fish multiple gear types throughout the year, all of which interact with black sea bass at some point during the year. Feedback from Research Fleet members indicated a desire to continue sampling for the Research Fleet when operating in gear types outside of what was included in On Deck Data. However, updating the application for every gear type desired was cost prohibitive and since the "other" gear types are utilized less frequently, the steering committee decided it was best to allow for Fleet Members to select "other" but not include any effort metrics as it would be difficult to collect in an easily quantifiable way. Instead, the CFRF just requests Fleet Members to include a note alongside submitted data which fishery the vessel was operating within when data is recorded with an "other" gear type.

All data collected by the Research Fleet is stored in the tablets until uploaded through wireless internet. Once uploaded, the data is removed from the tablet automatically to save space and is entered directly into a database operated by the CFRF. The CFRF routinely audits data for inconsistencies and errors. Research Fleet members are compensated through a monthly stipend system to cover time spent sampling; the total monthly sampling stipend amount is set by the CFRF after consultation with the project Steering Committee and the CFRF Board of Directors and is based exclusively off the number of black sea bass sampled in a month. Sampling requirements must be fulfilled to be eligible to receive a stipend each month; if sampling targets are not met within any given month; Research Fleet Members may be eligible for a reduced stipend if partial sampling was completed. For example, a full stipend will be paid out if more than half of the sampling target is sampled in a month, while a half stipend will be paid out if less than half (but more than zero) black sea bass are sampled. If no sampling was completed within a month, the Research Fleet Member is ineligible for a sampling stipend for that month. All sampling stipend decisions and payouts are verified against the number of black sea bass sampled with accompanying data submitted to the CFRF *via* the data collection application On Deck Data, for a stipend to be paid out the Fleet Member must first collect and submit the data to the CFRF. Beyond the time commitment required to sample during commercial fishing trips, Research Fleet members are also asked to attend annual Research Fleet meetings to discuss trends in the fishery over the past year and review all the collected data. The CFRF distributes data reports back to all Research Fleet members, alongside copies of the raw data individually collected, quarterly. All fishermen participating in the Research Fleet retain joint ownership of their own collected data with the CFRF and RIDEM.

The CFRF worked directly with lead data coordinators at the ACCSP to establish data submission protocols for Research Fleet collected data. Collected data was agreed to be submitted to the black sea bass biosamples database, which serves as the primary biological data repository for the black sea bass stock assessment. Data formats and parameters were agreed upon to allow for seamless incorporation in the existing black sea bass biosamples database. Data submission occurs biannually, with the first submission occurring in June 2017. Since the initial data submission, the CFRF has submitted data every six months with any newly collected black sea bass data. Specifically, the CFRF submits every individually measured black sea bass total length alongside visually determined sex, disposition, latitude and longitude of the gear haul, gear type, soak time, depth, and statistical area. After the methods to develop, support, and distribute data collected by the Research Fleet were established, protocols to track the implementation of the Research Fleet and monitor sampling were devised. Data requests for Research Fleet collected data submitted to the ACCSP may be made directly through the ACCSP (https://accsp.org). Requests must be made through the ACCSP data request form and reference the program ID "cfrfbsb."

All data was analyzed using R and R Studio (R, 2021). Sampling rates were calculated fleet wide for each of the five years of sampling. Sampling rates were calculated three ways; annual sampling rate, fished sampling rate, and interaction sampling rate. To calculate annual sampling rate, presence or absence was assigned for each month for each vessel in the Research Fleet if black sea bass samples were recorded or not. The total number of months with presence of samples each year divided by the total number of possible sampling months for the entire Fleet through the sampling year. For example, year-1 of sampling had eight active Research Fleet members potentially sampling from 12 months which would equal 96 total possible sampling months. To calculate fished sampling rate, each Research Fleet member provided the months which they actively fish each year. If the Fleet member did not fish year-round, the months where the Fleet member did not fish were removed from the total possible sampling months. In the above example, where year-1 had 96 total possible sampling months from eight Research Fleet members, the actual total possible sampling months would be reduced to 80 possible sampling months if half of the Research Fleet only fished eight months out of the year and the other half of the Fleet fished year-round. Finally, since black sea bass is a seasonal fishery for many of the Research Fleet members, Fleet members also provided the months in which black sea bass are encountered regularly as either a target species or as bycatch, this was used to calculate the interaction sampling rate. Every month where black sea bass was not expected to be caught as either a target species or as bycatch was removed from the total possible sampling months. For example, in the second example above for calculating the fished sampling rate in year-1, if the four vessels that fish year-round only expected to encounter black sea bass eight months out of the year and the four vessels that only fish eight months out of the year expect to interact with black sea bass every month fished, then the total possible sampling months would equal 64.

To further evaluate the consistency of data collection by the Research Fleet, preliminary exploration of the data was conducted. Discard ratios and size selectivity within the Research Fleet as well as between gear types were established. Gear-specific total length characteristics of black sea bass recorded by the Research Fleet were also investigated. Data was analyzed separately between discarded and commercially retained fish to further explain how discard characteristics vary between gear types. Finally, to evaluate the usefulness of Research Fleet collected data to assessment scientists and fishery managers, the acceptance of Research Fleet data into federal data repositories and data requests submitted and fulfilled were evaluated.

TABLE 3 All Black Sea Bass Research Fleet members, the gear types sampled, and the dates active in the Research Fleet.

Gear Type(s) Sampled	Dates Active (MM/YY)
Commercial Rod and Reel, Fish Pots, Lobster Traps	05/17 – 08/21*
Charter, Commercial Rod and Reel	07/17 – 12/21*
Commercial Rod and Reel, Fish Pots, Gillnet, Lobster Traps	12/16 – 06/20
Trawl	12/16 – 12/18
Trawl	11/16 – 06/17
Conch Pots, Fish Pots, Lobster Traps, Trawl	05/17 – 01/22*
Gillnet, Fish Pots, Lobster Traps	07/17 – 10/20
Charter, Commercial Rod and Reel, Oyster Aquaculture, Lobster Traps, Trawl,	12/16 – 12/21*
Lobster Traps	02/18 – 05/20
Trawl	03/19 – 05/22*
Fish Pots, Other	07/19 – 09/21*
Commercial Rod and Reel, Gillnet, Fish Pots	06/17 – 07/21*
Gillnet, Fish Pots, Lobster Traps	10/19 – 11/20
Lobster Traps	12/19 – 12/21*
Trawl	12/19 – 04/21*
Lobster Traps	05/21 – 04/22*
Fish Pots	05/21 – 05/22*
Fish Pots	04/21 – 08/21*
Fish Pots	06/21 – 05/22*
Fish Pots	05/21 – 05/22*

Dates are updated through May 2022. Asterisks (*) denote Research Fleet members that are considered active as of this date. Each line represents a single participant.

3 Results

The Research Fleet was officially launched in December 2016 with a project kickoff meeting for all new Black Sea Bass Research Fleet members. The newly formed Research Fleet included eight fishing vessel captains and/or owners representing 10 different vessels from six unique gear types. Two of the new members were the owners and operators of two vessels. Over the course of multiple years of operation, the Research Fleet has since grown to up to 20 total members representing eight gear types (Table 3). Vessels are considered inactive if the captain retires from fishing, the vessel is out of the water for an extended period for repairs, or no data is collected over a 12-month span. Inactive vessels may still retain their spot in the Research Fleet if desired. The Research Fleet has advertised open positions to the industry on three separate occasions over the past five years of operation. Every application announcement garners substantial interest from the industry with an excess of applications being received from each announcement. Nineteen vessels have had to be turned down from joining the Research Fleet due to lack of funding.

The Research Fleet has individually sampled 40,939 black sea bass over a five-year span from December 1, 2016 through December 31, 2021 with most of the sampling occurring between the months of May and November annually (Figure 1). The individual black sea bass were sampled through 2,288 distinct sampling sessions. Over the span of the five years of data collection, this represents a mean sampling rate of 49%. Sampling rates, cumulative and adjusted for months fished and months interacted with black sea bass displayed above in Table 4. The sampling rate by the Research Fleet was substantially higher (61% mean sampling rate) when analyzed by the months in which black sea bass is interacted with as bycatch or target species.

Overall, the Research Fleet interacts with the entire size range of black sea bass with total length records as small as 1 cm to as large as 63 cm (Figure 2). The mean total length recorded by the Research Fleet (31.5 cm) is well above the 11-inch (27.94 cm) Rhode Island commercial minimum size. Of the 40,939 total recorded black sea bass, 29,199 fish, or 71%, were discarded with the remaining 11,740 fish, or 29%, retained for commercial sale. Black sea bass are discarded

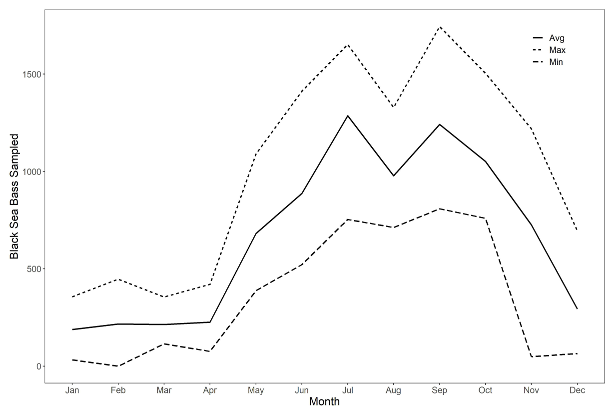

FIGURE 1
Minimum, maximum, and average number of black sea bass sampled per month by the Research Fleet across all years of sampling.

throughout the entire recorded size range by the Research Fleet (Figure 3). Discarding legal, including even the largest black sea bass with the highest ex-vessel price, is a common occurrence within the Research Fleet with 12,132 fish, or 42%, of all discarded black sea bass being above the Rhode Island minimum legal commercial size.

All gear types except, oyster aquaculture, discarded and retained black sea bass whereas all black sea bass caught in oyster aquaculture gear were discarded. Fish pot, lobster trap, rod and reel, and trawl all retained black sea bass from a similarly large range of total lengths with black sea bass total lengths ranging in size from just over the commercial minimum at 28cm to as large as 62cm (Figure 4). Gillnet gear retained black sea bass only from the largest of size classes with all retained black sea bass falling within a range of 38cm to 58cm total length. Conch pot retained a similarly small range of black sea bass as gillnet however it was on the other end of the size range and only included black sea bass just over the commercial minimum size ranging from 30cm to 48cm total length (Figure 4). Of the discarded black sea bass, fish pot, lobster trap, rod and reel, and trawl discarded a wide range of sizes. Oyster aquaculture and conch only discarded the smaller size ranges of black sea bass whereas gillnet was still on the other end of the spectrum, discarding only the largest of individuals of all gear types.

To date, all the data collected by the Research Fleet has been incorporated into the ACCSP biosamples database on the agreed upon biannual timeframe, and the commercial length and disposition data will be utilized in the upcoming black sea bass stock assessment. Beyond the direct submission and acceptance of Research Fleet collected data into the ACCSP biosamples database, the Research Fleet has also served as a valuable source of data for other regional efforts to manage and study the species. Predominately, the Research Fleet data has been used directly by RIDEM, including using the data to investigate the seasonal presence of larger black sea bass in inshore state water with potential management implications for altering the seasonal start of the fishery, as well as a length frequency supplement to the Rhode Island state trawl survey. Further, The Nature Conservancy has used Research Fleet data to cross-validate electronic monitoring collected data on vessels which participate in both the Research Fleet and an electronic monitoring project. The Research Fleet has provided a platform for the collection of black sea bass samples for laboratory work for multiple organizations. For example, the Massachusetts Division of Marine Fisheries used otoliths collected by the Research Fleet sample collection program in a published study that validated aging methods for black sea bass across regions (Koob et al., 2021). Northeastern University also utilized the Research Fleet to assist in whole specimen and tissue sample collections from southern New England for genetic work to compare origin of black sea bass in mid-coast Maine to northern Massachusetts and southern New England. In addition, the Research Fleet has provided over 2,400 otoliths to the largest black sea bass otolith aging database run by the Virginia Institute of Marine Science. Finally, the Research Fleet has also collected live black sea bass to support various graduate level projects at the University of Rhode Island to investigate ex-situ predation of Jonah crab and lobster by juvenile black sea bass as well as stable isotope ratios and trophic overlap with cod.

4 Discussion

Overall, the adaptation of the Research Fleet model to collect critically important catch and discard data from the rapidly expanding, multi-gear black sea bass fishery has been a success, and this approach can be applied to help fill in data gaps for other commercially important species that have been traditionally under sampled and/or species that are undergoing range shifts or expansions. The ability to consistently collect black sea bass catch and discard data from a citizen science Research Fleet model is proven by the fact that the Research Fleet has been able to measure and record data from over 40,000 individual black sea bass in the span of five years. The initial hesitation from industry members to self-report discard data was calmed through the collaborative nature of the Research Fleet. Close communication with stock assessments

TABLE 4 Sampling rates and adjusted sampling rates from the Black Sea Bass Research Fleet over the four years of data collection.

Year	Annual Sampling Rate	Fished Sampling Rate	Interaction Sampling Rate
2017	56%	62%	72%
2018	48%	53%	59%
2019	51%	55%	60%
2020	40%	45%	52%

Sampling rates displayed are the cumulative average of all vessels active through each year. Fished sampling rate represents are calculated based on the total number of months fished each year provided by each Research Fleet participants whereas Interaction Sampling Rate is the provided total number of months each Research Fleet participant interacts with black sea bass as catch or discards during their months fished.

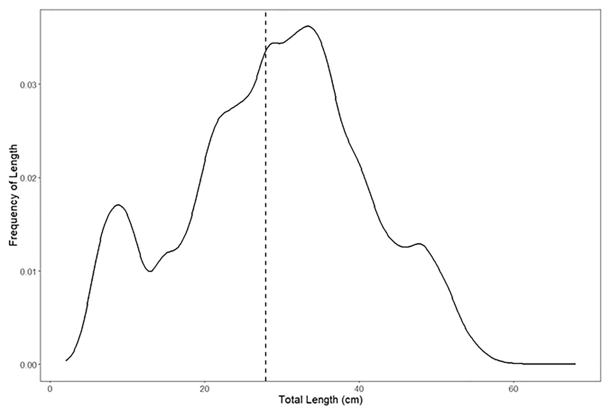

FIGURE 2
Frequency plot of black sea bass total length (cm) records (n=40,939). Dashed line indicates the Rhode Island minimum size of 11 inches (27.94 cm).

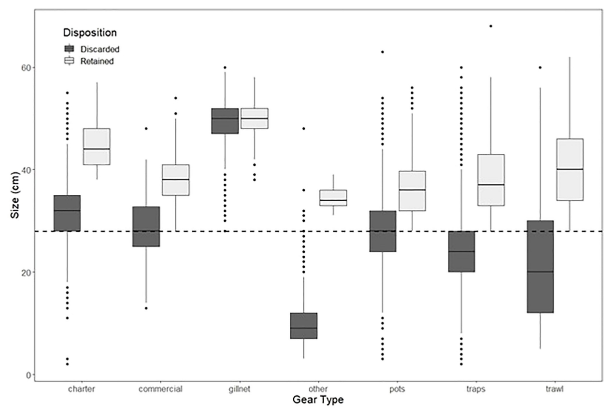

FIGURE 4
Median total length of black sea bass recorded by the Research Fleet in each gear type; dark boxes represent discarded black sea bass and light boxes represent retained black sea bass. Black dashed line indicates the Rhode Island minimum size of 11 inches (27.94 cm). Other includes oyster aquaculture and conch pots. Charter refers to for-hire recreational vessels, commercial indicates commercial rod and reel, gillnet is exclusively sink gillnet (large and small mesh), pots refer to fish pots, traps cover the mixed lobster and crab pot fishery, and trawl is exclusively bottom otter trawl gear.

scientists at RIDEM and federal agencies allowed industry members participating in the Research Fleet to fully appreciate and support the utility of the data collected and allowed for a first-hand perspective of how the data might allow for better management of the species. From the beginning, the CFRF and RIDEM were able to communicate to industry partners a shared project goal of more successful management of the black sea bass fishery. This is evidenced by the interest the Research Fleet has garnered by the local industry. Every open application period has received more applications than open slots and a wait-list of interested industry vessels is maintained for when new slots in the Research Fleet are available.

The success of the Research Fleet was accomplished by maintaining a close working relationship with the Research Fleet members and scientific community and being responsive to suggestions from both parties. The close working relationship serves as an opportunity to build trust amongst all stakeholders and is a significant motivator to encourage industry participation in citizen science (Ebel et al., 2018). Due to the multi-gear nature of the black sea bass fishery, it was

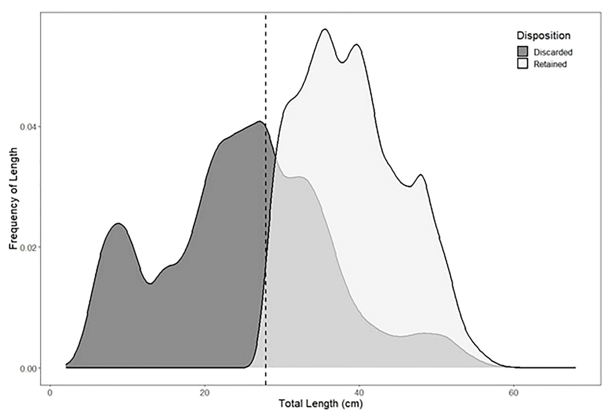

FIGURE 3
Frequency plot of black sea bass total length (cm) records (n=40,939) shaded by disposition status; dark shaded area represents discarded black sea bass while the light shaded area represents retained black sea bass. Black dashed line indicates the Rhode Island minimum size of 11 inches (27.94 cm).

critically important for the data collected to be applicable to each gear type but also useful to management and science. To accomplish this, the CFRF worked closely with commercial fishermen on the project steering committee and on the CFRF Board of Directors to develop data parameters which made sense to collect from each gear type. Further, the CFRF worked with fishery managers on the steering committee to plan the biological fields to collect from individual fish as well as protocols for which black sea bass should be sampled. Direct input from the steering committee members is what determined the various data fields collected to describe the sampling session, effort, and black sea bass catch.

During Research Fleet operation, it became apparent that the On Deck Data application must be a dynamic product that can be updated to accommodate feedback from the Research Fleet participants. Close contact with Research Fleet members creates a constant stream of feedback on performance of the sampling application and tablet and allow for the Research Fleet sampling to become ever more efficient while preserving the consistency and quality of the data being recorded. For example, due to comments received after the first year of data collection about how frequently large numbers of similarly sized black sea bass were caught, On Deck Data was updated to include a "quantity" field that allows users to efficiently record multiple black sea bass of the same total length, sex, and disposition status at once. The intention of incorporating Fleet Member feedback into the sampling process and On Deck Data was primarily to streamline sampling, however it also had an arguably more important impact on the overall success of the Research Fleet; increasing stakeholder buy-in through the integration of their knowledge directly into the protocols of the project. Willingness to listen to feedback and incorporate it into the design of the project can go a long way to building trust among stakeholders (Hartley and Robertson, 2009), it signals that participation within the Research Fleet has a positive impact over time and shows a respect for one another's opinions.

One major component contributing to the success of the Research Fleet was encouraging equitable participation among gear types. The original Research Fleet model was first developed for directed lobster and crab fisheries. However, with the goal of the Research Fleet being the characterization of discards from various commercial gear types, the threshold for participating in the Research Fleet and receiving a sampling stipend needed to be adjusted. Due to differing catch rates between gear types, sampling requirements to receive the stipend were relaxed to allow for more equitable participation. For example, commercial rod and reel/charter are highly mobile throughout the day and will often cover many unique locations throughout a single day of fishing and likewise will catch significantly less black sea bass per location compared to other gear types such as trawl. As a result, this prohibits some vessels from sampling 50 black sea bass per session due to the gear type and fishery the vessel operates within. To address this issue, the requirement to qualify for the monthly sampling stipend was changed to only consider total number of black sea bass sampled per month.

As each year of data collection passed the Research Fleet persisted with success, however the consistent collection of catch and discard data presented some unique challenges. Maintaining a high sampling rate was a difficult task. First, the black sea bass fishery is highly seasonal. In addition, unlike the original Lobster and Jonah Crab Research Fleet, the Black Sea Bass Research Fleet includes data collection from several gear types which, despite catching and landing black sea bass, are not primarily targeting the species during much of their fishing effort. Expanding on this issue, in some cases vessels are actively trying to avoid catching black sea bass because the vessel's daily quota may already be filled, the season may be closed, or it would impact the vessel's catch of primary target species. This resulted in a large amount of uncertainty in the anticipated sampling rates; as a result, sampling rates were lower than anticipated, however this created opportunity to regularly add new Research Fleet members and increase the number of gear-type replicates in the Research Fleet. The lesson learned from the highly variable sampling rates from year to year and between different gear types was a common one; to manage expectations. The expectation of a 100% sampling rate by the Research Fleet is not an attainable goal considering the rate at which various gear types operate within a fishery. Further, being receptive to the fact that participant Fleet Members' primary responsibility while on the water is the operation of their business; the goal of Research Fleet sampling design should be to fit smoothly within that normal operation.

The seasonality of the fishery is evidenced by the Research Fleet's variable average samples collected throughout the year (Figure 1). For example, the Research Fleet regularly exhibits large pulses in data collection in the summer and fall due to the increased presence of black sea bass inshore during these months, as well as the active status of seasonal fishing vessels, such as those using fish pot gear. Interestingly, the dip in average black sea bass sampled in August (Figure 1), when black sea bass are in greatest abundance inshore, is likely a result of seasonal closures. Many of the vessels in the Research Fleet are homeported in the state of Rhode Island which typically closes the commercial fishery for black sea bass in August. This results in several vessels reducing their fishing effort in the month of August. Closure of the fishery in August impacts fish pot vessel sampling activity more so than other gear types as black sea bass is one of their primary target species whereas most other gear types commonly have other species as the primary target. Sampling rates are then punctuated by dips in data collection through the winter and spring, as this is when black sea bass migrate further offshore and seasonal vessels conclude their fishing seasons (Moser and Shepherd, 2009) so we witness a smaller pool of Research Fleet vessels interacting with a smaller pool of black sea bass depending on gear type and area fished. This period of the year is dominated by samples from gear types such as trawl gear, of which the Research Fleet has fewer replicates compared to gear types such as fish pots and lobster/crab traps; this was an intentional decision as steering committee members identified the "non-trawl" fishery to have the largest need for additional data sources.

The self-reported data collected by the Research Fleet has proven to be useful to fisheries managers and scientists. This is evidenced by the fact that Research Fleet data has been accepted, and continues to be accepted, into the black sea bass biosamples database at the ACCSP and will be used in the upcoming stock assessment. Research Fleet collected data is now housed alongside traditional state and federal trawl survey data used in the stock assessment process making it available for use. For any new data source, such as the Research Fleet collected data, to be used within the stock assessment it must be verified against existing fishery independent or dependent data sources. That exact work is currently being done (Verkamp personal communication) for the Research Fleet as part of the 2022 black sea bass research track stock assessment. Research Fleet collected length and disposition data will be compared against data collected from the Northeast Fisheries Observer Program from vessels of comparable gear types. The process to assess the reliability of Research Fleet collected data is not new and will follow a similar set of principles laid out by Roman et al., 2009 which compared a similar, federally funded, industry collected data source; the Study Fleet, to Northeastern Fishery Observer Program data and seafood dealer data reported to the National Marine Fisheries Service. Beyond that, the inquiries and data requests received from The Nature Conservancy and RIDEM Division of Marine Fisheries have shown that the self-reported discard data can be used in other avenues outside of direct application to the stock assessment. The operation and stability of the Research Fleet over the past five years has allowed other regional researchers access to biological samples which may have been too costly to obtain without a direct connection to the industry.

The strength of the Research Fleet is the ability to leverage the time on the water of commercial fishermen to rapidly collect large amounts of data throughout the year over a large spatial scale. Traditional state and federally operated surveys will always serve a vital role in assessing and managing fisheries, however there are limitations to those data sources. For example, in the context of black sea bass, due to the species' association with structured habitats, black sea bass are poorly sampled by standard trawl surveys (Waltz et al., 1979; Steimle et al., 1999; Drohan et al., 2007; DeCelles et al., 2013). In addition, the limited coverage of black sea bass habitat and semi-seasonal (spring/fall) sampling schedule of the NEFSC trawl survey limit the suitability of this data for the stock assessment (ASMFC 2013). Mobilizing a citizen science-based Research Fleet can help fill data gaps that arise from traditional surveys, such as discard characterizations provided by the Black Sea Bass Research Fleet that can help reduce uncertainty in assessment results. A similar approach could be applied to other species in need of additional data sources for assessment and management, and this approach could be especially helpful for fisheries/species that are expanding at a rapid rate that outpaces the rate at which traditional state and federal surveys can adjust to compensate for such changes.

Further, through active participation and collaboration in the data collection process, the Research Fleet helps build trust between the fishing and management communities. Finally, the Research Fleet has provided resiliency to our fisheries management network. Throughout the year of 2020, numerous state and federal fisheries independent sampling surveys were postponed or had seasonal survey windows cancelled as a result of the COVID-19 pandemic. Although the pandemic certainly resulted in decreased fishing effort, the sampling rate remained consistent within the Research Fleet. Maintaining a consistent flow of fishery-dependent data, which can be quickly tailored and targeted for specific data gaps that arise from unforeseen circumstances can improve the fisheries management process and help build more resilient fisheries coastwide.

The development and implementation of the Research Fleet followed a similar set of principles for citizen science as described by Bonney et al. (2009). The first three steps; forming a scientific question, establishing a project team, and developing/refining data collection protocols were conducted early on in this Research Fleet project through the formation of a project steering committee of industry members, scientists, and managers. The project steering committee developed the scientific question; are there differences in the black sea bass discard characteristics between commercial gear types? Afterwards, the project steering committee assisted in the development of sampling protocols for the Research Fleet. Once the general outline of the Research Fleet duties was established, participants were recruited and trained through a public call for applicants and review by the project steering committee. The CFRF staff then trained selected citizen scientists in the sampling protocols and the Research Fleet was launched. The final steps outlined by Bonney et al. (2009) have been an ongoing task throughout the project; accept and edit data, analyze data, disseminate results, and measure outcomes. These steps have been completed through consistent fishery-dependent data collection by the Research Fleet, data management by the CFRF, submission of data biannually to the ACCSP, quarterly reports and communication delivered to Research Fleet participants, and presentation of project findings at conferences and meetings.

Overall, CFRF and RIDEM were able to adapt the Research Fleet model for the multi-gear black sea bass fishery to consistently collect fishery-dependent data on black sea bass catch and discards by following the steps of successful citizen science. The citizen scientists participating in the Research Fleet were able to consistently collect fishery-dependent biological data from their black sea bass catch and discards for over five years and counting. Finally, the data collected by the Research Fleet has already proven to be useful to outside fisheries scientists and will be incorporated into the black sea bass stock assessment after verification against other fishery dependent data sources currently in use (Verkamp personal communication). This latest adaptation of the Research Fleet concept highlights the willingness of fishers to participate in science when given the opportunity to contribute in a meaningful way, and the data collected by the Research Fleet represents a significant contribution to black sea bass data sources available for stock assessment and to inform management. This collaborative effort was a success due to the reliance on stakeholder input throughout the project as well as the commitment to the transparency of data collection and use among fishing industry, management, and scientific stakeholders. The incorporation of modern technology to capitalize on fishermen's time at-sea during commercial fishing trips, streamlined to make data collection as efficient and minimally intrusive as possible, allowed the Black Sea Bass Research Fleet to provide high quality, self-reported data throughout the first five years of sampling. Continued sampling by the Research Fleet will continue to increase the impact of this collaborative initiative.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

TH and JM contributed to the original design of the Research Fleet and HV and NB have expanded on and supported the Research Fleet after its inception. TH is the primary author and HV provided significant input and edits on the manuscript while JM and NB also reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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EDITED BY
Cornelia E. Nauen,
Mundus Maris, Belgium

REVIEWED BY
Steven Holmes,
National Institute of Water and Atmospheric Research (NIWA), New Zealand
Audric Vigier,
UK Centre for Ecology and Hydrology (UKCEH), United Kingdom
Georg H. Engelhard,
Centre for Environment, Fisheries and Aquaculture Science (CEFAS), United Kingdom

*CORRESPONDENCE
Steven Mackinson
steve.mackinson@scottishpelagic.co.uk

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The road to incorporating Scottish pelagic industry data in science for stock assessments

Steven Mackinson[1*], Katie Brigden[2], Jessica Craig[3], Elizabeth D. Clarke[3], Chevonne Angus[2] and Campbell C. Pert[3]

[1]Scottish Pelagic Fishermen's Association (SPFA), Fraserburgh, United Kingdom, [2]Shetland UHI (SUHI), Academic Partner of the University of the Highlands and Islands (UHI), Shetland, United Kingdom, [3]Marine Scotland Science (MSS), Aberdeen, United Kingdom

Fisheries data collection through industry-science partnerships have significant potential to support stock assessments and sustainable management, but few studies have described the steps taken *en route* to a successful partnership. This paper describes the development of the Scottish Pelagic Industry-Science Data Collection Programme; why and how it started, and what it has taken to develop a routine and consistent voluntary sampling regime of sufficient quality to become the main source of biological data on pelagic fish catches in Scotland. Using our experience, we emphasise the importance of establishing procedures that ensure the quality of methods and results, of working with institutions responsible for provision of national data, and of actively engaging with the International Council for the Exploration of the Sea (ICES) workshops and working groups on data quality, stock assessment and stakeholder engagement. The development of the programme has been, and remains to be, a mutual learning process which is reflected upon from our different institutional perspectives. The experience gained during this work has built knowledge useful for practitioners in other situations. Specifically, we identify five transferable design principles that we believe have been essential to success so far. Finally, we look at the steps ahead in our efforts toward continuous improvements.

KEYWORDS

collaborative research, stakeholder engagement, participatory research, fisheries science, data collection, co-creation, science-industry research collaboration, pelagic fisheries

1 Introduction

Strengthening the involvement of the fishing industry in the provision of data and experiential knowledge to support fisheries management is vogue (Stephenson et al., 2016; ICES, 2019; Steins et al., 2020; Holm et al., 2020; De Boois et al., 2021; Garmendia et al., 2021; Hart, 2021, Mangi et al., 2018; Steins et al., 2022). While the topic is far from new (Johannes, 1981; Neis, 1992; Neis et al., 1999; Neis and Felt, 2000; Haggan et al., 2007; Hind, 2015), recent proliferation in applications and debates is fuelled by new demands for information to service the ecosystem approach, as well as professionalisation of the industry and moves toward more inclusive governance approaches in science and management.

In Europe, there has been a subtle, but important, shift in the language of Europe's Maritime Fisheries and Aquaculture Fund, where recent revisions opt for knowledge-based, rather than evidence-based, science and management (EU, 2021[1]). It is here where advocates for systematic inclusion of experiential knowledge and data provided voluntarily by the fishing industry (e.g. Mackinson, 2022a; Steins et al., 2022) find a natural home supportive of strengthening Science-Industry Research Collaboration (SIRC, *sensu* Steins et al., 2020). But the subject of how to operationalise a more knowledge-based approach frequently exposes concerns around the themes of legitimacy and credibility; including how potential conflicts-of-interest may influence the integrity of scientific and management processes and the quality of scientific information itself (e.g. Dickey-Collas and Ballesteros, 2019; Steins et al., 2022; Ballesteros and Dickey-Collas, 2023).

The work described here has been propelled by a growing momentum for strengthening stakeholder participation in science and management in the UK (Defra, 2011; Scottish Government, 2020; Seafood 2040, 2021), and internationally (Dörner et al., 2015; Thompson et al., 2019; Holm et al., 2020; Steins et al., 2022), with doors now more frequently open to collaborative science-industry initiatives. In particular, the Scottish Government Future of Fisheries Management Strategy 2020 - 2030 (Scottish Government, 2020) states:

> "Our overarching aim is to focus on collaboration and cooperation, not conflict and controversy….
> One of the ways we can do this is by increasing our openness and transparency around data, improving our evidence base and taking account of the range of knowledge that exists, in particular valuing the knowledge of fishers and others who work at sea, and using this to help."

This approach echoes the ambitions expressed across the UK in the recent Joint Fisheries Statement (Defra, 2022), which describes a vision for Participatory Decision Making:

> Section 3.4.1. "Our future vision is that industry should take a greater, shared responsibility for sustainably managing fisheries, while making a greater contribution towards the costs. This can include, for example, work to develop new management practices and contributing to fisheries science, being more actively engaged in fisheries management decisions, and co-designing future policy".
> And section 4.1.12, "A move to a more collaborative approach to fisheries management, as noted in section 3 above, will enable the fishing sector to contribute its information on activities and impacts to help co-design management actions. In taking such an approach, the fisheries policy authorities and fishing industry can work collectively to contribute to the delivery of the fisheries objectives."

For some scientists, eNGOs and managers, efforts to enhance industry's responsibility for science evidence provision are seen as an integral stepping-stone in the evolution of co-management initiatives because they build skills and capacity relevant to specific management needs (FitF, 2022a; Martin, 2022). However, UK government policies toward co-management (Defra, 2011; Scottish Government, 2020; Defra, 2022) will have a bearing on the appetite for, and speed of progress, in these developments.

The pelagic industry's motivation for a deeper and more systematic engagement with science stems from several related concerns and perspectives on the use of scientific information. The most pressing of these is the prospect of precautionary management[2] being applied when information on stocks is considered poor or insufficient to achieve a good quality stock assessment. For instance, the western herring stock (International Council for the Exploration of the Sea (ICES) divisions 6.a and 7.b-c) is a good example where, until recently, lack of information on stock identity meant ICES' precautionary approach was applied, resulting in a zero catch advice. Highly uncertain assessments, resulting from, for example, limitations in data availability or knowledge of stock structure, are intuitively associated with poor quality scientific advice, and not trusted. Quality and reliability of stock assessments also becomes a concern for industry when changes in scientific advice do not appear to match perceptions of changes observed at sea (e.g. Fishing News, 2021). Both of these situations lead to questions about the availability and quality of data, and how they are used to assess stock status. To help avoid limitations in data and make continuous quality improvements, the pelagic industry is supportive of maximising the use of all available data, whether collected by scientific institutes or by themselves (SPFA, 2019). As regular observers of changes at sea, fishers believe that their observations can serve as early warning indicators of change that could aid in the planning of scientific surveys and offer prior knowledge for stock forecasts that depend upon assumptions about current state.

Other, non-scientific, factors related to the business of pelagic fishing also play a role in motivating industry engagement with

1 The term knowledge-based is used in:-**Recital 25** "The European Maritime Fisheries and Aquaculture Fund should support an effective knowledge-based implementation and governance of the Common Fisheries Policy under direct and indirect management through the provision of scientific advice, regional cooperation on conservation measures, the development and implementation of a Union fisheries control system, the functioning of Advisory Councils and voluntary contributions to international organisations.-**Article 14**. Specific Objectives: (d) Fostering efficient fisheries control and enforcement, including fighting against Illegal Unreported and Unregulated fishing, as well as reliable data for knowledge-based decision-making.

2 A precautionary approach: as information becomes increasingly limited, more conservative reference points should be used and a further margin of precaution should be adopted when there is limited knowledge of the stock status.

science. Since the UK became an independent Coastal State in 2020, zonal attachment (the principle allocating quota according to the share of the stock residing within a particular country's economic zone) has become an important feature in negotiations regarding fishing access agreements in the Northeast Atlantic. Therefore, the need to be able to provide high quality evidence on stock structure and distribution is of immediate concern to fishers to help secure an equitable division of fishing quota (e.g. Gatt, 2019). Reputational issues are also an important driver for industry, including the understanding that involvement in scientific data collection is an outward demonstration of their sustainability credentials and support for responsible stewardship of pelagic fisheries.

Our contribution to the rapidly evolving topic of science industry research collaboration focusses on the development of the Scottish Pelagic Industry-Science Data Collection Programme, initiated by the Scottish pelagic industry. The principal driver for this was, and remains to be, industry's motivation to contribute to improvements in the quality and reliability of information used to support scientific advice on pelagic stocks in the Northeast Atlantic. Thus, the main purpose of the programme has been to enable fishers to be active contributors to a process of continuous improvement in the data and evidence that is used by ICES to assess and advise on the state of pelagic fish stocks. It relies on the voluntary participation of the Scottish pelagic trawler fleet; large (~75m), state-of-the-art vessels which mainly target herring, mackerel, and blue whiting, and comprises two parts. The first part, the *self-sampling scheme*, piloted from 2018-2021, requires vessel crews to sample fish from every haul of every trip. Fish length and weight data are collected as the fish are pumped onboard, and haul information is recorded to connect the biological sample data to the location and date/time of the catch, and other operational and environmental parameters. The second part, the *co-sampling scheme*, piloted in 2020, requires samples of fish to be frozen and brought ashore for biological sampling by scientists at the laboratories of Marine Scotland Science (MSS) and Shetland-University of Highlands and Islands (SUHI). This paper largely focusses on the details and development of the self-sampling scheme.

While our example is specific to the Scottish pelagic fishing industry, which operates within internationally managed fisheries, it is a case study where practitioners in other worldwide fisheries can recognise many transferable processes and areas of good practice. Our aim is to use this example to communicate the practical and social dimensions of an industry-science initiative, with the intention to facilitate better understanding of many of the 'why and how to' aspects that are less well documented and remain somewhat 'mysterious' for collaborating partners across different science and industry sectors. In particular, we cover why and how it started, what it has taken to develop a routine and consistent voluntary sampling regime that provides quality data, and what is required to bring the data to the attention of potential end users. To identify critical processes and transferrable lessons that could help expedite other initiatives, we describe how the quality and results have evolved through a mutual learning process, and reflect on our different institutional perspectives on what so far have been the most challenging obstacles, and the routes to overcoming them. Finally, we look at the steps ahead in our efforts toward continuous improvements.

The development of this sampling programme was, and continues to be, an iterative process. To provide clarity on the path taken to transition from the idea of an industry-science collaboration to its physical implementation, the descriptions of methods and results include statements on the background and motivation behind decisions.

2 Methods

2.1 Inception

The work began in July 2016, when the Scottish Pelagic Fishermen's Association[3] (SPFA) appointed Dr. Steven Mackinson as its Chief Scientific Officer, with responsibilities for developing and implementing a long-term strategy for professionalising its contributions to science (see Figure 1 for programme development timeline from inception through to current status). The overall theme however, was conceived long before, with the SPFA (like other industry sectors in the UK) being actively engaged in following the process of fish stock assessments and advice from ICES, and regularly accommodating scientists in their work, either onboard or onshore since the 1970s. As early as 2004, the SPFA was pro-active in discussions about how to improve engagement of the fishing industry in science, particularly in relation to the incorporation of additional information from the fishing industry into stock assessments and research (ICES, 2004; ICES, 2007; ICES, 2008).

In 2016, discussions with pelagic industry members during an SPFA board meeting highlighted industry concerns and perspectives on the use of scientific information described above, catalysing development of a data collection strategy (SPFA, 2019). This includes a science plan (Figure 2) which has pelagic fishermen at its heart, with two key strands: a science engagement policy, with key elements of contributing to science, upholding scientific standards, collaboration with government and academic scientists, and raising awareness; and a data collection strategy, underpinned by data collection onboard vessels and in factories. This planning document led to the decision to develop a pelagic self-sampling scheme, aligned with the SPFA data collection strategy. Then followed two years of preparation and design (Mackinson et al., 2018) leading to a proposal to trial the scheme.

The foundations of the programme are based upon an understanding of the opportunities in which industry data can make a worthwhile contribution to information used in fisheries science and advice. Supplemental Table S1 identifies a broad suit of scientific applications where industry data collection programmes may have the potential to add value to improving data and knowledge on fish stocks and their fisheries, which while speculative, provides a basis for further consideration and discussion.

3 The Scottish Pelagic Fishermen's Association (SPFA) is a member association comprised of 20 (out of 21) owner/operators of Scottish pelagic vessels and 2 from Northern Ireland.

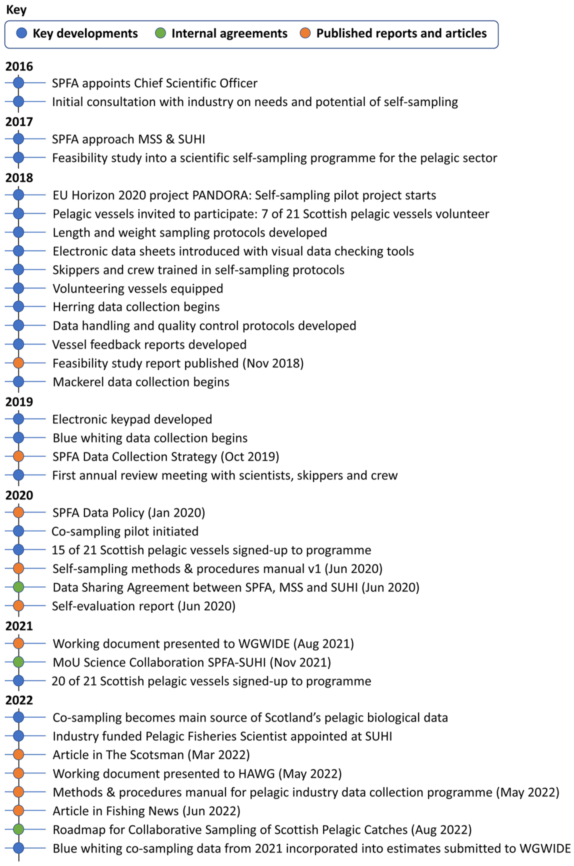

FIGURE 1
Timeline of events and milestone documents during development of the Scottish Pelagic Industry-science Data Collection Programme.

2.2 Collaborative approach

The programme has been developed by the Scottish Pelagic Fishermen's Association (SPFA – an association for the pelagic fishing fleet), Shetland UHI (SUHI - an academic partner of the University of Highlands and Islands (UHI)) and Marine Scotland Science (MSS - a division of the Scottish Government), with additional industry support from the Scottish Fishermen's Federation (SFF – an organisation that works for the collective interests of Scotland's fishermen's associations). From the very beginning, the approach has been to work in partnership with relevant national and international scientific and policy institutions, so that data provided by industry will be relevant, credible and trusted by the institutions that will use it.

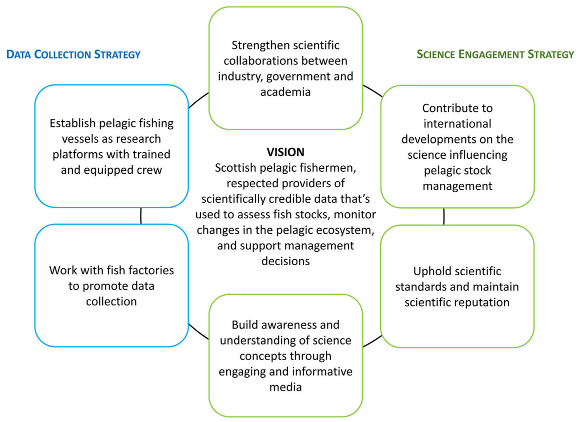

FIGURE 2
SPFA Science Plan (revised and updated from SPFA, 2019). The vision is enacted through the Data Collection Strategy and Science Engagement Strategy, which have defined objectives under which specific work activities occur.

Establishment of the pilot programme was made possible through the EU Horizon 2020 project PANDORA (pandora-fisheries-project.eu), which provided funding for dedicated staff time at SPFA, SUHI and MSS, as well as a commitment to report on the programme development.

Within the collaboration, each partner has specific roles that play to their strengths. The SPFA represents the Scottish pelagic vessels, with promotion and operationalisation of participation led by its Chief Scientific Officer. SUHI staff have worked closely with the SPFA throughout, providing the role of Sampling Coordinator and Data Manager, delivering training and ongoing regular communication with vessels. Over time, SUHI have developed a leading role in the day-to-day delivery of the programme. MSS works with the SPFA and SUHI to design sampling methods and protocols, and evaluate quality to ensure that the data collected meet required standards. Initially MSS' role was intended to be

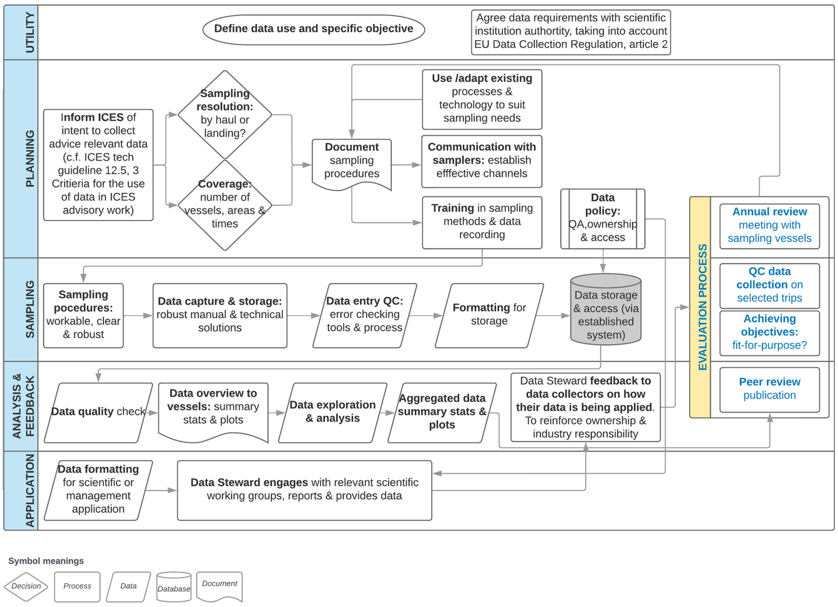

FIGURE 3
Generalized process plan for the Scottish Pelagic Industry-Science Data Collection Programme (revised from SPFA, 2019), indicating the components required to implement the self-sampling programme, moving through the stages of definition of utility, planning, sampling, analysis and feedback, through to application.

mostly advisory but, as the programme has developed, the role has evolved to full collaboration, focussed mainly on the co-sampling scheme and the requirements for provision of data to ICES. Laboratory sampling is undertaken by both SUHI and MSS. SFF provides logistical support to the sampling programme and contributes to the strategic work that seeks to see how lessons from the pelagic sampling might be translated to other sectors.

2.3 Practical implementation

The objective to provide data that can be used in fishery stock assessments to improve the quality of scientific advice has driven the design of each component of the programme. A generalized process plan for implementation was drawn up at the start of the process (Figure 3). The plan starts with the need to establish the utility by identifying information needs and corresponding objectives, which are essential in the planning stage. Implementation of data collection and its quality control in the sampling stage is followed by analysis and feedback to those involved in collecting the data. Finally, the data are prepared for application in relevant fora. While there are other research applications for the data collected under the Scottish Pelagic Industry-Science Data Collection Programme, these are not the key factors that influenced the design of the programme.

2.3.1 Developing methods and training

In 2018, member vessels of the SPFA were approached to participate in self-sampling. Upon joining the programme, each vessel was provided with a bespoke measuring board (Figure 4), sampling protocols, and data recording templates for haul and biological information (paper and electronic copies). Vessels use existing calibrated onboard weighing scales, which they use within their normal fishing activity to measure fish weights so that a price for their catch can be determined. Graphical sampling protocols were designed in consultation with MSS scientists and were kept to a single or two-sided A4 piece of paper. Information on the purpose of sampling and data collection is provided within the protocol. All the methods and protocols are documented in a sampling methods manual (Brigden et al., 2022) and additional detailed information on the programme development is reported in a PANDORA project technical report (Angus et al., 2021) and the PANDORA toolbox[4].

The initial focus of data collection was self-sampling of fish lengths and weights from all hauls during the fisheries for herring, mackerel and blue whiting. At first only herring was included, but the pilot was soon extended to mackerel later that same year (2018) and then blue whiting in 2019. Haul information is recorded to connect the biological data to the location and date/time of the catch and other operational and environmental parameters.

Prior to undertaking sampling, training sessions were provided to skippers and crew. Initially these were provided in groups (either at the factory or onboard a vessel), but an onboard one-on-one approach was soon adopted, with scientists joining vessels for

4 The PANDORA toolbox is an interactive website including a variety of resources ranging from simple meta-data and links to pre-existing tools to more complex, front-end platforms for displaying outputs from improved assessment and economic models (e.g. short- to long-term changes in distribution and/or productivity of fish stocks as well as economic trade-offs associated with different management strategies). https://www.ices.dk/PANDORA/Pages/default.aspx accessed 12/1/23.

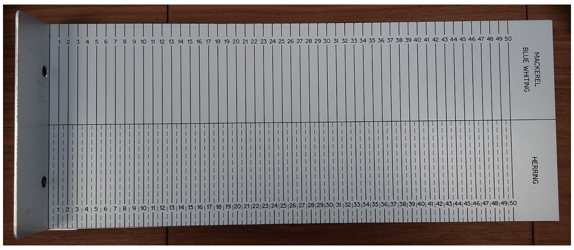

FIGURE 4
Bespoke measuring board, indicating the measurement intervals required for each species, provided to each vessel participating in the programme.

fishing trips or visiting vessels in port. While more time consuming, onboard training was more effective because processes could be demonstrated and tried by the crew using their own set-up. Accordingly, this meant that any questions and issues could be dealt with immediately and, importantly, that the scientists understood the operational conditions so that solutions could be tailored to individual vessels' needs. It was also vital in forming the personal foundations and means of contact necessary for good working relationships.

2.3.2 Quality control – documentation and data

A central part of establishing the programme was the development of reliable data handling and quality control measures, with fully documented processes and procedures, informed by published information on best practice. These serve to demonstrate that processes are scientifically rigorous and ensure the delivery of quality data. Providing full transparency of the programme, documentation is freely available on the SPFA website (https://scottishpelagic.co.uk/).

For the self-sampling data, which relies on crew collecting information onboard vessels, data checking tools were built into the electronic data recording sheet used by crew samplers to help identify data entry errors. These include summary statistics (maximum, minimum, and average length and weight values) and data plots that are automatically generated so that they can be used as immediate visual checks. As part of training, crews are taught how to read these plots and use them to recognise potential mistakes.

A data Chain of Custody is available for the self-sampling scheme, providing a stepwise guide of the QC processes at each stage of data handling, and the supporting documentation and tools required (Figure 5). Similar documentation is in development for the co-sampling scheme. The steps detailed in Figure 5 are applied to the self-sampling data, with each vessel providing two datasets (haul and length-weight) for every fishing season. Upon completion of each fishing season, the data are emailed or uploaded to an FTP site that is accessed by the programme data manager and saved to secure cloud storage. Data checking and quality control are undertaken by the data manager, which includes: ensuring that information matches between the length-weight and haul files so that information can be connected; checking for missing or erroneous information; checking that information is formatted correctly to be read in by data processing scripts. Data handling procedures are applied, and each step in the process is recorded by date in a log sheet. During data checking and quality control, the data manager will contact the vessel to query any issues if required. Further detail is given in a methods and procedures manual (Brigden et al., 2022). Following data checking and quality control, each vessel's self-sampling data are entered into new length-weight and haul data files before being appended into two pooled databases which contain the data for all vessels: a fish biological (length-weight) dataset and a haul dataset. The pooled length-weight and haul databases are used for reporting and are available for further analysis. Individual vessel data are also pooled to provide each vessel with all their fishery's data to date (see section *Communication and relationship building within the programme*). The processes for data re-formatting, entering, reporting and data pooling are each carried out using custom R (R Core Team, 2019) code, providing a consistent data handling approach that can be repeated for all vessels' data, at each processing step.

2.3.3 Technological evolution

To improve the sampling efficiency and minimise errors related to the paper recording and subsequent entry into a spreadsheet, efforts to develop a paperless system began in 2019. Several skippers had already taken it upon themselves to consider what type of system might work best, and, following a review and trials of various existing electronic recording systems (many of which were found to be over-engineered and overpriced for our needs), it was the skippers' idea for a simple keypad that was pursued. In collaboration with a local marine electronics supplier, a simple electronic keypad was designed and manufactured, along with bespoke software for live display, recording and reporting of sampling data (Figure 6). During development, feedback from skippers and crew on the design of a prototype keypad and software was crucial to making the system fit-for-purpose. The keypad is now installed in nearly all participating vessels and has the capability to record additional information on sex, maturity and fat content if needed. Some skippers are using the software's grading reports to provide their catch data directly to processors ahead of landing.

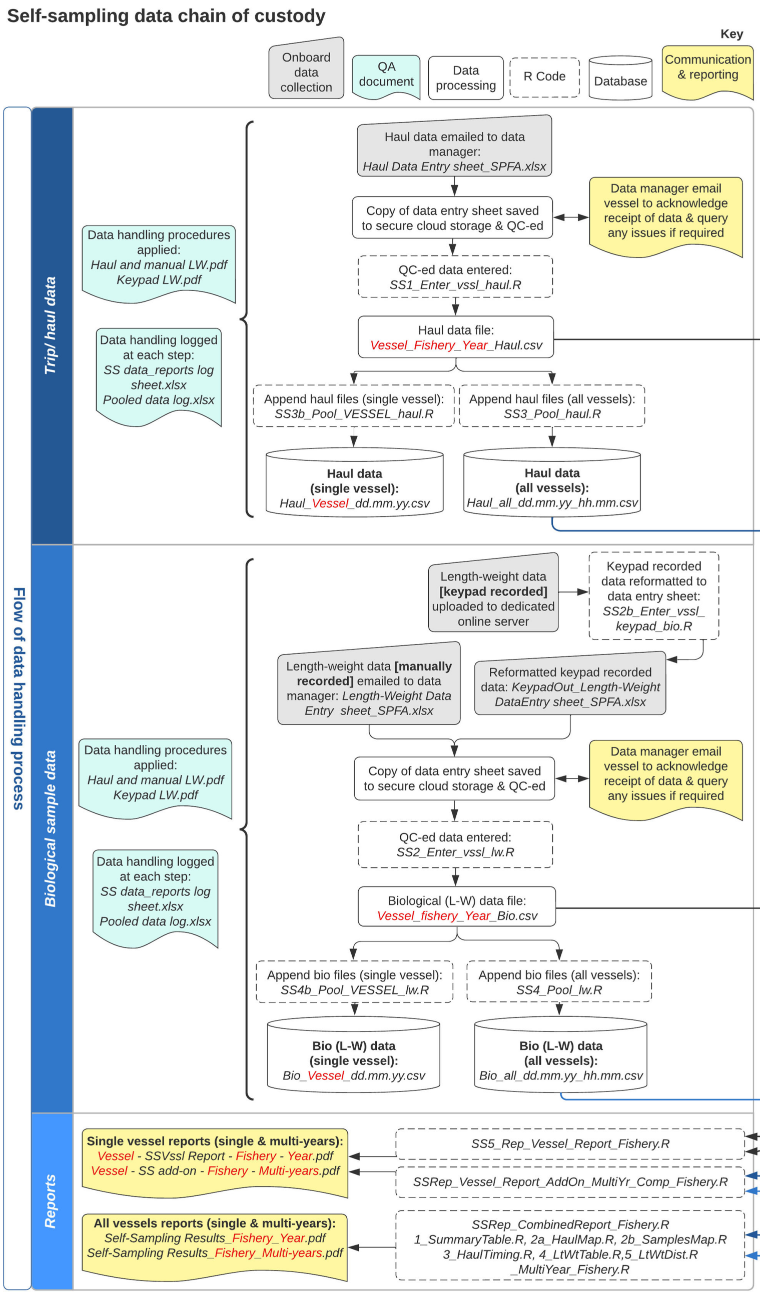

FIGURE 5
Self-sampling data chain of custody. Part of the programme documentation, providing a stepwise guide of the QC processes at each stage of data handling, and the supporting documentation and tools required. Notes: 1) Text in italics denotes file names; 2) Text in red italics ('Vessel', 'Fishery', 'Year/s') denotes the relevant vessel name, fishery and year/s (e.g. Altaire, Herring, 2020) 3) dd.mm.yy hh.mm denotes date/time labelling of file names relevant to processing date 4) QC=quality checked.

Samplers receive training on using the keypad at the time of installation, but in addition, a series of YouTube videos[5] have been distributed as an instructional aide, and to demonstrate the capabilities of the keypad system.

A key benefit of working with a local electronics supplier is that the company already provided services to many of the vessels and knew them personally. This made training and troubleshooting onboard easy and efficient, as well as providing a route for obtaining the feedback required to resolve any glitches and enhance capability, such as the recent development enabling direct upload of data from the keypad system to a dedicated online server.

2.3.4 Additional research

As part of the programme, specific experiments are being undertaken to assess any differences and determine any correction factors that may be required when fish are measured in either a fresh, chilled or frozen-thawed state. On-going

5 Example of instructional / information video for crew (accessed 10/3/23) https://youtu.be/WFbfVYY__Cs.

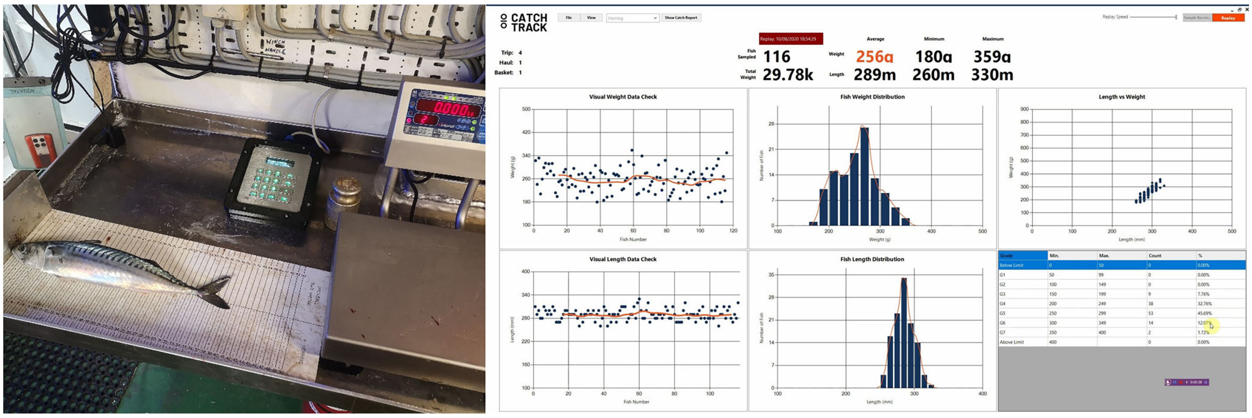

FIGURE 6
Electronic keypad for entry of fish length measurements, paired with weighing scales (left) and data visualisation and capture software on the bridge (right). The data visualisation provides real-time sample data and running average (left panels), size-frequency distributions (middle panels), tracking of the mean, minimum and maximum sizes (top values), a length-weight plot (top right) and percentage of samples in each user-defined grade category (bottom right).

Box 1. Key ICES workshops and working groups relevant to the development of the programme
Workshop on Science-Industry Initiatives (WKSCINDI; ICES, 2019)
Workshop on Data Standards and Guidelines (WKDSG; ICES, 2021a)
Workshop on Stakeholder Engagement Strategy (WKSHOES; ICES, 2021b)
Workshop to Evaluate the Utility of Industry-derived data for enhancing scientific knowledge and providing data for stock assessments (WKEVUT; ICES 2022a)
Working Group on the Governance of Quality Management of Data and Advice (WGQUALITY)
Working Group on Widely Distributed Stocks (WGWIDE)
Working Group on Commercial Catches (WGCATCH)
Herring Assessment Working Group (HAWG).

monitoring will continue to assess how data from samples collected onboard vessels compare with those collected elsewhere.

2.3.5 Data protection and sharing

The SPFA Data Policy (SPFA, 2020) describes the conditions and procedures regarding data access and use by the scientific community. All Data Products (data outputs resulting from aggregation of, or calculated from, underlying or aggregated data, and where individual vessel or personal data is not directly identifiable) are by default publicly available.

During the PANDORA project, a data sharing agreement between MSS, SPFA and SUHI, was established to enable all partners to access all data while ensuring compliance with the General Data Protection Regulation (GDPR) (EU, 2016). As part of the process, every individual vessel was required to give their written permission for the data on their catches collected by MSS to be shared with SUHI and the SPFA, the industry's representative association, because the data were being used for a purpose for which they were not originally collected. A data privacy notice (required under GDPR) and consent form were distributed to, and signed by, all relevant vessel owners.

The data sharing agreement includes descriptions of: the purpose, aims and benefits of the data sharing; limitations on the use of the data; the data to be shared; data required to match or link data sources; the process and basis of sharing; the information assurance and security for each institute; the Data Protection Impact Assessment and privacy notices; data retention and deletion, and management of the agreement. The data sharing agreement applies to data collected between 2018 – April 2022 (the end of the PANDORA project).

2.3.6 Communication and relationship building within the programme

Because the programme is reliant on the voluntary participation of each vessel, it is essential to maintain effective communication between all parties at different levels and for different purposes. This means thinking carefully about what information is needed by whom, when they need it, and in what format.

Using the SPFA's Chief Scientific Officer as a central point of contact, consultation with industry members on the needs and potential of the programme began in 2016, two years prior to its implementation. Since then, regular contact and the development of individual relationships with the skippers and samplers on each vessel has been pivotal in fostering understanding of the programme and the need to be consistent in providing high quality information.

Various means of communication are used depending on what best suits the different groups and individuals involved. Regular contact *via* phone call, WhatsApp, email, and visits to vessels ensures the flow of information in both directions (from scientists to industry and industry to scientists), helping to maintain the working relationships crucial for the programme's successful operation.

To demonstrate the value and utility of the information collected, programme participants receive a copy of their data and summary reports. An email is sent to each vessel at the end of every fishing season, including a standardised Excel file containing that vessel's data to date, and two reports displaying data summaries: (i) A season report provides information from the latest fishing season, including a map with haul locations, average length and weight per haul, length and weight distributions, length-weight relationship, and a comparison between the vessel's average fish weight and average weight of fish in the sample, (ii) A multi-season add-on report provides comparisons with previous years, regarding location, timing, and size of fish. At the end of each fishing season all participating vessel's data are combined and anonymised to provide a multi-vessel/multi-year report demonstrating the complete results of the industry sampling.

Establishing a close working relationship between scientists at the SPFA, SUHI and MSS has also been integral to the successful development and delivery of the programme. Bi-monthly planning meetings have been held and contact maintained throughout the development and implementation stages, with on-going consultation and review of the methods and data collected. It should also be noted that there has been continuity of personnel at all three organisations and this has helped maintain both stability and momentum.

Meetings involving all partners and participants are needed less regularly but are valuable occasions to provide and receive feedback. Since 2019 an annual review and planning meeting involving all participants and collaborators has taken place. In addition, quarterly SPFA directors board meetings provide regular opportunities for sampling to be discussed as needed.

2.3.7 Evaluation

Two years into the programme, a review of the first phase of the self-sampling scheme was undertaken by MSS. This self-evaluation applied published recommendations and guidelines to assess the self-sampling scheme in terms of sample sizes (Gerritsen and McGrath, 2007, Miranda, 2007; Schultz et al., 2016), sampling design (ICES, 2013; fishPi, 2016) and quality assurance (ICES, 2013; ICES, 2014; ICES, 2018a; ICES, 2018b). The report made specific recommendations aimed at minimising bias and ensuring data quality (see Annex 5 in Angus et al., 2021).

To assess the quality of industry self-sampling during the pilot period (2018-2021), data were compared with data collected through the long-established onshore sampling programme, co-ordinated by MSS and conducted under the EU Data Collection Framework (DCF) and its subsequent replacement in UK legislation. The full details of these comparisons are the subject for a paper currently in preparation.

2.3.8 Raising awareness

Beyond the efforts to promote the programme among pelagic fishers (including vessels outside the SPFA) the work has been promoted to other sectors of the Scottish and UK wide fishing industry *via* fishing and national press news articles (e.g. Fishing News, 2022; FitF, 2022b; Mackinson, 2022b) as well as through various industry forums, including: Seafish meetings, Fisheries Innovation Scotland, the Scottish Fishermen's Federation and Fishing into the Future[6]. Opportunities for knowledge exchange with other organisations involved in similar initiatives, and international engagement *via* academic conferences (e.g. World Fisheries Congress 2021 (Brigden et al., 2021), Marine Alliance Science Technology Scotland Conference 2019) have been valuable in programme development. But most important for building awareness of the programme and developing best practice has been participation in key ICES workshops and working groups (Box 1).

3 Results

3.1 Overview of self-sampling data

The growth and increased coverage of the programme over the first four years is shown in Table 1 and Figures 7, 8. Out of 20 Scottish SPFA member vessels, seven initially joined, the remaining vessels joining at various points over the following three years, as successful experiences of early-adopters built confidence in others. Full participation of Scottish SPFA member vessels was achieved in 2021. During the period of the development of the programme there was a simultaneous programme of vessel renewal within the fleet which contributed to the staggered participation. For example, the apparent dip in participation in 2019 compared to 2018 is due to the fact that some vessels participating in 2018 were sold and were not able to participate, while others started their sampling that year. To date, over 1700 hauls have been sampled, resulting in more than 190, 000 fish measured. The result of increased participation of the vessels was greater coverage of the full fleet activity in space and time of all the fisheries, which is highlighted in Figures 7, 8, which show how since the programmes start the overlap of sampling with the commercial fishing activity has developed from partial to complete coverage.

3.2 Evaluating the quality of self-sampling data

The self-evaluation report recommended developments to the sampling design and aspects of the quality assurance of the programme. To improve quality assurance it was recommended that additional clarifications and established quality indicators be added to existing documentation. The report also highlighted that potential bias in the self-sampling scheme would be reduced by implementing census or random sampling design of the full pelagic

6 Seafish – a public body supporting the UK seafood industry; Fisheries Innovation Scotland – a coalition of industry, government and experts driving strategic innovation in Scottish fisheries; Scottish Fishermen's Federation – an industry body to preserve and promote the collective interests of Scotland's fishermen's associations; Fishing into the Future – a UK-wide charity acting for sustainable and prosperous fisheries.

TABLE 1 Number of unique vessels, trips, hauls (% valid), and total valid fish samples (length and weight), from a total of 20 SPFA member vessels.

	2018	2019	2020	2021
Herring				
No. vessels	7	5	15	16
No. trips	41	14	65	64
No. hauls (% valid)	88 (83%)	31 (97%)	153 (84%)	179 (83%)
No. fish (valid)	8017	3640	16754	20466
Mackerel (autumn)				
No. vessels	7	7	15	18
No. trips	29	20	67	67
No. hauls (% valid)	64 (83%)	47 (83%)	156 (85%)	189 (73%)
No. fish (valid)	6866	4577	16289	20281
Mackerel (winter)				
No. vessels	n/a	7	14	18
No. trips	n/a	23	45	67
No. hauls (% valid)	n/a	46 (91%)	95 (86%)	142 (97%)
No. fish (valid)	n/a	4862	9429	15977
Blue whiting				
No. vessels	n/a	1	5	9
No. trips	n/a	4	20	40
No. hauls (% valid)	n/a	29 (55%)	69 (100%)	136 (92%)
No. fish (valid)	n/a	1893	8002	15170

Samples are classified as valid (or invalid) during data checking and quality control undertaken by the data manager (see section Quality control – documentation and data). Only valid samples are used in further data analysis. n/a, not applicable for 2018 mackerel (winter) and blue whiting because the scheme was not yet operational in those fisheries at that time.

fleet. As a result of the evaluation, further effort was put into recruiting skippers, aiming to achieve full participation of the fleet. An advantage of undertaking the self-evaluation mid-way through the pilot phase was enabling the implementation of the recommendations in a timely manner.

The self-sampling scheme provides a finely resolved (haul level) dataset that covers the full spatial distribution of the fishery (Figure 7). It yields quality checked scientific data, and, where sampled trips coincide, is shown to have length distributions that are consistent with length distributions from MSS onshore sampling: the length distributions shown in Figure 9 demonstrate close similarity between the two datasets (onshore sampling and self-sampling), with the self-sampling dataset further resolved by length distributions at the haul level (black dotted line).

In addition, the programme includes additional information on fish weight to be combined with data on fish length, enabling seasonal and inter-annual variations in growth patterns of cohorts to be captured, which could potentially be incorporated into data submitted towards stock assessments. It also provides valuable data for research on species ecology. These data are commonly collected on scientific research surveys but were not previously routinely collected from commercial catches in Scotland. The example in Figure 10 indicates that the mean weight-at-length of mackerel of intermediate lengths observed from self-sampling data is greater than the mean weight-at-length predicted by the Length-Weight relationships used by MSS in spring 2021. In addition, the relationship appears to be more linear, rather than the exponential function assumed by the MSS weight-length relationship.

3.3 Extension to a new co-sampling scheme

Building on the at-sea success of the self-sampling scheme and mindful of the fact that stock assessment models require age data, the collection of otoliths (from which the ages of fish are determined) by crew onboard vessels was investigated by SUHI and MSS scientists in 2018. However, this was not deemed to be a feasible task for crew in the time they have available for sampling onboard, and alternative approaches were considered. This led to a trial in 2019, of the collection of frozen samples on selected trips, with scientists at MSS and SUHI laboratories carrying out the standard biological processing of these fish, namely the collection of information on age, length, sex and maturity. This is referred to as 'co-sampling', because both the industry and scientists take part in the collection of the data.

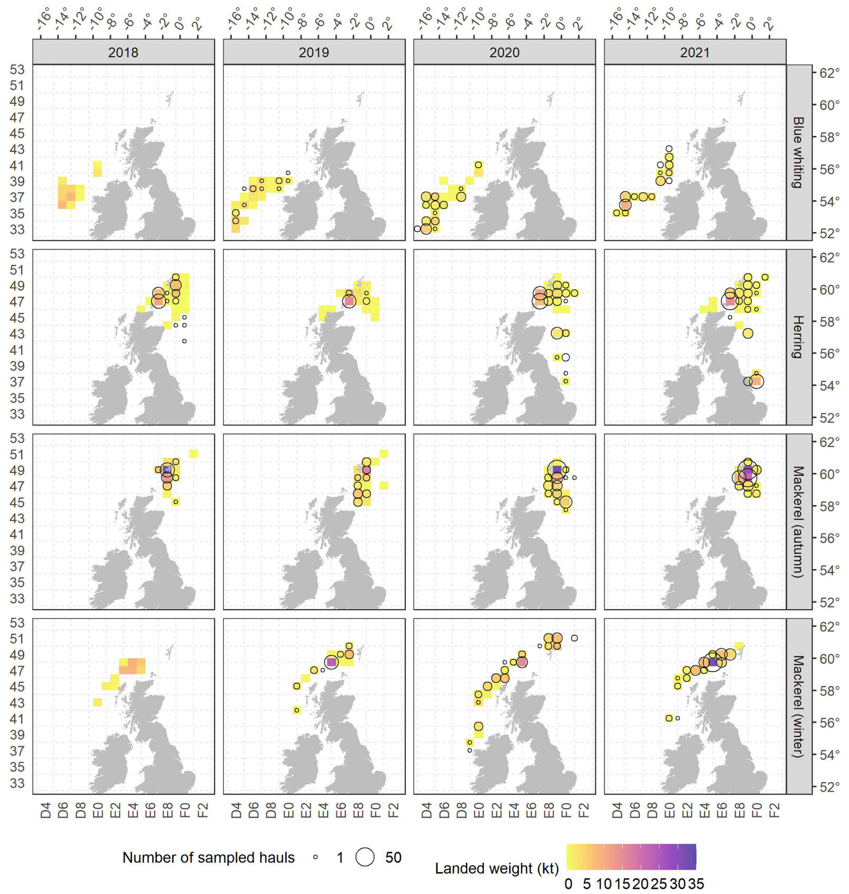

FIGURE 7
Total landed weight (kt) of commercial catches during the blue whiting, herring and mackerel fishing seasons per statistical square (colour scale) by the Scottish pelagic fleet (21 vessels) from 2018 to 2021, with the total number of individual hauls with valid samples collected through the self-sampling scheme (circles). Notes: 1) Samples are classified as valid (or invalid) during data checking and quality control undertaken by the data manager (see section Quality control – documentation and data). Only valid samples are used in further data analysis; 2) the plots in 2018 for mackerel (winter) and blue whiting do not include self-sampling data because the scheme was not yet operational in those fisheries at that time.

In 2020 the co-sampling trial evolved further to include the random selection of trips from which samples are taken, with SUHI or SPFA monitoring fleet activity and notifying vessels to take samples when their trip is randomly selected. In 2020 and 2021, co-sampling was undertaken alongside the MSS onshore sampling programme, providing comparative biological samples. Following this comparison period, in January 2022, co-sampling was adopted under Scotland's national sampling programme to become the main mechanism for collecting biological data on the catches of pelagic fish to be used in stock assessment.

4 Discussion

4.1 Benefits and good practice

The purpose of developing the Scottish Pelagic Industry-Science Data Collection Programme has been to enable fishers to be active contributors to the data and evidence that is used by ICES to assess and advise on the state of fish stocks and the marine environment. Over the course of 2018 - 2022, sampling and data collection by industry rapidly accelerated to become an established collaborative programme covering the whole fleet, with data being used in the ICES 2023 pelagic stock assessments by HAWG and WGWIDE. The success of this initiative has been recognised publicly through two awards: the Fishing News Sustainability Award in 2019 and the Marine Stewardship Council Ocean Leadership Award in 2022[7].

The data generated from the programme offer several benefits and opportunities in efforts to ensure continuous improvements in the quality of stock assessment and ICES advice for each of the pelagic species. There are several aspects of particular importance to data quality, as illustrated in Figures 7–10. First, sample coverage is representative of the activities of the whole fleet because even vessels that land overseas can sample their catches. Second, every haul of every trip is sampled, thus providing an accurate representation of the true catch composition, resolved finely both spatially and temporally. Thirdly, measurements of both the weight and length of fish provide important information on changes in fish growth; and avoid the need to rely on length-weight relationships to

7 Fishing News Sustainability Award: https://fishingnews.co.uk/2019-fishing-news-awards-winners/#sustainability.Marine Stewardship Council Ocean Leadership Award 2022: https://www.msc.org/uk/msc-uk-awards.

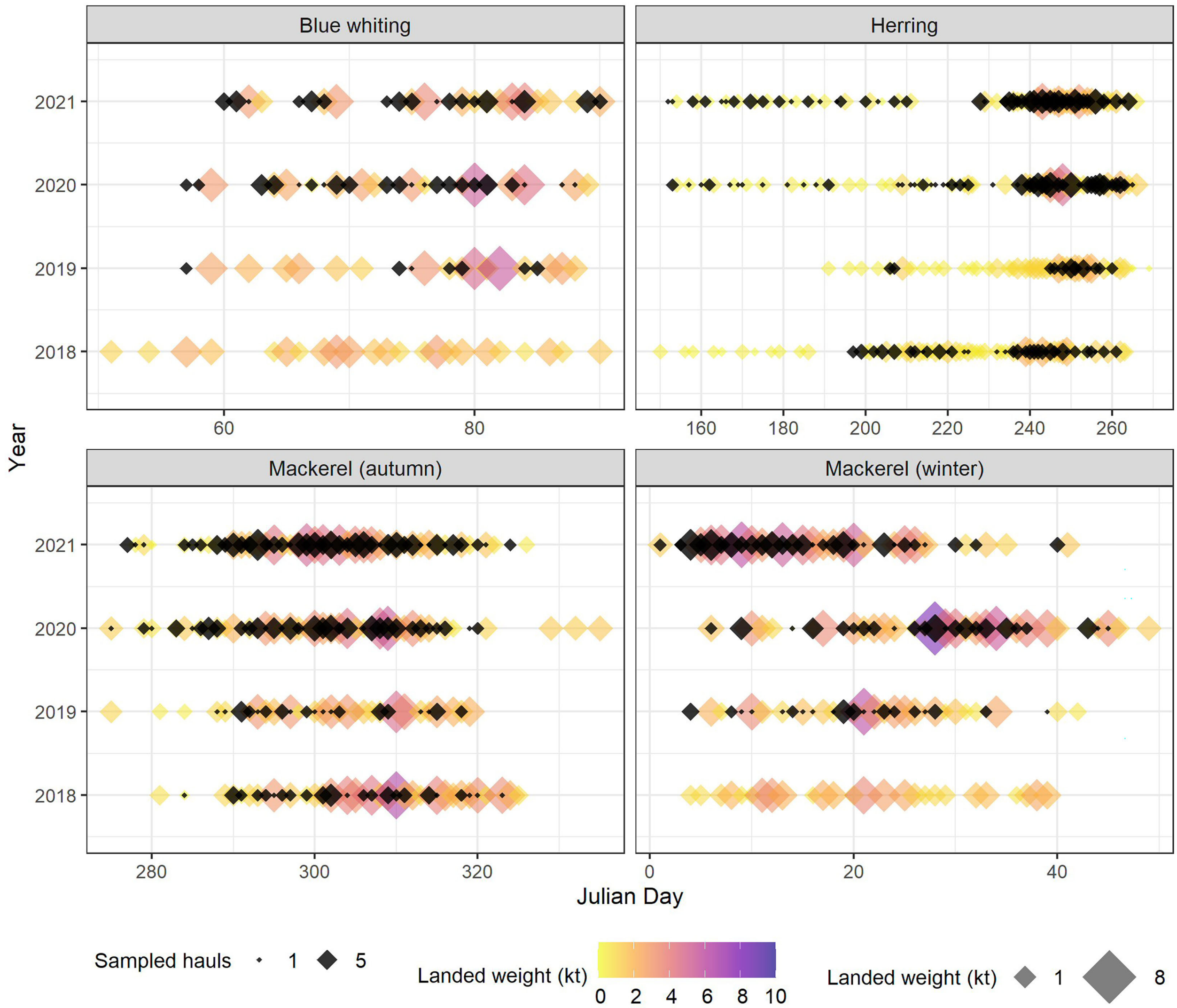

FIGURE 8
Total number of self-sampled hauls undertaken per day from fishing trips during the blue whiting, herring and mackerel fishing seasons (black diamonds), with the total commercial landed weight per day (coloured diamonds) by the Scottish pelagic fleet (21 vessels) from 2018 to 2021. Note: the plots in 2018 for mackerel (winter) and blue whiting do not include self-sampling data because the scheme was not yet operational in those fisheries at that time.

estimate fish weight data inputs to assessments, as was the case in the MSS onshore sampling programme.

From January 2022, co-sampling was adopted under Scotland's national sampling programme to become the main mechanism for collecting biological data on the catches of pelagic fish to be used in stock assessment. The main driver for this was the success of the self-sampling scheme, including almost the whole fleet, and showing that fishers could be relied upon to provide data and samples according to agreed protocols.

The core design principles that we believe have been essential to the success so far are not unique to the pelagic sector, therefore we believe they are transferrable to other sectors. They include:

i. Identifying where there is both opportunity and utility in information that fulfils a need expressed by industry or science.
ii. Always being open and honest with others and understanding that participation is better when fishers have a sense of ownership. The approach has focussed on engaging fishers on the scientific issues relevant to them, and importantly, encouraging an attitude where fishers want to provide data. Fundamental to this is the need for openness and transparent communications, because they help to build trusting and productive working relationships, where everyone can gain the confidence they need to do their job well and with pride. In the case of the sampling programme, we see the advantages, whereby skippers and samplers can - and do - contact programme scientists directly when they have questions or concerns.
iii. Creation of effective feedback mechanisms between scientists and the skippers and crew involved in

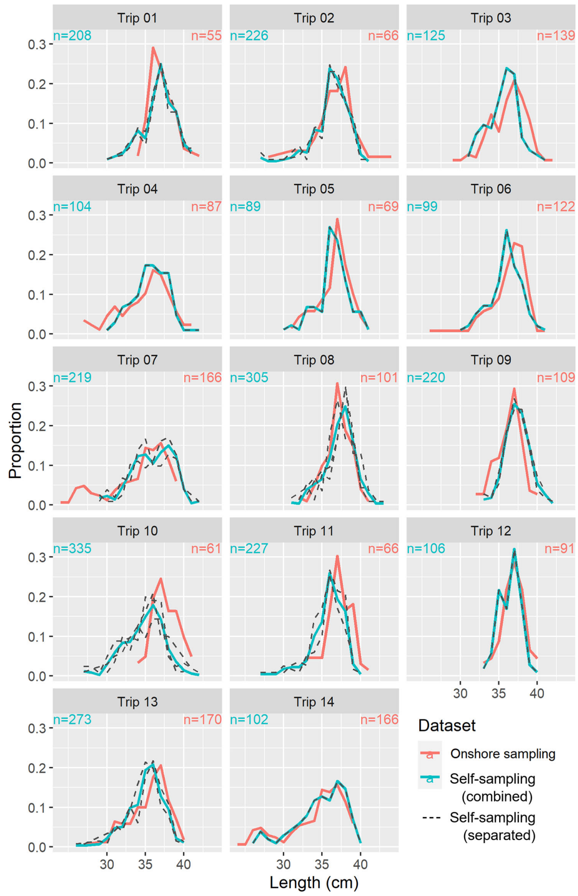

FIGURE 9
Length distributions from mackerel winter fishery trips in 2021, plotted by dataset (colours). Pink line=MSS onshore sampling (one sample in a single trip). Blue line=self-sampling (multiple samples in a single trip, combined). Black dotted line=self-sampling (multiple samples in a single trip, separated).

sampling. The purpose of these mechanisms is to provide the participants with information from which they can assess whether their efforts are rewarded with something of value to them (i.e. the 'what's in it for me?'), as well as to understand each other's roles and to provide opportunities for scientists to listen to operational needs so that they can adapt processes to be fit-for-purpose.

iv. Establishing transparent quality assurance and quality control processes and documentation that serve to assure data users that they can be confident that the information they receive is an accurate representation of the fishery catches.

v. Constructively engaging, challenging and supporting necessary developments in national and international institutional processes that determine whether data from industry programmes have the chance to be applied in stock assessments.

4.2 Perceptions, perspectives and priorities

Though this programme emerged from an industry initiative in the pelagic sector, represented by only one industry body, and comprising a series of seasonal single-species fisheries, its development has not been straightforward. Undoubtedly it is less challenging than developing a sampling programme with, for example, a large fleet of vessels operating in a multi-target mixed-species fishery and with multiple industry representatives. While successful so far, its development has been, a mutual learning process in which, at times, challenges and tensions have had to be navigated.

While these examples are specific to our study, they are the types of issues that would undoubtedly arise in other similar initiatives during their development phases. Being aware and prepared for these types of issues will allow others to develop mitigation measures and strategies from the outset. Applying our different institutional perspectives, we reflect below on six areas where challenges and sensitivities needed to be overcome.

4.2.1 Initial perceptions

While the industry (SPFA scientist and members) felt that being proactive to contribute to pelagic data collection would be welcomed, it perceived the reception from MSS as reticent and reluctant. However, this perceived reluctance was simply an awareness of the challenges that might be faced in trying to integrate a new data source into existing stock assessment models

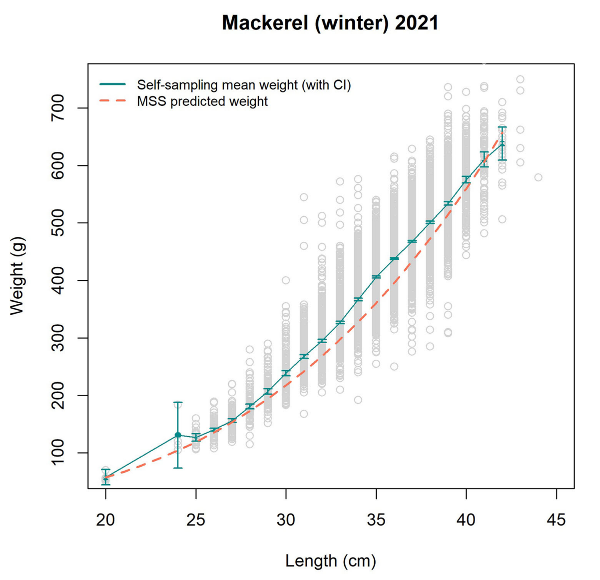

FIGURE 10
Fish length-weight relationship for mackerel 2021 (winter, Jan/Feb) plotted by dataset (colour and line type). Lengths are rounded down to the nearest 0.5 cm. Pink line=MSS predicted weight-at-length currently used by MSS for provision of data to ICES (W=0.003001*L^3.29). Blue line=self-sampling mean weight-at-length with confidence intervals (CI). Grey circles=self-sampling length-weight data (n=15,822 [Jan n= 15,259, Feb n= 563]).

(expanded upon in *Quality and continuity of data* below), and that such a change could need the agreement of other ICES scientists and was not necessarily within the gift of MSS scientists. However, as the industry have taken requirements onboard and addressed them, initial concerns of government scientists have been allayed, and similarly, industry have seen government scientists welcome the industry contribution and endorse the quality of the data.

The partnership between MSS, SPFA and SUHI became organised through engagement in the pilot phase funded as part of the PANDORA project, marking a key milestone in the development of the programme. This involved defining the aims and scope of a pilot study and the roles that each partner would play, which created a task-focussed structure for enabling conversations. The co-development of sampling protocols and joint participation in training actions during early stages were both important to alleviate the initial concerns and to build a starting point from which to expand up on. These provided a framework for everyone to start to navigate and address relevant issues on a case-by-case basis, rather than being overwhelmed by the whole task.

4.2.2 Opening the gate

For the SPFA and SUHI, recognition that government scientists are an institutional bedrock of ICES scientific assessment and advisory processes meant that there was a perception that, without MSS engagement in developing a collaborative approach, the chances of industry making a contribution to the scientific information used in ICES seemed slim. The reason for this is that while, in theory, industry derived data can enter the ICES system independently, the infrastructure and processes in ICES are not yet ready to facilitate that. Furthermore, the industry realised that trying to establish a pathway for industry to 'go it alone' could come across as confrontational and risk being seen as less than helpful. It soon became clear that including industry in the provision of data required by the current stock assessment model was the most efficient way to begin the process, while more speculative approaches, such as developing new assessment methods, would take longer. This meant the development of a more collaborative approach to the collection of age data, and hence to the development of the co-sampling scheme.

The decision to use industry samples as the main source of information for pelagic assessment was made by MSS in 2021. The reason for this was three-fold. Firstly, the pilot had successfully demonstrated the reliability of the industry to be responsible for collecting samples and data to a high standard. Secondly, the almost complete participation of the fleet (Table 1) meant that co-sampling presented an opportunity to facilitate random sampling of all landings, including catch landed abroad. Thirdly, the success of the co-sampling pilot meant that MSS resources were over-stretched when handling samples from both the co-sampling scheme and the existing MSS onshore sampling programme. Together, these reasons meant that the decision to concentrate effort on the co-sampling scheme became clear.

Even though SUHI, MSS and SPFA have been collaborating for several years, with the end of the PANDORA project there is a need for a new formal written agreement underpinning the arrangements (see next section). Despite the high-level UK policy statements suggesting that collaboration is now the *modus operandi*, first it has been necessary for the foundations of trust and confidence to be built between individuals. This has been achieved after several years of successful collaboration.

4.2.3 Quality and continuity of data

As the main responsible authority for scientific data on the key UK pelagic stocks, MSS has a responsibility to provide high quality data. Changes to the data collection methods, even when they improve the data, have the potential to create a step-change in the time series of data provided to ICES, and was thus a legitimate concern for MSS. This concern was understood, and to some extent shared, by SPFA and SUHI because during the early stages of the pilot phase the success of the engagement, willingness and ability of crews to take on new work was yet to be tested. A shift to greater collaboration with the fishing industry requires a continued commitment from participating vessels for a minimum of several years; something that is now close to being formalised under the planned Memorandum of Understanding (MoU) on science collaboration between the partners (SPFA, MSS and SUHI), which will complement existing MoUs between MSS and SUHI and SUHI and SPFA. The commitment for a shared MoU is expressed in a roadmap for collaborative sampling of Scottish pelagic catches established in August 2022.

The consequences of using a new data source needs to be fully considered, because the inclusion of new biological data into an existing time series has the potential to cause a shift in the data that could be spurious and misinterpreted as a change in the structure of the stock. Thus, prior to the introduction of any new data, examination of the resulting effects on estimates would be required. Having knowledgeable staff within MSS that are directly involved in ICES working groups on assessments, catch data, quality assurance and regional database development has been important to ensure that such evaluations have taken place and the programme is fit-for-purpose. Similarly, the engagement of SPFA and SUHI in relevant ICES assessment and quality working groups as well as workshops on industry-science initiatives has been important in this respect.

Concern for the quality of scientific sample data itself has been less of a worry to industry than the perception that their new role in the co-sampling scheme might be driven more by the government's wish for a cheap source of sampling, rather than a wider commitment toward enhancing scientific engagement with the industry. The concern of being a cheap source of sampling cannot, however, be justified because of the similar workload and costs compared with the onshore sampling programme.

4.2.4 Reputational concerns

Combined with concern for the quality of science, MSS and SUHI take care to maintain their scientific integrity and independence so there is no cause for real or perceived conflict of interest coming from external sources. Such concerns might be assumed not to apply to the industry, but this is not the case. The risks of reputational damage from failing to act professionally and live up to expected standards are keenly felt there too because it has a bearing on industry's sustainability credentials and thus their social licence to fish.

Transparency, documentation and communication have been key to mitigating possible reputational concerns from internal or external sources. Throughout, the collaborators have worked on a series of public and scientific communications that explain the aims, plans and operational details of the pelagic sampling programme. Quality assurance documentation and public access to it has also been important in this regard. A particularly important document is the Data Sharing Agreement. This document is explicit about the conditions and processes for sharing the detailed data necessary for scientific collaboration, and, not being our personal area of expertise, the drafting of it was a challenging process. The experience of having to consider such details has been fundamental to build trust and assure each collaborator that safeguards are in place.

Reputational concerns remain present and come to the fore from time to time. Being mindful of them ensures that the collaborators continue to make considered efforts to demonstrate and maintain the credibility of the work as well as the integrity of the institutions and individuals involved.

4.2.5 Pace of change

One of the challenges that has been particularly difficult to manage from the industry side is balancing the pace of progress with expectation. Some participating vessels have regularly expressed frustrations that progress toward integrating industry sampled data into assessments was slower than they expected. This is despite the fact the pilot study was planned to take 3 years, without any plans for data to be used in assessments within that time frame (SPFA, 2019). When industry decides to make changes to any operation, skippers are quick to mobilise crew and apply them, so it is hard for them to understand why change cannot be so immediately implemented elsewhere. At times, the frustration has led to an imminent risk of people pulling out of the (voluntary) programme. A combination of very active personal engagement from SPFA and a dedicated member of SUHI staff responsible for the day-to-day operations of the programme, has been fundamental to prevent this, as well as capitalising on the peer pressure among the fleet. It was also beneficial that the recruitment of new vessels in the first year was relatively slow because it gave time to implement procedures that worked well, thus avoiding the risk of vessels becoming disengaged if processes were not fit-for-purpose.

From the MSS scientists' point of view, however, the pace of change has been faster than planned and required a flexible approach, both with the roll-out of the initial self-sampling pilot, and with the inclusion of additional trials, in particular the co-sampling trial, which resulted in a rapid increase in the workload of scientific samplers. This increase in workload was not fully anticipated, and was not sustainable longer term, thus stimulating efforts on the design of new sampling arrangements. Furthermore, additional infrastructure, for example, the data sharing agreement (specifying what shared data can be used for), databases, and code, needs to be updated to keep pace with these changes.

Naturally, there are also differences in the time each partner has available to work on the programme over the course of a year, with some partners being employed to focus on the work, while others have limited resource to allocate to development work on top of their other commitments and are not able to reprioritise their work in response to the demands of the programme. These differences in the timing and overall time available of each partner to work on the programme leads to differences in the pace and timetable of output that can be achieved. Expectations are managed during monthly meetings, using time management techniques of setting realistic time scales for individual tasks and prioritising them, so that there is greater alignment and improved understanding in the timing of delivery.

4.2.6 Communication

At the start of the programme all meetings were chaired and minuted by the same partner. After some confusion about actions agreed at an earlier meeting, a meeting protocol was agreed, key points of which included rotation of management of the meetings between institutes, a review of agreed actions and conclusions during the meetings, and a specified date for all participants to review and agree the final meeting minutes. Establishing this meeting protocol has been helpful in reducing misunderstandings between partners.

Since 2020 all meetings between SPFA, SUHI and MSS have been held online. Although this has the advantage of easier access to meetings for all, this does lead to reduced interaction between individuals which may have impacted on a sense of team building. It is expedient to prioritise areas of disagreement during focussed online meetings, but these offer less opportunity to appreciate mutual agreements and successes that might be afforded by unstructured social time spent together.

Where differing perspectives, priorities and ways of working clash it can be characterised as conflict. Although at times difficult to navigate, it is also worth acknowledging the benefits that these sometimes-opposing forces bring. For example, ambition to move the work forward at pace, taking the time to consider all the details, questioning the relevancy of certain aspects of the work. At times, these themes have been experienced as friction, however, ultimately these different points of view also provide a focus for discussion on how to deliver a better programme.

5 Conclusion and future

Over a relatively short period of time, industry sampling and data collection has been implemented and is now routine within the Scottish pelagic fishing industry. There are a number of factors that have enabled this to occur, principally the willingness and drive of all concerned and, the staff time and financial resources to enable it to happen. All parties have already demonstrated their commitment to continued collaboration on pelagic science and data collection. The Scottish pelagic industry have demonstrated their commitment to the continuation of the programme from 2022-2026 with the establishment of a Memorandum of Understanding between the SPFA and SUHI and creation of a new industry funded Pelagic Fisheries Scientist post based at SUHI. Further evidence of industry's commitment is visible among new vessels that have chosen to install scientific grade echosounders and sampling equipment, and even build specific spaces onboard dedicated to scientific sampling activities. Similarly, the commitment from MSS is clear through the winding down of their onshore sampling programme. As ever, a collaborative approach will be adopted because for industry sampling data to be used, both industry and relevant national administrations responsible for data submissions will need to commit to working toward this objective. Our foundation for this will be a 3-way MoU that helps formalise operational plans, agreements and policies to help ensure scientific integrity of the data and the institutions. Continued engagement with ICES is also necessary to ensure that the apparatus of the receiving system is in place to accommodate the data. This includes addressing issues regarding data access, use, delivery and formats needed to meet the requirements of emerging tools (e.g. ICES Regional Database and Estimation System (RDBES) (ICES, 2022b)) and processes (e.g. Quality Assured Assessment Framework) necessary to facilitate the use of industry data.

Our example provides valuable lessons for others in terms of both the practical and social dimensions of collaborative research endeavours. It offers a partial 'roadmap' for others considering self- and co-sampling initiatives that are underpinned by a shared objective to continuously improve the science that supports long-term sustainability of fisheries.

Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions

All authors were involved in the editing and revision process, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1075345/full#supplementary-material

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EDITED BY
Matthew R. Baker,
North Pacific Research Board, United States

REVIEWED BY
Taner Yildiz,
Istanbul University, Türkiye
Valeria Mamouridis,
Independent researcher, Rome, Italy
Kotaro Ono,
Norwegian Institute of Marine Research (IMR), Norway

*CORRESPONDENCE
Anna J. M. Mercer
anna.mercer@noaa.gov

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Bringing in the experts: application of industry knowledge to advance catch rate standardization for northern shortfin squid (*Illex illecebrosus*)

Anna J. M. Mercer[1]*, John P. Manderson[2], Brooke A. Lowman[3], Sarah L. Salois[1,4], Kimberly J. W. Hyde[1], Jeffrey Pessutti[5], Andrew W. Jones[1], Robert Ruhle[6], Bill Bright[7], Troy Sawyer[8], Meghan Lapp[9], Jeff Kaelin[10], Katie Almeida[11] and Greg DiDomenico[10]

[1]Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration (NOAA), Narragansett, RI, United States, [2]Open Ocean Research, Philadelphia, PA, United States, [3]ERT, Inc. under contract to National Oceanic and Atmospheric Administration, Narragansett, RI, United States, [4]School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, MA, United States, [5]Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration (NOAA), Highlands, NJ, United States, [6]F/V Darana R, Wanchese, NC, United States, [7]F/V Retriever, Cape May, NJ, United States, [8]F/V Debbie Sue, Narragansett, RI, United States, [9]SeaFreeze Shoreside, Narragansett, RI, United States, [10]Lunds Fisheries, Cape May, NJ, United States, [11]The Town Dock, Narragansett, RI, United States

Sources of fisheries information outside of fishery-independent surveys (e.g. fishery-dependent data) are especially valuable for species that support productive fisheries and lack reliable biological information, such as the northern shortfin squid (*Illex illecebrosus*). Fishery-dependent data streams are available for most species, however collaboration with industry members is critical to ensure that these fishery-dependent data are collected, applied, and interpreted correctly. Despite the need for collaboration and the frequency that fishery data are used in scientific research, there is limited literature on the structure of interactions and knowledge sharing that inform the analysis and application of fishery data. Between 2019 and 2022, a group of researchers collaborated with members of the northern shortfin squid fishing industry to bring together research data sets and knowledge from harvesters and processors to better describe the fishery dynamics, distribution, life history, and oceanographic drivers of the species. The collaboration focused on developing custom standardized fishery catch per unit effort (CPUE) indices to provide indicators of population trends that accounted for the impacts of technical and economic aspects of harvesting, processing and marketing on fishing effort, selectivity and landings of northern shortfin squid. We describe the methods used to inform and interpret the CPUE analyses, focusing on novel structure of interactions we had with industry members, and suggest best practices for integrating industry knowledge into CPUE standardization. The information shared and research products produced through this science-industry research collaboration advanced understanding of northern shortfin squid population and fishery dynamics, and contributed directly to the 2022 stock assessment and management process. Given the complex and stochastic nature of the northern shortfin squid population and fishery, we found it critical to maintain open communication and trust with processors and harvesters, who have unique insight into the factors that may be driving changes in catch, landings, and productivity of the valuable resource species.

KEYWORDS

shortfin squid, stock assessment, cooperative research, local ecological knowledge, northeast United States, catch per unit effort, fisheries dynamics

1 Introduction

For many marine resource species, it is infeasible to collect comprehensive fishery-independent data due to mismatches between survey scope and species distribution, phenology, or life history (short lived). For these species, fisheries science and management rely heavily on fishery-dependent data collected by harvesters, processors, and dealers, commonly included in the form of catch per unit effort (CPUE) indices in stock assessments (Hilborn and Walters, 1992; Maunder et al., 2006). These data sets contain valuable information about resource species, but are also influenced by the socioeconomic and technical aspects of fishing (Walters, 2003; Quirijns et al., 2008). Thus, it is essential to collaborate with the fishing industry to understand these data, inform analytical approaches, and interpret results (Steins et al., 2022; Calderwood et al., 2023). The statistical methods used for CPUE standardizations are well described (Maunder and Punt, 2004; Bishop et al., 2004; Bishop, 2006; Bentley et al., 2012; Cheng et al., 2023), however, the methods for effectively engaging with industry to identify relevant explanatory variables and interpret CPUE indices are rarely implemented and not well documented. Fishery data are used extensively in scientific research, but there is limited literature on the science-industry research collaborations that are key to informing the analysis and application of fishery data (Mangi et al., 2018; Steins et al., 2022; Calderwood et al., 2023). In this manuscript, we present recent research on the northern shortfin squid (*Illex illecebrosus*) that sought to establish best practices for gathering information from the fishing industry and integrating that information in CPUE standardizations.

Northern shortfin squid is a semi-pelagic squid with a lifecycle of less than a year that occupies Slope Sea and continental shelf habitats from Florida to northern Canada (Dawe and Hendrickson, 1998; Hendrickson, 2004; Jackson and O'Dor 2001). Their distribution and growth are highly variable, largely due to the impact of oceanographic dynamics on physiology and movements (Dawe and Warren, 1993; Boyle and Rodhouse, 2005; Salois et al., 2023). Northern shortfin squid are semelparous, with females dying shortly after they mate. Research suggests that they spawn throughout the year and produce multiple cohorts, but recruitment dynamics of northern shortfin squid are poorly understood (Hendrickson, 2004). Northern shortfin squid inhabit the Slope Sea (water mass between the Gulf Stream and the continental shelf) during the winter months and migrate onto the continental shelf during the late spring and early summer months (Dawe and Beck, 1985; Hatanaka et al., 1985; Perez and O'Dor, 1998). Spring and fall fishery-independent bottom trawl surveys of the continental shelf from Cape Hatteras, U.S. to Nova Scotia, Canada sample a portion of the population; however, these surveys do not occur during periods of peak northern shortfin squid abundance on the continental shelf (Hendrickson, 2004).

In the northeastern United States, northern shortfin squid are targeted by a bottom trawl fishery during summer months (May-September), with landings ranging from approximately 2,000 to 28,000 metric tons (Arkhipkin et al., 2015; Doubleday et al., 2016; Northeast Fisheries Science Center (NEFSC), 2021). Vessels targeting northern shortfin squid range from approximately 15 to 45 meters in length and harvest northern shortfin squid on the outer continental shelf at depths of 109-365 m (Lowman et al., 2021). The Mid-Atlantic Fishery Management Council sets an annual quota for northern shortfin squid that is shared by all permitted vessels.

Because of the species' variable abundance and its use of habitats beyond the range of fishery independent surveys, northern shortfin squid are difficult to assess and manage, as are many squid stocks around the world (Arkhipkin et al., 2021; Northeast Fisheries Science Center (NEFSC), 2006). In the absence of comprehensive survey data, many squid assessments rely upon fishery-dependent data to develop indicators of fishery and population dynamics and population condition (Pierce and Guerra, 1994; McAllister et al., 2004; Roa-Ureta, 2012; Arkhipkin et al., 2021). The interpretation of fishery CPUE as an indicator of population trend, however, is potentially confounded by global market drivers, management measures, technical constraints of fishing, and gear selectivity, among other factors (Maunder and Punt, 2004; Maunder et al., 2006). In order to identify the social and economic factors impacting catch rates and account for them in CPUE standardization, it is necessary to assimilate the experiential knowledge of harvesters and processors (Steins et al., 2020; Mackinson, 2022; Steins et al., 2022). Novel modeling tools, such as spatiotemporal delta-generalized linear mixed models, structured additive distributional regression, and simulations further enable researchers to identify bias in and derive population trends from fishery dependent data (Mamouridis et al., 2017; Clegg et al., 2022; Ducharme-Barth et al., 2022; Karp et al., 2022).

Over the years, researchers have developed collaborations with the northern shortfin squid industry to address specific research needs including biological data collection (Johnson, 2011). Several recent research efforts associated with the 2021 Northern Shortfin Squid Research Track Stock Assessment focused on developing science-industry research collaborations (SIRC) to increase our understanding of the species and inform science-based management of the fishery (Northeast Fisheries Science Center (NEFSC), 2021). These recent collaborations are rooted in a mutual recognition of, and appreciation for, the valuable knowledge that the northern shortfin squid industry has accumulated over many decades. The research collaboration we describe here leveraged industry knowledge to better understand the dynamics of the northern shortfin squid population, fishery, and associated environment. Specifically, this paper details a SIRC that integrated the technical and economic knowledge of northern shortfin squid harvesters and processors into the development of standardized CPUE indices as measures of abundance for northern shortfin squid. We describe the approaches to industry collaboration that were utilized to inform the CPUE standardization process, including a northern shortfin squid summit with both industry and scientists, as well as a series of semi-structured conversations. We also discuss how the information shared by industry was integrated in the stock assessment process. In the absence of a model-based stock assessment, the management of northern shortfin squid is informed by other research products, including the work presented in this manuscript. By describing this SIRC process and the strategies used, we hope to provide a model for bringing industry knowledge into assessments of other stocks.

2 Phases and outcomes of northern shortfin squid science-industry research collaboration (SIRC)

2.1 Overview

Here we describe four layers of collaboration with the northern shortfin squid industry that helped to facilitate the development of robust and high-resolution CPUE series: 1) an initial summit with industry, scientists, and managers, 2) a subsequent series of structured conversations with individual processors and harvesters, 3) quantitative application of industry knowledge to CPUE standardizations, and 4) sustained communication throughout the stock assessment process. These interactions occurred in sequence, and represented an organized framework for developing scientific products from fishery-dependent knowledge and data sources.

2.2 Initiating collaborations through northern shortfin squid summit

A two-day "Northern Shortfin Squid Population Ecology and Fishery Summit" hosted by members of the northern shortfin squid fishing industry was held in November 2019 to discuss current understanding of the northern shortfin squid and its fishery, and to identify research priorities leading up to the 2022 stock assessment. The Summit brought together over 30 harvesters, processors, academic scientists, government scientists, and fishery managers to discuss the ecology, population dynamics, and management of northern shortfin squid. The summit was sponsored by the fishing industry and was held outside of formal stock assessment and management proceedings. The goal was to develop a framework for establishing collaborative research products in the near term that could reduce scientific uncertainties limiting responsive fishery management (Manderson, 2020). The priorities identified and relationships formed during this summit kickstarted several science-industry collaborations that ultimately informed northern shortfin squid stock assessment and management. The information detailed below was obtained explicitly through the Northern Shortfin Squid Population Ecology and Fishery Summit, which exemplifies the value of such forums for sharing knowledge and data, and building relationships.

One major summit product was the definition of the different fleets participating in the northern shortfin squid fishery and description of fishing operations characteristic of each fleet. Specifically, northern shortfin squid processors and harvesters emphasized that fleet type is a critical factor influencing fishing behavior and catch rates, with the freezer trawler fleet that catches and freezes squid at sea operating significantly differently than the "wet boat" fleet that temporarily stores squid in Refrigerated Seawater Systems (RSW) or on ice before offloading fresh squid at shoreside processing plants. While it is rare for vessels to switch from one fleet to another, two freezer vessels have been retrofitted with RSW systems since 2010 to enable operational flexibility. This information is well known by the fishing industry, but is not well documented in the scientific literature or previous stock assessments. While the hold type of individual vessels could not be documented during the summit, general differences between fleet types were discussed. Since the late 1990s, the wet boat fleet has dominated the northern shortfin squid fishery during periods when the species is widely available, while the freezer boat fleet has been a stable component of the fishery in all years (Figure 1). In recent years, the freezer trawler fleet (<10 vessels, 23 - 45m in length) has been approximately one-third the size of the wet boat fleet (>30 vessels, 15 - 30m in length). Because they process and freeze squid at sea, freezer trawlers typically remain at sea for longer periods of time and search over larger areas compared to wet boats. Freezer trawler catch, effort, and landing rates are largely driven by the relatively long handling times associated with freezing squid at sea; freezer trawlers can only freeze a certain quantity of squid at a time, and thus, have to stop fishing to process squid after a certain amount are caught. Freezer trawler operations are less influenced by

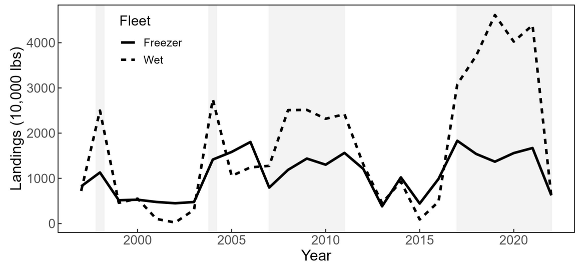

FIGURE 1
Northern shortfin squid (*Illex illecebrosus*) landings from 1997 to 2022. Dashed line represents wet boat landings. Solid line represents freezer trawler landings. Shaded grey areas highlight years in which the 'Wet Boat' fleet reported higher annual landings than Freezer Trawlers.

price than the wet boat fleet and are unlikely to switch species if northern shortfin squid are less available or if prices are low. Conversely, wet boats have short handling times and catch, effort, and landing rates can be high if northern shortfin squid, which are highly perishable, are available at locations less than about 72 hours from shoreside processing plants. Trip durations of the wet boat fleet are short, and effort is strongly driven by the price and availability of squid. Wet boats are more likely to switch to other species if northern shortfin squid prices or availability are low. An action item moving forward from the summit, and now being considered by the Mid-Atlantic Fishery Management Council (MAFMC) as a management requirement, was to document individual vessel hold types to be able to formally account for fleet type in CPUE calculations and other data analyses.

Another important summit product was the description of the global market dynamics that impact the northern shortfin squid fishery. Specifically, northern shortfin squid from the Northwest Atlantic compete in the global market with Argentine shortfin squid (*Illex argentinus)* squid caught in the Southwest Atlantic (Falkland Islands to Southern Brazil) and Japanese flying squid (*Todarodes pacificus)* caught in the North Pacific. Annual landings of squid in the Southwest Atlantic and North Pacific are typically 30-35 times larger than northern shortfin squid production in the Northwest Atlantic. The Argentine shortfin squid fishery in the Southwest Atlantic occurs during the austral summer and closes just before the beginning of the northern shortfin squid fishery season in the northwest Atlantic, which begins when northern shortfin squid migrate onto the continental shelf. As a result, the supply of squid from the Southwest Atlantic fishery regulates demand, and sets the baseline price and risk appetite for inventory for the U.S. northern shortfin squid fishery. Documenting annual trends and scale of landings of Argentine shortfin squid and Japanese flying squid for integration into CPUE standardizations and further analyses was, therefore, identified at the summit as an important next step (Table 1).

The summit also provided a valuable opportunity for members of the fishing industry and science community to share information about the dynamics of the northern shortfin squid population and fishery, develop priorities for research efforts going forward, and form industry-science relationships to facilitate ongoing collaboration. The research efforts prioritized at the summit included 1) quantify the overlap between the U.S. northern shortfin squid fishery and stock distribution to better estimate availability, escapement and the impact of fishery removals (Lowman et al., 2021); 2) define the hold type (freezer, RSW, ice) of each vessel participating in the fishery to enable explicit integration of the impacts of differences in handling in CPUE standardization and stock assessment modeling; 3) explore methods to quantify market dynamics impacting fishing behavior and include in CPUE standardizations; 4) explore how environmental conditions affect the distribution and productivity of northern shortfin squid; and 5) develop a streamlined mechanism to compile northern shortfin squid mantle length and body weight data collected by processors and use data to better understand northern shortfin squid movement, growth, and environmental drivers. In order to address these research priorities, additional conversations with individual harvesters and processors were required for data collection, hypothesis formulation, and interpretation purposes.

2.3 Documenting knowledge through targeted conversations with industry

Following the summit, we held semi-structured conversations with representatives of six northern shortfin squid processors and 17 northern shortfin squid harvesters. The six processors have been responsible for processing and marketing 75-90% of the total landings of northern shortfin squid in U.S. waters since 1997. Most of the 17 harvesters had participated in the northern shortfin squid fishery for at least a decade. The harvesters collectively represented all ports participating in the fishery and included six that fish out of New Jersey, eight that fish out of Rhode Island, and three that fish out of Massachusetts. Of the 17 harvesters consulted, four operate vessels that freeze squid at sea, seven operate vessels that store squid on ice, and six operate vessels with RSW systems. Thus, all vessel/processing types described above were represented. In addition to the 23 industry members consulted *via* semi-structured conversations, an additional 63 harvesters were contacted to characterize the hold type for each vessel that had participated in the fishery since 1997.

Conversations with harvesters were guided by a list of standard questions about technical and economic factors influencing catch and effort in the fishery developed collaboratively by members of

TABLE 1 Food and Agriculture Organization (FAO) capture production for northern shortfin squid, Argentine shortfin squid in the southwestern Atlantic and Japanese flying squid in the north Pacific and the relative scale of northern shortfin squid capture production to these fisheries (capture production ratio).

	FAO Capture Production (metric tons)			Capture Production Ratio	
Year	Northern Shortfin	Argentine Shortfin	Japanese Fying	Argentine Shortfin/ Northern Shortfin	Japanese Flying/ Northern Shortfin
1997	34,561	991,799	603,367	29	17
1998	26,989	700,443	378,605	26	14
1999	5,667	1,153,279	497,887	204	88
2000	6,245	984,589	570,427	158	91
2001	2,296	750,452	528,523	327	230
2002	3,044	540,414	504,438	178	166
2003	4,437	503,625	487,576	114	110
2004	18,234	178,974	447,820	10	25
2005	10,841	287,590	411,644	27	38
2006	16,868	703,804	388,087	42	23
2007	5,132	955,044	429,162	186	84
2008	9,526	837,935	403,722	88	42
2009	11,727	261,227	408,188	22	35
2010	20,654	189,967	359,322	9	17
2011	23,821	187,822	414,100	8	17
2012	14,696	311,754	350,381	21	24
2013	10,991	496,211	337,925	45	31
2014	7,568	862,867	339,685	114	45
2015	4,355	1,011,356	295,304	232	68
2016	9,094	146,645	197,252	16	22
2017	24,431	335,998	155,573	14	6
2018	28,350	301,157	97,180	11	3
			Median	35.5	33
			Minimum	8	3
			Maximum	327	230

Data from http://www.fao.org/fishery/statistics/global-capture-production/en.

the Northern Shortfin Squid Research Track Stock Assessment Working Group. The questions were sent to harvesters to review before conversations were held either by telephone, video meeting, or in person. Notes were compiled for each conversation, which were provided to each harvester to review for accuracy and completeness. Follow up conversations to clarify responses and mechanisms were *ad hoc* and numerous.

During semi-structured conversations with industry members, further details about freezer trawler and wet boat fleet dynamics were identified by the industry and discussed. For example, industry members described how the availability of northern shortfin squid and alternative stocks, changes in the global market, and investment in shoreside processing have caused the northern shortfin squid fishery to change from one dominated by trawlers freezing squid at sea, to a fishery in which vessels store squid in RSW systems or on ice and sell them to shoreside processor/dealers (Figure 1). Freezer trawlers can store up to 650,000 pounds of frozen squid in a 7-10 day fishing trip and usually complete around 12 fishing trips per year. Freezer trawlers generally make fewer trips in years when the global market is saturated with squid, prices are low, and large inventories are held in cold storage. While catch rates of freezer trawlers are limited by shipboard freezing rates, capacities to store large quantities of frozen squid shipboard allow the vessels to fish grounds distant from shoreside facilities. Alternatively, large RSW vessels can land up to 300,000 pounds in a 1-2 day fishing trip, usually completing well over 20 trips per fishing season. Since northern shortfin squid are highly perishable and the vessels generally need to return to port within 72 hours of first catch, RSW and ice vessels are profitable when the squid are concentrated on fishing grounds near enough to shoreside processing plants so that vessels can reach plants before squid begin to spoil. Rapid transit from fishing grounds to processing plants is particularly critical for vessels that store squid on ice, which is less effective than RSW at quickly reducing product temperature to maximize product quality. Thus, the perishability of squid combined with market demand for high quality product imposes constraints on the duration of fishing trips, location of fishing grounds, and the timing of landings for ice and RSW vessels that deliver to shoreside processors. Wet boats and shoreside processing are profitable when squid are persistently available in large quantities.

Beyond fleet type and market dynamics, industry members identified several other factors that impact northern shortfin squid catch and effort: fuel price, hold/tank capacity, length of time catch remains fresh, gear conflicts, recent increases in participation in the northern shortfin squid fishery, weather, time of day, and environmental conditions.

Fuel price was cited by several harvesters as an important determinant of fishing behavior. Specifically, when fuel price is high, harvesters are less likely to search over large areas, as the potential benefit of more productive fishing grounds is outweighed by the high cost of fuel. Thus, in years or weeks when fuel price is high, catch or landings per unit effort indices may be decoupled from the condition of the northern shortfin squid population, as vessels are more likely to continue to fish on lower densities of squid to conserve fuel.

Hold or tank capacity was also described as a major driver of fishing behavior. Vessels with larger hold or tank capacities are more likely to steam farther from port to fish in areas where northern shortfin squid densities are highest. This is particularly true for freezer vessels, which are not constrained by the perishability of fresh squid. RSW vessels with larger hold capacities can also benefit from larger area searches, as the benefit of highly productive tows outweighs the cost of the extra steam time as long as the squid can be kept from spoiling. Vessels with lower tank or hold capacity are more likely to fish closer to port where squid densities are lower, as they do not require high densities of squid to fill their hold/tanks.

The length of time that catch remains fresh was specifically identified as impacting fishing location, likelihood of changing fishing locations, and limits to catch per tow for ice and RSW vessels. As described above, the length of time that catch remains fresh depends on the vessel type, with ice vessels having the shortest time that catch remains fresh (48 hours), followed by RSW (72 hours), and freezer (weeks). Thus, wet boats are more likely to fish closer to port, even if northern shortfin squid are less productive in those areas. Wet boats are also less likely to change fishing locations, as time spent steaming between fishing grounds is time when squid quality is degrading and no additional catch is occurring. Finally, total catch per tow is limited by the amount that can be processed while staying cold enough to maintain quality.

In addition to the vessel-specific factors impacting northern shortfin squid catch and fishing effort described above, harvesters also identified several management-related factors that drive when, how, and where they fish. Restricted Gear Areas, which are intended to separate mobile gear and fixed gear, preclude mobile gear vessels from fishing along the shelf break from the northern edge of Hudson Canyon to Atlantis Canyon during the northern shortfin squid fishing season (Figure 2). Fishing regulations (e.g. small mesh restricted areas) and technical constraints also limit northern shortfin squid fishing throughout most of the Gulf of Maine.

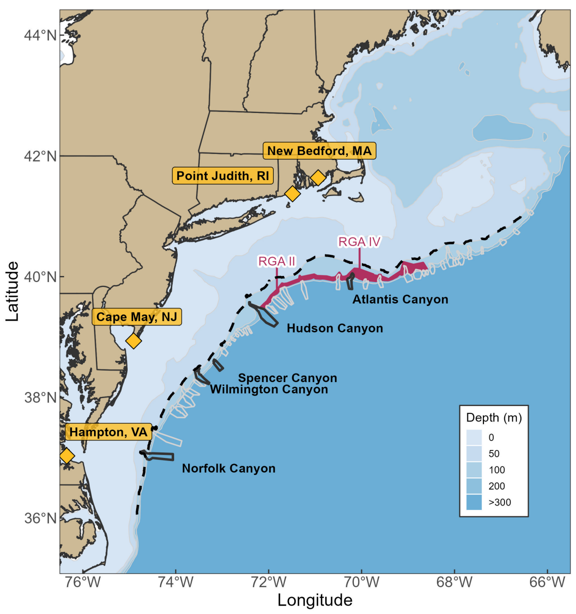

FIGURE 2
Map of the general extent of northern shortfin squid fishing grounds (dotted black line), Restricted Gear Areas (RGA - solid maroon polygons), ports with squid processing facilities (yellow diamonds), and major canyons (solid lines of black or grey) along the continental shelf (approximately 200 m isobath).

Thus, lack of landings from these areas are not due to the absence of northern shortfin squid, but due to the exclusion of mobile gear or all fishing. In addition to formal gear restricted areas, there are also areas where the density or location of fixed gear makes it impossible to fish mobile gear and harvest northern shortfin squid. These areas vary by year, following the distribution of the offshore lobster and crab fisheries.

As mentioned previously, there has been a significant change in the composition and number of participants in the northern shortfin squid fishery in recent years. The static and common quota for northern shortfin squid has always resulted in some level of competitive fishing. In 2017-2021, with more vessels harvesting northern shortfin squid and a limited and common quota, the quota was harvested faster. This has changed the dynamics of the fishery substantially.

Another factor affecting fishing behavior of northern shortfin squid harvesters is weather. Severe weather (strong winds, high seas) can impede vessels from safely sailing, from keeping their gear on the bottom, or from effectively catching squid. Severe weather also makes it difficult to maintain ship stability on RSW and ice boats when they transport large volumes of fresh squid to shoreside processing plants in rough conditions. Squid are also sensitive to the conditions of the water column and often disperse during large storms. Thus, northern shortfin squid catch and landings may decline or cease for weeks during years in which large storms have impacted the Mid-Atlantic or offshore Southern New England. Weather plays into a harvester's decision about whether to fish, but it is variable by vessel type, vessel size, port, and captain. Further research is needed on the threshold of weather conditions that prevent fishing or scatter northern shortfin squid, and therefore effectively shut the fishery down temporarily.

Many harvesters noted that the catch rate of individual tows varied greatly throughout the day. The most productive tows most commonly occur at dawn or dusk, with midday tows yielding lower catch rates. This is likely related to the diel vertical migration of northern shortfin squid, with squid more strongly associated with the seabed, and thus more available to bottom trawling, during daylight. Aggregation near the seabed is especially pronounced during morning and evening twilight on the outer edge of the shelf during the summer months (Benoit-Bird and Moline, 2021). In addition, harvesters noted that northern shortfin squid fishing is typically less productive on and around the full moon.

Finally, harvesters largely agreed that there are oceanographic drivers of northern shortfin squid. Specific oceanographic drivers discussed by harvesters included Gulf Stream position, Gulf Stream warm core rings, eddies, filaments, streamers, southerly winds, and upwelling zones. Although hypotheses were abundant, the harvesters consulted were not confident that pre-season oceanographic conditions could be used to forecast the productivity or availability of northern shortfin squid in a given year. While oceanographic features may be observed to be associated with high or low quantities of northern shortfin squid at one time, the relationships are often not consistent (Dawe et al. 2007; Rodhouse et al. 2014; Moustahfid et al. 2021). Harvesters recommended that additional research is needed on this topic to identify and test hypotheses related to the oceanographic drivers of northern shortfin squid.

2.4 Applying industry knowledge to Catch Rate standardization

The knowledge shared by members of the northern shortfin squid fishing industry were used to define how fishery dependent data were handled and which covariates were applied in the development of CPUE indices. For example, we used information provided by industry members to define and differentiate freezer trawler and wet boat fleets within the data, which enabled discrete CPUE modeling of the two fleets. We used a stepwise approach to prioritize the other factors that industry members described as important in driving catch and effort for inclusion as covariates in CPUE standardization. First, we determined which factors were consistently identified by members of the fishing industry. Second, we determined which factors were likely to be correlated due to similar underlying drivers. Third, we determined which factors were quantifiable with available data. These factors were then used as covariates in the CPUE standardizations.

Ultimately, three fishery dependent data sets maintained by the Northeast Fishery Science Center (NEFSC) were used for the landings and CPUE standardizations: dealer/logbook, Observer program, and Study Fleet program (Figure 3). The dealer/logbook data set is a census of landings that comprehensively describes northern shortfin squid landings, as they have been collected for every northern shortfin squid fishing trip since 1996 as part of federal reporting requirements. The spatial resolution and time step of the data set, however, are relatively coarse, with landed catch information recorded at the sub-trip level (i.e. one record of total landed catch per statistical area per fishing trip). As part of routine data auditing procedures, mandatory dealer reports are compared to the self-reported logbooks to verify reported landings. The Observer program data set comprises catch, bycatch, and fishing effort information for individual tows collected by independent observers through the Northeast Fisheries Observer Program during a subset of randomly selected northern shortfin squid fishing trips since 2011 (Wigley and Tholke, 2020). The observer data set covers 4-10% of northern shortfin squid fishing trips in a given year, with lower coverage in recent years, especially during the COVID-19 pandemic. Finally, the Study Fleet data set is composed of detailed catch, bycatch, fishing effort, and bottom water temperature data for individual tows that are self-reported by harvesters participating in the Study Fleet program (Jones et al., 2022). The Study Fleet data set covers up to 45% of northern shortfin squid fishing trips in recent years.

We used conventional statistical methods for building standardized CPUE indices. All statistical analyses were performed using R version 3.6.2 (R Core Team, 2019). Generalized additive models (GAMs) were fitted using the mgcv package (Wood, 2011). Based on histograms of CPUE and LPUE, we investigated several error distributions: lognormal, gamma (with log link), and negative binomial (with log link). Based on the most

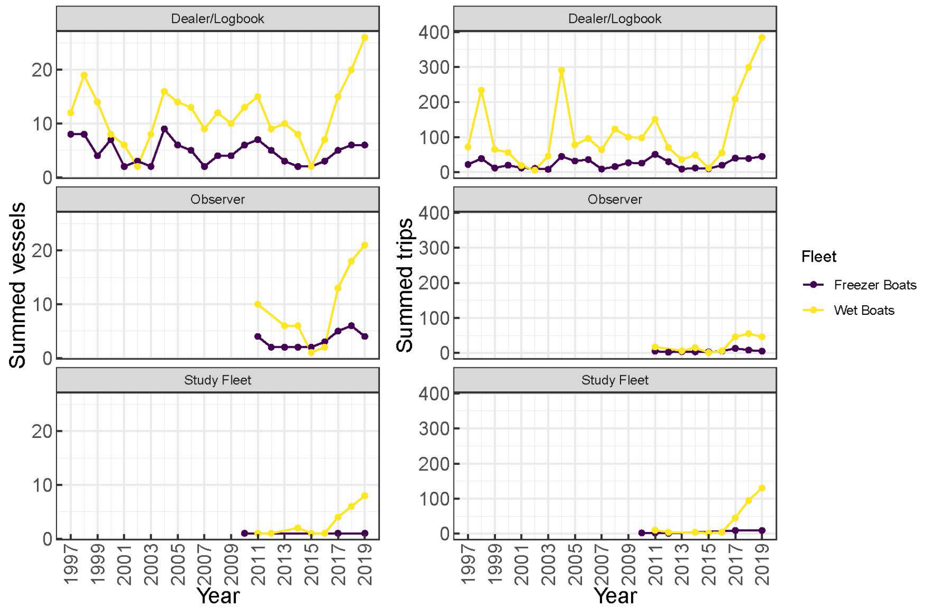

FIGURE 3
Time series of northern shortfin squid fishery participation (number of vessels, left panels) and effort (number of trips, right panels) across the Dealer/Logbook, Observer, and Study Fleet data sets. Purple lines indicate freezer vessels. Yellow lines indicate wet boats (ice and refrigerated sea water).

promising set of diagnostics (quantile-quantile plots, Cook's distance, and residuals), we built GAMs with the corresponding distribution using forward stepwise selection of explanatory variables with AIC and percent deviance explained as the selection criteria. For further detail on statistical methods, see Supplementary Material. Additional information is also available as a working paper supplement to the 2022 Illex Research Track Assessment (available online through the NEFSC Stock Assessment Support Information portal at https://apps-nefsc.fisheries.noaa.gov/saw/sasi.php).

A variety of social and environmental factors identified by the fishing industry at the summit and during individual conversations were considered as covariates in the CPUE standardization. These included year and week effects, weekly domestic squid and fuel

TABLE 2 Factors that impact northern shortfin squid catch and effort identified by industry collaborators and considered in CPUE standardization.

Factor	Source	Freezer Fleet CPUE		Wet Boat Fleet CPUE		
		Dealer/ Logbook	Observer	Dealer/ Logbook	Observer	Study Fleet
Fleet (freezer or wet boat)	Summit, Conversations	X	X	X	X	X
Year - factor	Summit	X	X	X	X	X
Weekly domestic price of Illex - smooth	Summit	X	X	X	X	X
Landing port - factor	Conversations	X		X		
Days absent - linear	Conversations	X		X		
Fishing location - two-dimensional smooth	Summit	X	X	X	X	X
Week of the year - factor	Summit					X
Distance (straight line, km) from fishing grounds to landing port - linear	Conversations		X			
Landing port state - factor (aggregated due to low sample size in individual ports)	Conversations				X	
Weekly diesel price	Conversations					
Global Ommastrephid landings	Summit					

The source of factors included in final CPUE models are marked with an X in the corresponding model column. Comparison of top catch rate standardization models for each fleet in each data set.

prices, the state and port where squid were landed, the number of days a vessel was absent from port, the location of the fishing activity, the distance from the landing port to the fishing location (a straight line distance estimate), and global Ommastrephid production. A subset of these variables were ultimately included in final models to each data set for each vessel hold type (freezer or wetboat: see Table 2). Models were fit to each data set, rather than a combined data set, due to differences in spatiotemporal resolution across data sets. For example, the Observer and Study Fleet data sets contain northern shortfin squid catches for individual fishing tows, while the dealer/logbook data set contains total northern shortfin squid catch from a fishing trip. Additionally, not all data sets include records of discarded catch, therefore we used landings per unit effort (LPUE) as the response variable in modeling. Because discards are negligible in the northern shortfin squid fishery, landings are nearly equivalent to catch and we therefore use the terms LPUE and CPUE interchangeably.

Domestic prices for northern shortfin squid by week are included in the CPUE and LPUE standardizations because some harvesters noted that they modified their fishing behavior based on fluctuations in price. For example, when price is high they may stay on a less dense aggregation of squid and accept a lower LPUE, when they would otherwise move on to search for denser fishing ground when prices are lower. Domestic price is calculated based on total landed value divided by the total landings (pounds) for each week. Prices were adjusted for inflation by standardizing to 2019 USD, using the Gross Domestic Product Implicit Price Deflator from the Federal Reserve Economic Data (U.S. Bureau of Economic Analysis). Prices from the week preceding a fishing trip were used to reflect the fact that fishing decisions are made based on the information available when boats leave the dock, not the price when they land.

Global harvest of Ommastrephids was consistently reported by industry members as a major factor affecting northern shortfin squid LPUE. Therefore, annual global landings of Argentine shortfin squid (*Illex argentinus*) and Japanese flying squid (*Todarodes pacificus)* were included in the CPUE and LPUE standardizations as indicators of the global Ommastrephid squid market (Tables 1; 2). The Argentine shortfin squid fishery occurs primarily in the first half of the year before the U.S. northern shortfin squid fishery, so Argentine shortfin squid landings were not lagged during covariate development. Conversely, the Japanese flying squid fishery occurs primarily in the second half of the year, so Japanese flying squid landings were used from the year previous to the northern shortfin squid fishing year.

Fuel price was reported by harvesters to impact fishing behavior in a similar way to the domestic northern shortfin squid price. When fuel is more expensive, harvesters are less willing to search or move off a moderately productive spot. Diesel price for the New England region of the U.S. was pulled from the Energy Information Administration and prices were adjusted for inflation by standardizing to 2019 USD using the Gross Domestic Product Implicit Price Deflator from Federal Reserve Economic Data.

Landing port and days absent (trip duration) were also included as covariates in the CPUE and LPUE standardizations, as harvesters noted longer trips were often associated with lower CPUE. In addition, the distance to fishing grounds was calculated as the straight line distance between the reported fishing location and the landing port.

Using the data sets described above and covariates highlighted by industry, we developed GAMs using forward stepwise selection with Akaike's Information Criterion (AIC) and percent deviance explained as the selection criteria (Wood, 2017). Ongoing discussions with fishing industry collaborators and the stock assessment working group produced suggestions for model adjustments, insight into the CPUE trends produced, and explanation of the non-linear effects of covariates. Feedback was received during one-on-one or small group conversations with fishing industry collaborators as well as during stock assessment working group meetings. The process was iterative, with the CPUE models and outputs taking many shapes along the way. Ultimately, the CPUE and LPUE indices developed were utilized to assess the general trends in northern shortfin squid abundance across years (Figure 4). Each distinct CPUE and LPUE series provided useful insight into the dynamics of the northern shortfin squid fishery in addition to species abundance. Further, congruence between these CPUE and LPUE with other indices developed for the northern shortfin squid stock assessment, provided confidence in the accuracy of the trends (Figure 5). For additional information on CPUE model building, see Supplementary Materials.

2.5 Integration of fishery knowledge into the stock assessment

Several members of our research team formally and informally participated in the Northern Shortfin Squid Research Track Stock Assessment Working Group, which was initiated several months after the summit. Industry members also regularly participated in stock assessment working group meetings, which were open to the public. To ensure that industry knowledge gathered both at the summit and through individual conversations was integrated into the stock assessment process, we developed a working paper detailing the technical and economic dynamics of the northern shortfin squid fishery, as well as the ecology and environmental drivers of the species, as reported by industry (Northeast Fisheries Science Center (NEFSC), 2021). This information was referenced regularly throughout the stock assessment process. We also engaged the Northern Shortfin Squid Research Track Stock Assessment Working Group in progressing application of industry knowledge to CPUE modeling. This enhanced the quality of the standardized CPUE model.

The knowledge shared and documented throughout this SIRC was also critical to the development, parameterization, and interpretation of a generalized depletion model for the northern shortfin squid stock assessment (Northeast Fisheries Science Center (NEFSC), 2021; Arkhipkin et al., 2021). Depletion modeling requires robust fishery dependent data, including documentation of the socioeconomic and technical factors that impact catch (Roa-Ureta, 2012; Roa-Ureta et al., 2015). The knowledge that industry shared during this SIRC was essential to determining the structure of the generalized depletion modeling and in interpreting the

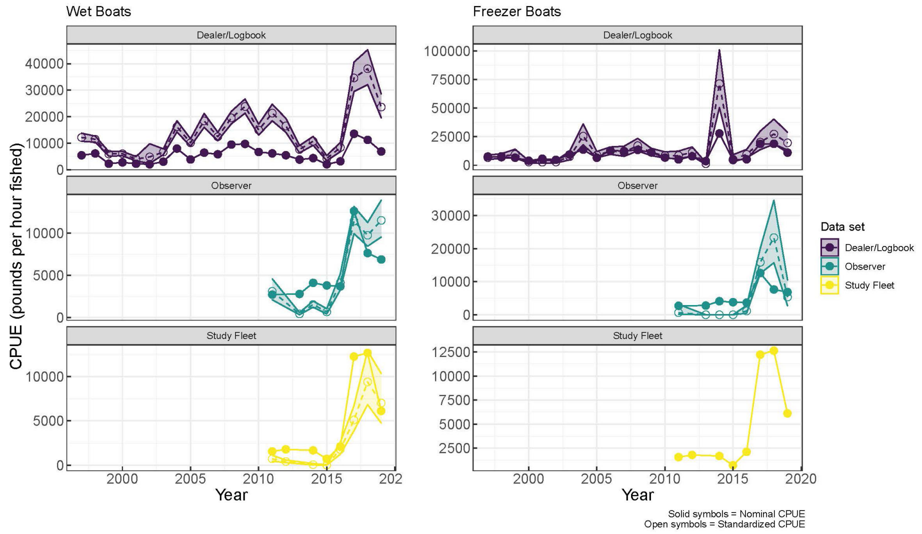

FIGURE 4
Nominal (solid symbols) and standardized CPUE (open symbols) series for the Wet Boat fleet and the Freezer Boat fleet. The shaded region indicates +/- SE. Top panel shows the dealer/logbook data, middle panel shows the observer data, and bottom panel shows the Study Fleet data.

outputs. Industry knowledge about gear selectivity and species catchability were also applied in the development of a mass balance model, an envelope model, and an escapement model for northern shortfin squid (Rago 2020; Northeast Fisheries Science Center (NEFSC), 2021).

The SIRC developed during this research evolved and expanded to cover several other topics that were identified as priorities during the stock assessment process. For example, it became clear throughout the stock assessment process that enhanced data on northern shortfin squid body size and weight are essential for understanding the structure of the population as well as the movement of cohorts onto and off of the continental shelf. In response to this need, industry collaborators shared insight on northern shortfin squid growth throughout the fishing season as well as squid body size and weight data collected by processors. This exchange of information initiated a formal research initiative to develop an electronic data collection system for use by the region's northern shortfin squid processors to collect individual squid size and weights during the vessel offload process. In 2021 and 2022, six northern shortfin squid processors collected over 60,000 northern shortfin squid mantle lengths and weights through this initiative.

Further research to evaluate the oceanographic drivers of northern shortfin squid was also prioritized during the stock assessment process. Thus, a team of researchers and industry members formed the "Squid Squad" to share observations and develop hypotheses to explore analytically. The "Squid Squad" collectively developed a conceptual model and identified oceanographic features and fishery data to explore, resulting in new hypotheses and areas for research (Salois et al., 2023). Regular (~weekly) meetings provided industry, scientists, and managers

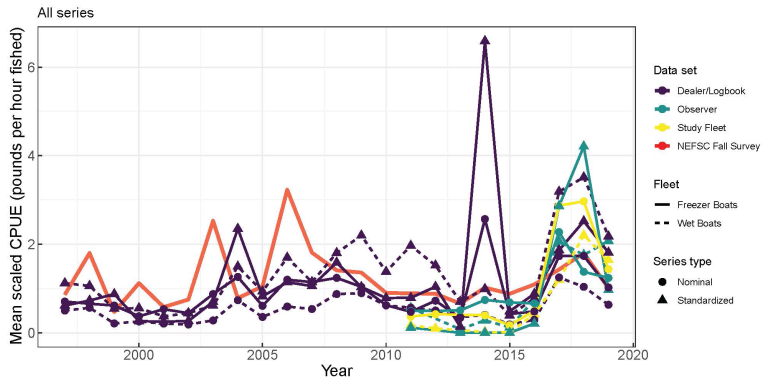

FIGURE 5
Comparison of standardized northern shortfin squid Catch Per Unit Effort (triangles), nominal northern shortfin squid Catch Per Unit Effort (circles), and NEFSC Fall Bottom Trawl Survey index (red line) from 1997 to 2019. For standardized CPUE time series, line color indicates data set (Purple = Dealer/logbook, Blue = Observer, Yellow = Study Fleet) and dash type indicates standardization approach (Short dashed = Freezer boat CPUE standardization; Long dashed = Wet boat CPUE).

with an informal opportunity to discuss the status of the fishery and the surrounding ecosystem. These meetings continue to be an effective tool for progressing this collaboration and pursuing multiple research questions related to the northern shortfin squid. In 2022, the “Squid Squad” executed a novel process-oriented research cruise, with a commercial fishing vessel sampling for northern shortfin squid within and around a mid-depth salinity maximum intrusion that was simultaneously being mapped by an oceanographic research vessel (Gawarkiewicz et al., 2022). The relationships developed and results produced throughout this process have laid the foundation for meaningful collaborations between the scientific and fishing communities in the future.

The 2021 northern shortfin squid research track stock assessment did not produce an acceptable stock assessment model for the species (Northeast Fisheries Science Center (NEFSC), 2021). Thus, the research products described above are critically important for informing management of the northern shortfin squid fishery.

3 Summary recommendations

As exemplified through this research, the insights and knowledge of members of the fishing industry are essential to the proper application and interpretation of fishery dependent data. In the case of northern shortfin squid, industry collaborators played a key role in identifying the factors that impact fishing selectivity, effort, and landings, as well as refining CPUE models and interpreting results. Northern shortfin squid processors and harvesters identified many technical and economic factors that drive the catch and landings of northern shortfin squid. The most frequently identified factors impacting northern shortfin squid catch and landings were 1) vessel type (freezer or wet boat), 2) market dynamics (global production of Ommastrephids), 3) price for northern shortfin squid, and 4) availability of northern shortfin squid to the fishery (abundance of northern shortfin squid in fishable areas, and proximity of productive fishing grounds to ports). With these factors explicitly accounted for, we believe CPUE and other fishery-dependent data analyses can be useful tools for assessing the trends in and condition of the northern shortfin squid population. Frequent and meaningful dialogue with members of the northern shortfin squid fishery is necessary to ensure that technical and socio-economic factors are accounted for appropriately.

In addition to identifying the factors that are important to consider when analyzing and interpreting northern shortfin squid fishery data, this research also highlights the importance of using the appropriate effort metrics when calculating CPUE for northern shortfin squid. Given the highly variable tow times, catch handling techniques and technical constraints on trip length, we suggest using tow time, rather than days absent or number of tows, as an effort metric in CPUE analyses. Accompanied with precise fishing locations and data on squid sizes and weights, CPUE indices can be a powerful tool for understanding the northern shortfin squid population and fishery.

Catch rate standardizations can be challenging to construct, as they require a nuanced understanding of fishing behavior and the fishery-dependent data sets collected within a region, which researchers and managers often do not independently possess. As demonstrated by this research, documenting and incorporating industry knowledge can be an effective means to advance catch rate standardizations. Furthermore, several existing CPUE standardization methods suggest enhanced integration of local ecological knowledge, but the types of approaches for engaging with industry members are not well described (Bishop, 2006; Bentley et al, 2012). In the research presented here, three phases of collaboration contributed to the effective integration of industry knowledge: 1) a summit of scientists and industry members, 2) a series of semi-structured conversations, and, 3) application of industry knowledge to CPUE standardization, and 4) ongoing discussions throughout the stock assessment process.

Each phase of collaboration provided insight into different aspects of the northern shortfin squid fishery and the biology of the species, together providing the comprehensive understanding needed for accurate catch rate standardization. The continued and constructive communication between science and industry partners throughout all phases was essential to building trust and laid the groundwork for information sharing. The summit allowed us to gain important insights into general trends in catch through time and high-level factors that may be important to collect at a higher resolution. For example, vessel hold type, which became a key variable in stratifying the data, was identified at this stage. Following this event, it was clear that follow up conversations were needed to generate data on vessel hold type for each vessel participating in the fishery, and while soliciting this information, additional questions about fishing practices could be asked as well. These follow up conversations allowed us to get more detailed information about the factors influencing catch rates and ensured that a diversity of perspectives was documented. Following the individual conversations, working through model development and iterative fitting during the stock assessment process allowed considerations about time series length, data set coverage, and other logistical considerations to be worked through such that insights from industry could best be translated into time series of catch or landings per unit effort. The industry’s belief in the value of this research and trust in scientific collaborators grew throughout all phases of this research and was paramount to its success.

4 Conclusion

Overall, this work exemplifies the value of engaging the fishing industry in research to inform stock assessments and fisheries management. Members of the fishing industry hold valuable experiential knowledge that can inform data treatment and analysis, offer unique data collection opportunities to meet research needs, and have unique insights into and hypotheses about the environmental drivers of resource species that are derived from many years on the water. Initial focus on building trust and open communication and identification of mutually beneficial research products are essential to science and industry collaborations. Proper application and interpretation of fishery dependent data requires the insights and knowledge of members of the fishing industry.

This research highlights the unique benefits and outcomes of engaging with members of the fishing industry through large-group summits, one-on-one conversations, and during the formal stock assessment process. We suggest that large-group summits are most effective for developing initial relationships and trust between science and industry collaborators, gaining insight into the major factors influencing fishery dynamics, and identifying research priorities. Semi-structured conversations with individual industry members are immensely helpful to dig deeper into specific factors that influence fishery dynamics, identify potential covariates to be included in catch rate standardizations, and to review research results and identify areas for future work. Finally, bringing scientists and industry members together during the stock assessment process can be an effective method for refining catch rate standardization models and identifying other avenues for applying industry knowledge. Together, these approaches for building, maintaining, and applying science-industry research collaborations have been demonstrated to be highly effective at informing catch rate standardization and should be applied in this research area more regularly.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the animal study because there was no interaction with live animals for this research.

Author contributions

JM and AM conceived of the study in collaboration with industry partners. AM, JM, BL, JP, SS, and KH collected and documented the knowledge shared by industry. RR, BB, TS, ML, JK, KA, and GD contributed knowledge and assisted with documentation. BL, AM, and AJ completed the CPUE analyses. AM and JM contributed the original draft. All authors contributed to the editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author BL was employed by company ERT, Inc.. Author ML was employed by company SeaFreeze Shoreside. Authors JK and GD were employed by Lunds Fisheries. Author KA was employed by The Town Dock.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1144108/full#supplementary-material

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EDITED BY
Steven Mackinson,
Scottish Pelagic Fishermen's Association,
United Kingdom

REVIEWED BY
Katie Brigden,
University of the Highlands and Islands,
United Kingdom
Michela Martinelli,
National Research Council (CNR), Italy

*CORRESPONDENCE
Noelle A. Olsen
nolsen@cfrfoundation.org

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Integrating fishers' knowledge with oceanographic observations to understand changing ocean conditions in the Northeast United States

Noelle A. Olsen[1*], Frank Bahr[2], N. David Bethoney[1], Anna M. Mercer[3] and Glen Gawarkiewicz[2]

[1]Commercial Fisheries Research Foundation, Kingston, RI, United States, [2]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, United States, [3]Northeast Fisheries Science Center, National Marine Fisheries Service, Narragansett, RI, United States

Recent warming in the Northeast United States continental shelf ecosystem has raised several concerns about the impacts on the ecosystem and commercial fisheries. In 2014, researchers from the Commercial Fisheries Research Foundation and Woods Hole Oceanographic Institution founded the Shelf Research Fleet to involve fishers in monitoring the rapidly changing ocean environment and encourage sharing of ecological knowledge. The Shelf Research Fleet is a transdisciplinary, cooperative program that trains commercial fishers to collect oceanographic information by deploying conductivity, temperature, and depth (CTD) instruments while commercially fishing. A total of 806 CTD profiles have been collected by the Shelf Research Fleet through December 2022. Participating vessels can view the conductivity and temperature water column profiles they collect in real-time. These profiles help inform their fishing practices and give insights when unexpected species appear in their gear or if their catch composition changes from previous years. The data collected by the Shelf Research Fleet are shared with and processed by researchers from numerous partnering institutions. The Shelf Research Fleet data have been used by researchers to better understand oceanographic phenomena including marine heatwaves, shelf-break exchange processes, warm core rings, and salinity maximum intrusions onto the continental shelf. The scope of the Shelf Research Fleet has grown over time to include efforts to more directly link oceanographic results with biological observations to better understand how changing ocean conditions are affecting commercially important species. This article describes the approach, successes, challenges, and future directions of the Shelf Research Fleet and aims to outline a framework for a cost-effective research program that engages fishers in the collection of oceanographic data, strengthening partnerships between fishing industry members and the scientific community.

KEYWORDS

warm core rings, salinity maximum intrusions, shelfbreak exchange processes, collaborative research, Southern New England

1 Introduction

Changes in climate and ocean conditions in the continental shelf and slope regions of the Northwest Atlantic are impacting living marine resources and ecosystems as well as the people and communities who depend on those resources (Gaichas et al., 2014; Colburn et al., 2016; Hare et al., 2016). Two major oceanographic changes include the frequency of marine heatwaves and the patterns of shelf-break exchange processes. Since 1950, there has been an increase in the intensity, duration, and frequency of marine heatwaves in the North Atlantic (Scannell et al., 2016; Großelindemann et al., 2022). Marine heatwaves are regions of large-scale and anomalously warm sea surface temperature (Chen et al., 2014; Scannell et al., 2016). In the Southern New England continental shelf region, the most notable marine heatwave in recent history occurred in 2012 where the sea surface temperature was 1-3°C warmer than the 1982 – 2011 average and lasted about six months (Mills et al., 2013). At the end of 2016, another marine heatwave occurred in this region, lasting about four months with temperature anomalies up to 6°C and salinity anomalies above 1 PSU (Gawarkiewicz et al., 2019; Perez et al., 2021). The marine heatwave in 2017 was likely the main driver of the lowest average chlorophyll *a* concentration over the Northwest Atlantic continental shelf since 1998 (Gawarkiewicz et al., 2019). There is also concern of prolonged changes to ocean temperatures disrupting seasonal cycles, including alteration of the magnitude and timing of seasonal extremes and stratification (Taboada and Anadón, 2012). In Southern New England, mid-depth salinity maximum intrusions are pushing closer to shore and are saltier than previously reported (Gawarkiewicz et al., 2022). Similarly, warm core rings and Gulf Stream water masses and slope waters are penetrating onto the continental shelf and moving further onshore, potentially shifting the distribution of primary productivity and living marine resources (Gawarkiewicz et al., 2018; Salois et al., 2023).

Large-scale environmental changes can have profound effects on marine organisms' spatial distribution, abundance, mortality, disease prevalence and severity, growth, settlement, and reproductive cycles. For example, Green et al., 2014 demonstrated the impact of temperature and salinity on the growth, sexual maturity and reproduction, mortality, disease, and catchability of commercially important crab and lobster species. Short-lived species, such as northern shortfin squid *Illex illecebrosus* and longfin squid *Doryteuthis pealeii*, are especially sensitive to environmental conditions which can cause large fluctuations in abundance (Mills et al., 2013; Moustahfid et al., 2021). Hare et al. (2016) conducted a climate vulnerability assessment on 82 fish and invertebrate species in the Northeast United States to evaluate the extent to which climate change and decadal variability could impact a species' abundance or productivity. Their assessment indicated that a number of species were highly or very highly vulnerable to climate impacts and variability, and about half of the species studied would be negatively affected by these changes. Furthermore, Nye et al., 2009 documented that many of New England's commercially important fish species have already exhibited a northward shift in their distributions as well as a shift into deeper waters due to warming ocean temperatures. Changes in community interactions (e.g., predator-prey dynamics) is a lesser understood consequence of the potential co-migration of shifting fish species in response to changing ocean conditions that may affect fishery dynamics (Hollowed et al., 2013; Cohen and Satterfield, 2020; Kroeker and Sanford, 2022). Although fishers may welcome an influx of new commercially-valuable species in their region, skill development and economic and regulatory constraints may inhibit their ability to harvest these new species. Additionally, if species shift out of the area accessible to the fishery, fishers may be forced to target different species or leave the fishery itself (Pinsky and Fogarty, 2012). Ultimately, climate-related shifts in species' distributions will have implications for the availability of marine resources to harvesters and could lead to a spatial redistribution of fisheries (Pinsky and Fogarty, 2012; Mills et al., 2013).

In recent years, substantial budget cuts to hydrographic monitoring programs in the Northeast United States region have significantly decreased the amount of oceanographic data available to understand these changing ocean conditions. Additionally, there are prohibitive factors associated with oceanographic sampling including the high costs of instrumentation which requires regular servicing and calibration as well as specialized training (Gawarkiewicz and Malek Mercer, 2019; Van Vranken et al., 2020). Innovative solutions to fisheries and oceanographic monitoring are vital to counteract these budget cuts, and partnering with the commercial fishing industry is one such solution (Gawarkiewicz and Malek Mercer, 2019). A rich history of collaborative research projects with commercial and recreational fishers exists in fisheries science, resource management, and oceanographic monitoring around the globe (National Research Council 2004; Manning & Pelletier, 2009; Patti et al., 2016; Van Vranken et al., 2020; Ito et al., 2021; Jones et al., 2022).

The benefits of partnering with industry members are well-documented and can include reduced costs of science, increased sampling capacity, utilization of fishers' knowledge and skills, new fishery opportunities, enhanced communication and trust, increased transparency in the scientific and management process, and relationship building (National Research Council 2004; Johnson and van Densen, 2007; Feeney et al., 2010; Yochum et al., 2011; Gawarkiewicz and Malek Mercer, 2019; Holm et al., 2020; Steins et al., 2020). Yochum et al. (2011) describes how the degree to which industry partners are involved with the project from the outset affects the potential benefits from a collaborative approach particularly in regards to the amount of trust, communication, and mutual education between the groups, and the confidence of the fishers in the research results. Fishers often target the same species in similar areas over the span of multiple decades and have an in-depth knowledge of localized species distribution and their catch composition (Jones et al., 2022; Mercer et al., 2023 *In Press*). In addition to specialized biological knowledge, fishers also possess a comprehensive understanding of the local habitat, hydrographic, and weather conditions over time (Manning & Pelletier, 2009; Ashoka Deepananda et al., 2015). Van Vranken et al. (2020) described the utility of fishing gear platforms for sub-surface oceanographic observing systems largely due to the widespread spatial distribution of fishing effort and provided several examples of such programs on a variety of types of vessels worldwide. Van Vranken et al. (2020) concluded that fishing vessels equipped with hydrographic gear could increase the effective observation range as well as provide instrument validation if fishing effort spatially overlaps with higher-resolution observation systems. In the Northern Kyushu prefectures of Japan, Ito et al. (2021) equipped small fishing boats with conductivity, temperature, and depth (CTD) instruments in coastal areas which improved the spatiotemporal resolution of the traditional ocean observation systems.

In 2011, the National Science Foundation held a series of public hearings to discuss the installation and five-year operation of the Ocean Observatories Initiative (OOI) Coastal Pioneer Array off the coast of Southern New England. The OOI Coastal Pioneer Array is an observatory system of moorings, gliders, and autonomous underwater vehicles with the purpose of studying shelfbreak processes and shelf-deep ocean exchange (Gawarkiewicz and Plueddemann, 2020). The shelfbreak region is biologically productive and supports commercial and recreational fishing activities in the area. Throughout the fall of 2011, the Commercial Fisheries Research Foundation (CFRF) facilitated a series of workshops with OOI Coastal Pioneer Array scientists and fishing industry representatives to address concerns related to the placement of the array and provide recommendations to help minimize multi-use conflicts. At these meetings, oceanographers and Woods Hole Oceanographic Institution (WHOI) scientists connected with CFRF scientists and fishing industry members. Some of the fishers shared their observations of changing currents and expressed an interest in learning more about how the ocean was changing. Discussions about the changing shelfbreak ecosystem continued beyond these meetings, and a funding opportunity through the MacArthur Foundation arose six months later to propose a collaborative research effort to investigate these changes and fill data gaps onshore of the OOI Coastal Pioneer Array.

In 2014, the CFRF-WHOI Shelf Research Fleet was founded. The primary idea was to use fishing vessels to collect hydrographic data throughout the year for multiple years to examine seasonal and inter-annual variability of the temperature, salinity, and density fields as well as determine the signatures of several shelfbreak exchange processes. The main project goals included: (i) examining the development and breakdown of the seasonal thermocline; (ii) investigating the frequency, timing, and the extent to which warm, saline intrusions of slope and Gulf Stream waters are penetrating onshore onto the continental shelf; and, (iii) a long-term goal of understanding how factors like the Jet Stream position affects seasonal stratification and temperature and salinity extremes during periods of rapid change. Another important goal was to relate hydrographic variability and shelfbreak exchange processes to important fishery resources as well as on their distributions within Southern New England ecosystems (Gawarkiewicz and Malek Mercer, 2019). Additionally, this program aimed to facilitate knowledge exchange between science partners and fishing industry members related to changing ocean conditions. This article describes the approach and successes of the Shelf Research Fleet, including some operational use cases of the collected data, with the aim to provide a framework for future collaborative, industry-based hydrographic research programs.

2 Methods

2.1 Shelf Research Fleet development and communications

In the summer of 2014, an open call to participate in the Shelf Research Fleet was distributed by CFRF to a list of commercial fishing vessel owners in Rhode Island via postal mail. The application form asked a series of questions about the vessel's target species, the amount of time spent fishing per year, whether they fish in or transit through the study area, and if they have any previous collaborative research experience. Additional calls to participate were advertised via word of mouth, the CFRF electronic mailing list, and the CFRF Facebook page. Ten commercial fishing vessels were initially selected to participate, and a total of seventeen vessels have contributed to sampling efforts. Location and timing of fishing effort were used to prioritize vessel selection to maximize the sampling potential and area covered. A variety of fishing vessel types have participated in the Shelf Research Fleet including lobster and pot fishers, gillnetters, scallopers, and trawlers. Work agreements were formulated by CFRF and signed by vessel captains which included a brief description of the project goals, vessel responsibilities, monetary compensation, and data sharing plans.

The RBR*concerto* CTD instrument (RBR Global, https://rbr-global.com/) was selected for this program due to its high degree of accuracy (± 0.03 mS/cm and ± 0.002°C) as well as its user-friendly operation and RBR Ruskin app interface (Gawarkiewicz et al., 2019). Four CTDs were circulated among the Shelf Research Fleet participants, and a rotating sampling schedule was established to distribute effort across space and time. In the fall of 2014, the research team met with the selected vessel owners to present background information on the project and goals, train the fishers how to use the CTD and tablet, and answer any questions. Printed briefing documents, training materials, and user guides were given to the Shelf Research Fleet participants. There were in-person demonstrations on how to use the CTDs instruments and the Ruskin iPad application at commercial fishing docks in Rhode Island. Frequent communication was particularly important at the start of the project to ensure that any issues with the equipment or methodologies were quickly resolved to minimize frustration.

Once the program was underway, the Shelf Research Fleet research team hosted public meetings roughly twice a year to discuss sampling efforts, summarize and share research results, ask new research questions, share any upcoming funding opportunities, and discuss any oceanographic events (e.g., marine heatwaves, storms, warm core ring related processes) and trends in salinity and temperature occurring in the area. Fishers were provided a platform to share field observations related to biological and physical phenomena, ask questions, and share their own hypotheses. Fishing industry members and scientists external to the Shelf Research Fleet program were allowed to attend these meetings. The meetings were typically hosted at the CFRF office or held at a local fishing gear shop located next to commercial docks and seafood processing plants in Rhode Island. Meetings were held in the early evening to accommodate fishers who go out fishing in the early hours of the day, and attendance was typically higher on dates with unfavorable fishing weather. The COVID-19 pandemic paused in-person ocean conditions meetings and the research team pivoted to using webinars with call-in options to increase accessibility. In between the meetings, members of the fishing industry were encouraged to contact Shelf Research Fleet research partners with questions and observations.

The Shelf Research Fleet research team employed a variety of engagement techniques to disseminate the results from and bring awareness to this program. In addition to publishing data results in scientific journals, more informal media were used to reach broader audiences such as websites, blog posts, press releases, media coverage, and social media. For example, this project has had several National Public Radio (NPR) interviews featuring Shelf Research Fleet participants and WHOI and CFRF scientists. WBUR estimates that their programming reaches about seven million listeners each week (WBUR, 2018). The CFRF maintains a project-specific webpage on the Shelf Research Fleet with a promotional video advertising the program (Available: http://www.cfrfoundation.org/shelf-research-fleet). Additionally, research updates and relevant information were shared via CFRF's social media pages and newsletters. Figure 1 is a timeline of a variety of the accomplishments of the Shelf Research Fleet including journal publications, media coverage, and the progression of sampling throughout the program. Figure 1 Supplemental Material lists the titles of the media articles and publications and their associated hyperlink or DOI.

2.2 Data collection and processing

Since November 2014, Shelf Research Fleet participants have deployed RBR*concerto* CTD instruments across the continental shelf to measure cross-shelf exchange processes. The sampling area was split into six Fishing Zones between the boundaries of 41.305°N to 40°N and 71.5°W to 70.5°W (Figure 2). The total area is about 12,348 km^2. Zones 5 and 6 partially overlapped with the OOI Coastal Pioneer Array that was initially deployed at the end of 2013

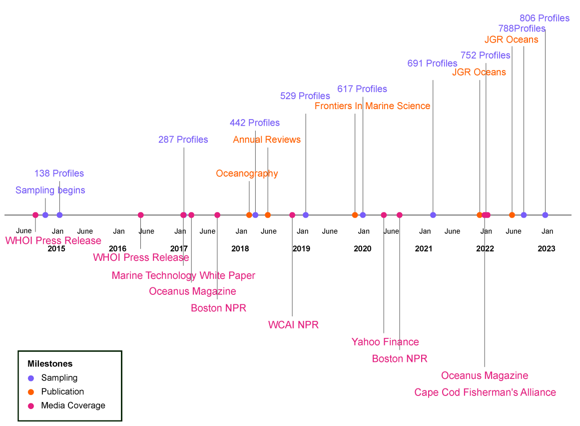

FIGURE 1
A timeline of Shelf Research Fleet project milestones including the number of Shelf Research Fleet CTD profiles collected, the publication of peer-reviewed journal articles, and a variety of media articles and interviews from September 2014 through December 2022.

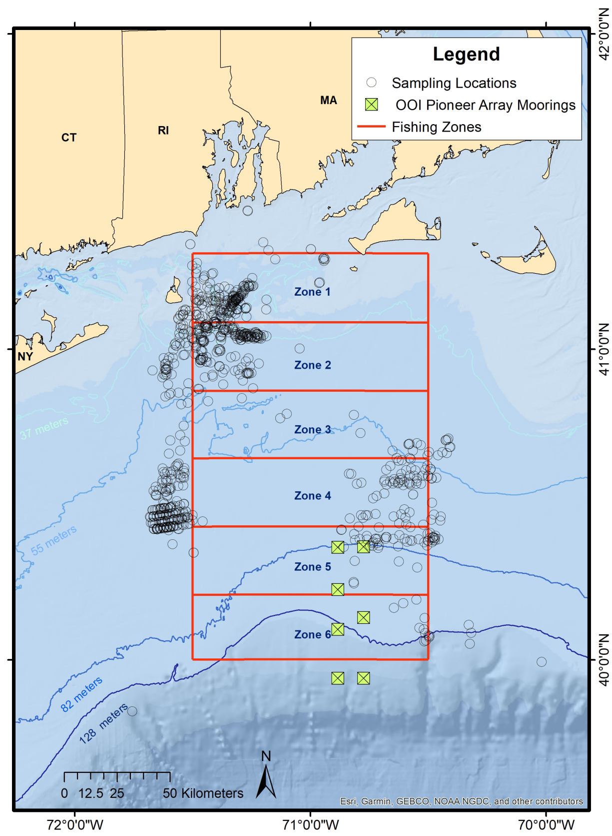

FIGURE 2
The study area is split into six cross-shelf Fishing Zones. The circles represent the locations of the 806 validated Shelf Research Fleet CTD profiles sampled from November 2014 to December 2022. The Ocean Observatories Initiative Coastal Pioneer Array moorings are represented by the square crosses.

(Gawarkiewicz and Plueddemann, 2020). However, numerous profiles were collected at fishing locations outside of the longitude boundaries and these have also been analyzed and used in published research (Figures 1, 2). Vessels were typically assigned two Fishing Zones and were asked to conduct a CTD cast in each of their zones weekly. The CTDs were cast over the side of their stationary vessels while they were out commercially fishing and/or transiting through their assigned Fishing Zones. There were minimum monthly sampling requirements to receive the stipend, but individual vessels could sample more if desired. Weekly sampling was targeted from 2015 – 2017 to achieve the spatial and temporal data resolution necessary to capture ocean phenomena like warm core rings interactions and salinity intrusions, but reduced to bi-weekly sampling from 2018 to 2022 due to changes in funding (Gawarkiewicz and Malek Mercer, 2019).

The CTDs measured conductivity and temperature, providing a vertical profile from the water surface to the bottom at each sampling location, and the GPS location was recorded. The CTD profiles were uploaded to the Ruskin app via a Bluetooth connection, the app calculated and displayed salinity and temperature at depth, and the fishers could view the profiles in real time while out at sea. This feature allowed fishers the opportunity to compare their catch to the ocean conditions at the time, help inform their fishing practices, and check whether their CTD cast was successful. Once the vessel returned to the dock and the iPad was connected to WiFi, the CTD profiles were uploaded to science partners at CFRF and WHOI.

At WHOI, temperature and conductivity profiles were combined to derive salinity and density. Only the ascending portion of each profile was used, as surface effects from the rapid deployment of the probe typically contaminated the upper parts of the descending portion. The first few seconds of the ascending path were also removed for a number of profiles that had been contaminated by bottom sediments after landing on the ocean floor. An advantage of the open cell design of the RBR CTD sensor is the capability of allowing quick flushing on the ascent to the surface. Finally, the original 6Hz time series was vertically averaged into one-meter bins. WHOI maintains a publicly available database that provides monthly summaries, visualizes the fisher-collected temperature and salinity profiles by Fishing Zone over the years, and provides access to the Shelf Research Fleet data (Available at https://scienceweb.whoi.edu/seasoar/cfrfwhoi/).

3 Results

3.1 Analysis of Shelf Research Fleet CTD profiles

A total of 806 validated CTD profiles were collected by the Shelf Research Fleet from November 2014 through December 2022 (Figures 1, 2). Weekly and bi-weekly sampling in each Fishing Zone was not always achieved. About 6% of the profiles collected were not included in analyses due to high error readings in the GPS fix in the RBR software, possibly caused by poor GPS reception. Temperature and salinity data collected in Zones 5 and 6 were supplemented by the OOI Coastal Pioneer Array technologies which began implementation in late 2013. Figure 3 displays a time series of the monthly averaged temperature and salinity in each of the Fishing Zones. The eight-year time series of monthly averages help visualize large-scale events such as temperature and salinity anomalies seen in the winter of 2016 – 2017 and in the summer of 2021 (Figure 3).

The Shelf Research Fleet data have been used to study shelfbreak exchange processes. Figure 4 highlights examples of Shelf Research Fleet CTD profiles that provided insight into several large-scale oceanographic events on the continental shelf and slope regions. For example, in January 2017, Shelf Research Fleet data were used to identify an extensive intrusion of warm, salty water onto the continental shelf, contributing to the documentation of a warm core ring-induced marine heatwave (Chen et al., 2022). Chen et al. (2022) analyzed the dynamics of this intrusion and utilized a numerical hindcast to show that this was primarily a bottom-trapped intrusion. The bottom intrusion reached as far north as Block Island, Rhode Island, nearly 100 km shoreward of the shelfbreak. This marine heatwave event led to warm anomalies over a four-month period over the spatial extent from the Great South Channel, just west of Georges Bank, to Cape Hatteras (Gawarkiewicz et al., 2019). In addition to this event being captured by the Shelf Research Fleet profiles, this event simultaneously was highlighted by commercial fishers who noticed unusual bycatch for winter including Gulf Stream flounder *Citharichthys arctifrons* and juvenile black sea bass *Centropristis striata* (Gawarkiewicz et al., 2018). The blue profile in Figure 4 exemplifies an instance in December 2020 in which a bottom water intrusion was occurring and affecting the monkfish *Lophius americanus* catch for a Shelf Research Fleet participant.

The increasing influence of Gulf Stream water masses is also evident in the increasing frequency of occurrence of mid-depth salinity maximum intrusions. The black profile in Figure 4 is an example of a mid-depth intrusion from September 2021. Shelf Research Fleet profiles from 2015 – 2019 were used in an analysis of historical trends in the characteristics of salinity maximum intrusions and showed a significant increase in the frequency of occurrence relative to the time period 1960 – 1998 (Lentz, 2003; Gawarkiewicz et al., 2022). These intrusions were saltier, featured more complex layering, and about 10% of these profiles contained multiple salinity maxima at different depths. To account for this complexity and reduce ambiguity in analyses, the threshold criterion used to identify salinity maximum intrusions within profiles was increased from $\Delta S \geq 0.1$ in Lentz (2003) to $\Delta S \geq 0.2$ in Gawarkiewicz et al. (2022). Thus, the increase in the frequency of occurrence of intrusions over time was likely underestimated (Gawarkiewicz et al., 2022).

3.2 Research applications of Shelf Research Fleet data

The community science efforts using Shelf Research Fleet data have had significant impacts that complemented traditional basic science. Shelf Research Fleet profiles with mid-depth salinity maximum intrusions supported two process-oriented field efforts to map intrusions in three dimensions on the Northeast continental shelf in the summers of 2021 and 2022. Given that salinity maximum intrusions are sub-surface features, traditional tools such as remote sensing could not be used. Shelf Research Fleet participants actively collected more profiles and shared information about fishing and hydrographic conditions in the weeks leading up to the research cruises which ensured an efficient use of ship time. The profiles provided knowledge of the cross-shelf position of the Shelfbreak Front, cold pool temperatures, and stratification in addition to the timing and position of salinity maximum intrusions. Live updates from the research cruises were shared with the Shelf Research Fleet participants when possible.

The Shelf Research Fleet continued to operate throughout the COVID-19 pandemic. While the entire University National Oceanographic Laboratory System fleet of research vessels were suspended from operations, the fishing community was active and collecting data. The Shelf Research Fleet data were important in capturing large temperature anomalies that occurred across the continental shelf in 2020 and 2021. The Shelf Research Fleet collected 127 CTD profiles from March 2020 through the December 2021. The CTD profiles were primarily collected inshore of the Pioneer Array Inshore Mooring, located at the 95 m

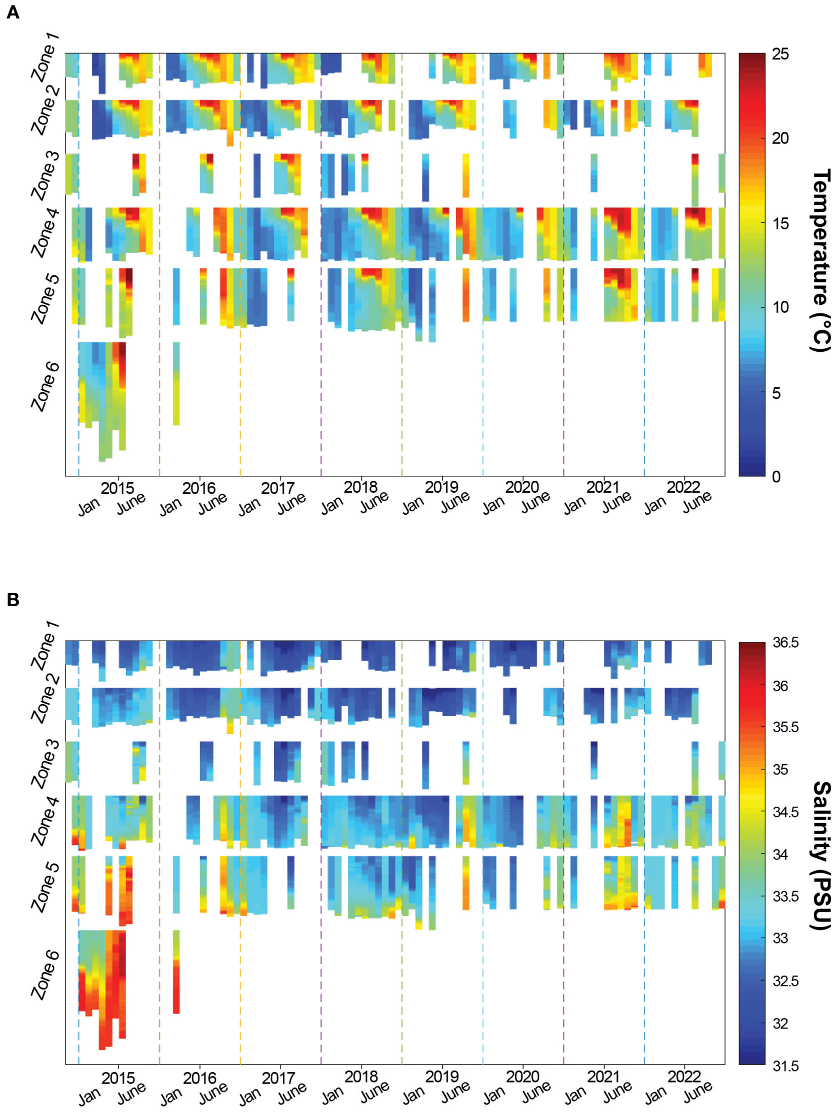

FIGURE 3
Time series of monthly averaged vertical CTD profiles for **(A)** temperature (°C) and **(B)** salinity (PSU) within each of the six Fishing Zones from November 2014 through December 2022. The maximum depth reached by the Shelf Research Fleet CTD profiles ranged from 17 – 52 m in Zone 1, 24 – 60 m in Zone 2, 52 – 77 m in Zone 3, 57 – 80 m in Zone 4, 77 – 122 m in Zone 5, and 119 – 336 m in Zone 6.

isobath. This is the mean position of the foot of the Shelfbreak Front. These profiles helped identify bottom intrusions from offshore that could have significant impacts on the catch of benthic species such as lobsters and Jonah crabs. The bottom intrusions may be important in transporting nutrients onto the continental shelf.

The Task Force Ocean New England Shelf Break Acoustics (NESBA) experiment, an Office of Naval Research funded effort, also relied heavily on the collection of data on the continental shelf from the Shelf Research Fleet. The primary focus area of this experiment was between the 100-meter and 1000-meter isobaths over the continental slope. The sampling locations of the Shelf Research Fleet participants naturally supported the NESBA experiment and the CTD profiles provided important information on stratification over the continental shelf shoreward of the ship operations in the spring of 2021. These data were used extensively in developing accurate numerical models for the circulation and thermohaline structure of the shelfbreak environment. This, in turn, was used to develop forecasts for acoustic propagation which can help contribute to National Security Issues.

4 Discussion

The CFRF-WHOI Shelf Research Fleet is an example of a cost-effective sampling program that leverages commercial fishers' time on the water to help characterize oceanographic processes in Southern New England. Working collaboratively with commercial fishers has increased the availability and timeliness of collecting *in-situ* water column profiles at a critical time of rapidly changing ocean conditions and simultaneous budget cuts to hydrographic sampling programs in the region (Gawarkiewicz and Malek Mercer, 2019). The OOI Coastal Pioneer Array is expected to be relocated to

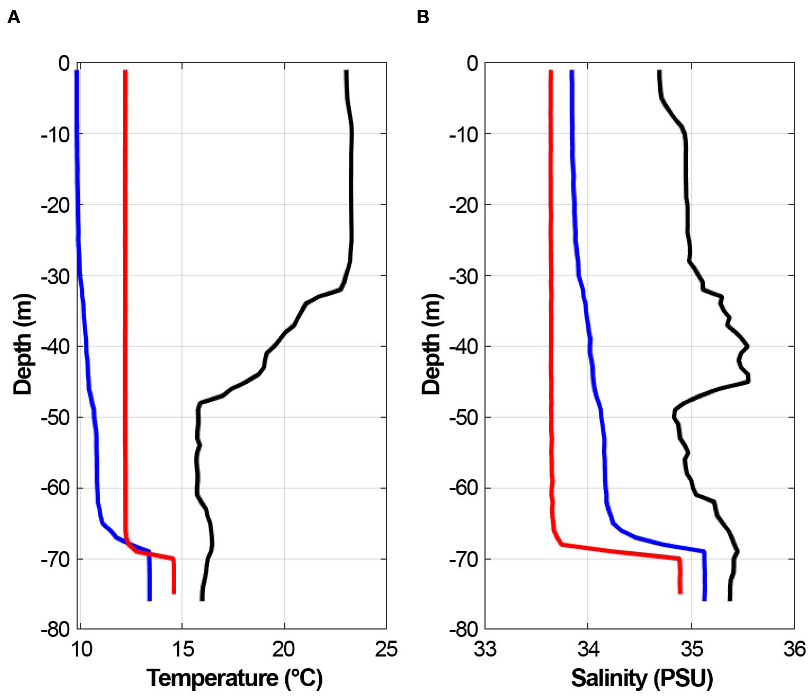

FIGURE 4
The **(A)** temperature (°C) and **(B)** salinity (PSU) at depth (m) of three Shelf Research Fleet CTD profiles showing bottom and mid-depth salinity maximum intrusions. These profiles were sampled in January 2017 (red), December 2020 (blue), and September 2021 (black).

the Southern Mid-Atlantic Bight between Cape Hatteras and Norfolk Canyon by 2024 which will limit the hydrographic research capacities in the continental shelf and slope regions (Ocean Observatories Initiative, 2022). Thus, the continuation of this project is crucial to monitoring this hydrographically and biologically dynamic region.

A majority of the CTD profiling occurred in the northernmost areas, Zones 1 – 4, which coincides with areas of higher fishing effort by Shelf Research Fleet participants. The targeted sampling rates were not always achieved due to a variety of reasons including bad weather, issues with the equipment, periods when boats were hauled out for repairs, fishing area closures, and periods when captains were unable to devote the time to sampling. A future iteration of the Shelf Research Fleet could include more participating vessels to increase the sampling coverage in the region, help the study area expand elsewhere, and increase the diversity of fisheries involved with the program. CTDs could be equipped with additional probes like a pH sensor to help sample for other emerging issues like ocean acidification. In recent years, RBR has developed additional software to further enhance the data via temporal lagging and filtering, in particular to address salinity spikes around unusually sharp vertical gradients. The Shelf Research Fleet research team hopes to test and implement this code in the future as funding opportunities arise. Although the Shelf Research Fleet participants openly share their catch observations at the public Ocean Conditions meetings, there is no formal process to document and catalog biological observations specifically tied to individual CTD casts. This is currently out of the scope of the participant work agreements. Monetary compensation for increased sampling time, privacy concerns related to individual fishing locations, and possible new technological requirements (e.g., a new tablet or phone application) would need to be considered. Sharing fish logbook information could be a way to expedite the inclusion of catch data (Manning & Pelletier, 2009; Patti et al., 2016).

On a broader scale, the coupling of biological and hydrographic observations has the potential to enhance fisheries management, decision making, and ocean use planning by better understanding the interplay between changing ocean conditions, species' distributional shifts, and fishery dynamics (Patti et al., 2016; Schmidt et al., 2019; Van Vranken et al., 2020). In addition, scientists and managers could better detect and analyze climate adaptation strategies (Mills et al., 2013). The Shelf Research Fleet research partners participated in the Northern Shortfin Squid Working Group and Research Track Assessment process and will continue to contribute to the understanding of the relationship of shortfin and longfin squid to ocean events like warm core rings and salinity intrusions along the continental shelf and slope regions.

One of the most valuable attributes of the Shelf Research Fleet program has been the ability to view CTD profiles while at sea and pair these data with personal observations of weather events, ocean dynamics, and fishery catch information in real time. The close communication about research results meant that fishers could use the profiles they collected to make significant business decisions, as for example, shifting from fishing to having repairs done on vessels during a time in which a bottom salinity intrusion is occurring (WHOI, 2022b, Audio available at https://www.youtube.com/watch?v=FVmzHeBsCgA). The fishers' regional expertise in their fisheries increased the research capacity of this project by providing a human dimension that is absent from uncrewed ocean observation tools. Because the CTD profiles were taken primarily where the vessels commercially fish, their observations at sea were critical to contextualizing the hydrographic research within the realm of local fisheries resources. Additionally, the continued enthusiasm and interest in sampling by Shelf Research Fleet participants has helped garnered support from funding agencies to continue and grow this research program over the years.

The Shelf Research Fleet has helped researchers describe and better understand oceanographic phenomena in a rapidly changing environment through a collaborative effort with commercial fishers. In addition to the scientific merits of this collaborative project, the Shelf Research Fleet has also strengthened partnerships between the local scientific and fishing communities while equipping participants with new tools to help them better understand how changing ocean conditions may be affecting their commercial catches. The integration of fishers' knowledge into the various research applications has strengthened the program's research capacity and broadened its scope over time. The Shelf Research Fleet research team hopes to continue working collaboratively with commercial fishers to help support research that aids in the advancement of ecosystem-based fishery management efforts in Southern New England.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://scienceweb.whoi.edu/seasoar/cfrfwhoi/.

Author contributions

GG and AM contributed to conception and design of the study. FB and GG performed data analyses. FB managed the database. FB and NO contributed figures. NO wrote the first draft of the manuscript. All authors contributed to the text, revisions, and approval of the submitted manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1144178/full#supplementary-material

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Mechanisms and models for industry engagement in collaborative research in commercial fisheries

Matthew R. Baker[1*†‡¶], Robert Alverson[2||], Ruth Christiansen[3||], Keith Criddle[4¶], Danny Eilertsen[5§||], Robert J. Foy[6§||], John Gauvin[7‡], Scott E. Goodman[8§||], Leigh Habegger[9||], Bradley P. Harris[10‡], Nicole Kimball[11§||], Anna Malek Mercer[12¶], Edward Poulsen[13||], Matt Robinson[14||], Jeremy Rusin[6||], Rebecca Skinner[15||], Claus Reedtz Sparrevohn[16§||], Kevin D. E. Stokesbury[17§||] and Daryl R. Sykes[18§||]

[1]North Pacific Research Board, Anchorage, AK, United States, [2]Fishing Vessel Owners' Association, Seattle, WA, United States, [3]United Catcher Boats, Seattle, WA, United States, [4]Pollock Conservation Cooperative Research Center, University of Alaska, Juneau, AK, United States, [5]Liberty, Nordic Inc., New Bedford, MA, United States, [6]NOAA Alaska Fisheries Science Center, Seattle, WA, United States, [7]Alaska Seafood Cooperative, United States, Seattle, WA, United States, [8]Bering Sea Fisheries Research Foundation, Bothell, WA, United States, [9]Seafood Harvesters of America, Washington, DC, United States, [10]Alaska Pacific University, Anchorage, AK, United States, [11]Pacific Seafood Processors Association, Seattle, WA, United States, [12]NOAA Northeast Fisheries Science Center, Narragansett, RI, United States, [13]Bering Sea Crab Vessels, Seattle, WA, United States, [14]Bristol Bay Economic Development Corporation, Anchorage, AK, United States, [15]Alaska Whitefish Trawlers Association, Kodiak, AK, United States, [16]Danish Pelagic Producers Organization, København, Denmark, [17]Department of Fisheries Oceanography, University of Massachusetts, Dartmouth, MA, United States, [18]New Zealand Rock Lobster Industry Council, Wellington, New Zealand

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EDITED BY
Yngvar Olsen,
Norwegian University of Science and Technology, Norway

REVIEWED BY
Maria Adelaide Ferreira,
Center for Marine and Environmental Sciences (MARE), Portugal
Bianca Haas,
University of Wollongong, Australia

*CORRESPONDENCE
Matthew R. Baker
matthew.baker@nprb.org

†Symposium Convenor

‡Symposium Steering Committee

§Keynote Speakers

||Panel Participants and Moderators

¶Presenter

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Data and insights from fishers are essential sources of information to advance understanding of fishery and ecosystem dynamics. Incorporating fisher and industry knowledge holds prospects for improving marine science and fisheries management. We address cooperative research in the context of collaboration between fishers, scientists, industries, universities, and agencies to develop applied research to understand marine ecosystems, inform fishery management, enhance sustainability, govern resource use, and investigate social-economic dynamics. We leverage the insights of more than 100 research scientists, fisheries managers, industry representatives, and fishers to outline actionable recommendations for effective approaches and mechanisms to integrate industry data, perspectives, and insights in fisheries science. We also highlight opportunities and address challenges and limitations to such collaboration.

KEYWORDS

fisheries management, fisheries science, fishing industry, cooperative research, science-industry research collaboration

1 Introduction

"You can't look at a problem with knowledge of only one aspect of it. The best group to solve problems will have experience from different perspectives."

Cooperative research (CR) in fisheries and marine science refers to scientific research conducted in partnership with communities, fishers, or the fishing industry (NRC, National Research Council, 2004). In the latter instance, this integration of industry perspectives, equipment, and skills with scientific approaches, applications, and processes has proven effective for compiling fisheries data (Johnson and van Densen, 2007; Hind, 2015), addressing data gaps (Heimann et al., 2023), generating knowledge (Hartley and Robertson, 2008; Jones et al., 2022), monitoring ecosystems (Olsen et al., 2023), engaging stakeholders (Mackinson et al., 2011 Calderwood et al., 2023), and informing management (Wilson, 2003; Baker et al., 2014; Gray and Catchpole, 2021; Mackinson et al., 2023). Science-industry collaboration in fisheries research is gaining further momentum (Steins et al., 2022) and there is increased effort to provide policy recommendations toward facilitating industry contributions to science and management (Murphy et al., 2022; Baker et al., In Press; Steins et al., In Press).

Here we present findings and recommendations from more than 100 fishermen, industry representatives and research scientists participating in panel discussions at the Lowell Wakefield Fisheries Symposium on Cooperative Research – strategies for integrating industry perspectives and insights into fisheries science (Baker et al., 2019a; https://alaskaseagrant.org/events/wakefield-fisheries-symposium). Symposium participants included scientists from government agencies, academics, research institutes, and industry, as well as fishermen and fishing industry representatives from 17 industries in 11 large marine ecosystems. These industries include large-scale fisheries in the commercial sector and collectively represent 26% of global commercial landings and 14% of global commercial fishing landings value (2.45 million metric tonnes and $2.77 billion USD; DDPO, 2023; FAO, 2022; NOAA, 2023; NZRLIC, 2023). Case studies that highlighted industry-led presentations and science-industry teams provided concrete examples of effective collaboration and identified best practices and lessons learned (Figure 1). This symposium aimed to identify challenges, highlight opportunities, and outline actionable recommendations for facilitating effective CR to inform fishery science and management.

In the following sections, we define challenges and opportunities to effective CR in industrialized commercial fisheries and outline actionable recommendations. All quotes are from the scientists, fishers, and industry leads listed here as authors, extracted from discussions at the symposium.

2 Policy options and implications

2.1 Outlining frameworks for finances and funding

"It's incumbent upon everyone who uses the resource, to pay to play. In some cases, that's funding, in some cases that's just participating in the research."

One of the challenges in navigating effective CR is establishing processes for funding and resources. Investment, either by government or industry, raises questions related to responsibilities, priorities, and mechanisms. Most governments with jurisdiction to manage fisheries invest in science. There is often a legal obligation on the government to invest in research to inform decisions related to the use and disposition of a public trust resource (Criddle, 2008). Important questions emerge – How does supplemental funding or financing by industry collaboratives complement government-supported science? To what extent does the funding source help or get in the way? When does it replace it? What are the frameworks that reduce barriers to investment?

2.2 Responsibilities for investment

"The public contribution is the baseline. The money from the industry is designed to enhance that investment. But it's really hard to push back on that tendency to take that additional funding for granted, to rely on that funding, and put any new funding in some other area that doesn't have organizational capacity to provide supplemental private funding. All of a sudden, now we're funding what used to be a government mandate. How do you go backwards?"

Engaging stakeholders in informing management for the sustainable use of living marine resources is critical. Sometimes, that may mean directly financing the science that informs management. However, the caveats are numerous. A common concern for the industry is ambiguity in whether they are getting involved or taking over. Finding the line where government responsibilities end and opportunities for external investment start may be challenging. In the context of management, a core mission of government science should be funding the minimum information needed to manage stocks and set fishing at levels that maintain a fishery into the future. Beyond that, the industry may be well positioned to refine biomass estimates, improve understanding of stock distribution, or inform of how environmental conditions or market variability may influence stocks and markets. There are also devolved approaches to achieving these objectives. In New Zealand, the approach is to specify performance metrics for research and open a process for bids on contracts to conduct the research. A related example would be when agencies contract with Tribes, communities, consulting firms, or university research institutes to undertake studies or maintain data monitoring programs that provide information needed for management. Devolved approaches may be particularly important in regions where government capacity is limited or is costly or impractical for centralized research programs.

Another common concern is that industry investments in CR will result in government funds being re-allocated to other areas. In that case, the industry may be burdened with continuing to support research that was formerly the responsibility of the management agency. The risk is that, when the industry steps in to provide the funding, it will later be difficult to get the government to resume funding in the future.

FIGURE 1
Cooperative research efforts in fisheries detailed in case studies in the Lowell Wakefield Symposium, including **(A)** New Zealand rock lobster fisheries, **(B)** North Sea small pelagic fisheries for herring, smelt and sandeel, **(C)** Northwest Atlantic scallop fisheries, and **(D)** Alaska groundfish and crab fisheries. Photo credits: D.R. Sykes, C.R. Sparrevohn, B. Eilertsen, and M.R. Baker.

2.3 Managing conflict of interest

"There are always external influences and internal biases. If the optics look bad, extra time should be devoted to ensure the process is rigorous, the science is sound, that we're following first principles.

There are inherent dilemmas in industry participation in fisheries science (Jacobsen et al., 2012; Sparrevohn et al., 2019). The aim is to enhance science and increase legitimacy without jeopardizing credibility (de Boois et al., 2021). Questions arise as to whether joint efforts represent collaboration or collusion (Sykes, 2019). These challenges may be recognized and explicitly addressed through contracts, performance metrics, quality-control processes and other mechanisms to ensure transparency and oversight. In many regions, including New Zealand, Europe, Canada, the northwest Atlantic, the northeast Pacific, and Alaska, there appears to be evidence of a paradigm change in how fishery, science and advice are interacting (Ma et al., 2019; Mercer et al., 2019; Sheridan and Templin, 2019; Sparrevohn et al., 2019; Sykes, 2019). Challenges include – how to increase industry confidence in the research and how to adapt scientific processes to incorporate the knowledge and insights of fishers. To maintain stakeholder support, research processes must be clearly articulated, well-substantiated, impartially applied, and respectful of sources of knowledge and ways of knowing. Core components to success have been clear protocols for information sharing (early and often), strong frameworks for coordination, communication and response, and a priority on increasing stakeholder trust in processes and outcomes. Transparency in the engagement process is critical to internal and external audiences, and effective implementation and application to management requires a thorough understanding of stakeholder motivations for participation. Finally, submitting the research to rigorous external peer-review will often address perceptions of bias or concerns about conflicts of interest.

"There's a number of people who have said, 'we shouldn't have industry involved at all.' Why are we not conducting science in a manner that allows us to follow the math, identify the biases, spot flaws in the process, and identify where the outcome has been driven by a particular input?"

3 Actionable recommendations

"OK, we've got to do something."

CR is often conducted on a large scale through organized mechanisms that incentivize involvement. Successful examples include research set-aside programs, cost recovery, fisheries collaboratives, and cooperative research institutes and programs. We discuss each in the following sections.

3.1 Models for industry-financed science

"Government investments change over time, and we may be left with data gaps that hurt industry. There are risks with industry taking over the funding, but there are also huge benefits to ensuring that we have the information and data that we need."

In the New Zealand Rock lobster fishery, where industry leads research, industry stakeholders gain confidence that funding will be directed toward issues most critical to the fishery (Sykes, 2019). Similar results have been noted in fisheries collaboratives in Alaska (Behnken and Sylvester, 2019; Oliver et al., 2019) and New England (Mercer et al., 2019; Stokesbury and Eilertsen, 2019), where formal agreements between industry, scientists, community stakeholders, research institutes, and management authorities result in collaboratives able to address budget shortfalls and ensure sufficient resources to manage fisheries in an informed manner.

3.2 Research set-aside programs

"We started out with 1% of our total allocation. And that 1% would go out for bids. Science organizations could write proposals. There was a panel to review proposals and award bids to support research. The captain, the crew, the owner – would get a smaller percentage, but with a return. And now we've increased it to 2%. The industry drove that, the industry wanted it."

Research Set-Aside (RSA) programs provide a mechanism to fund research and compensate vessel owners participating in research through the sale of fish harvested under a research quota. The New England Council (and until recently, also the Mid-Atlantic Fishery Management Council) set-aside is awarded through a competitive grant process managed by the National Oceanic and Atmospheric Association (NOAA), with priorities established by the Councils. Solicitations for RSA proposals are posted at www.grants.gov and distributed widely through the Councils and NOAA Fisheries public relations channels. In New England and the western Atlantic region, RSA programs have a demonstrated track record for supporting applied research that informs fishery management decisions and improves stock assessments. RSA programs have been applied to the Atlantic Sea Scallop, Atlantic Herring, and Monkfish Fishery Management Plans. Examples of research include habitat analyses and evaluation of fishing impacts (Stokesbury and Harris, 2006).

3.3 Cost recovery

"The investment in rock lobster fishery science has partial cost recovery. The rough rule of thumb is 75% of the cost of research has to be recovered by the industry. And because we are paying, we have a say in what is funded."

Another approach is cost recovery. While most countries use general tax revenues to fund fisheries research, others levy the commercial fishing industry to recover research costs. In this context, research costs are shared between the sector and taxpayers. A more direct relationship between the primary beneficiaries of fisheries management (i.e., fishermen) may lead to more efficient interventions. Fishers may be more incentivized to pressure governments for services that meet needs in an efficient manner (e.g., Organization for Economic Co-operation and Development, Wallis and Flaaten, 2000). Cost recovery is applied in Canadian and New Zealand fisheries (Dewees, 1998). In British Columbia, this occurs through community-based self-management and government-community co-management cost-sharing arrangements (Thompson et al., 2019). In New Zealand, quota owners pay resource rents on the quota through a cost-recovery regime. The rationale is to (1) secure revenue to offset fisheries management costs; (2) encourage greater industry responsibility to reduce regulation and costs; (3) provide industry voice in the development and delivery of fisheries management; and (4) match levies to resource rent (Harte, 2007).

3.4 Fisheries collaboratives

"Institutions enable cooperative research, but people conduct cooperative research."

Fisheries collaboratives are agreements between industry, communities, agencies, and other actors with vested interest in a particular fishery. In Alaska, the Bristol Bay fisheries collaborative (https://www.bbsri.org/bbfc) includes the state management agency and a federally-authorized regional community development quota program, representing local fishermen, villages, and municipalities. The formal agreement commits the signatories to contribute and raise funding from the fishing industry and other stakeholders to ensure that fishery managers have sufficient resources to manage salmon for the benefit of all users. Benefits include a consolidated and reliable funding mechanism and a more coordinated research approach, that simultaneously examines multiple projects and their potential to maximize benefits to the fishery.

3.5 Industry-led cooperative research institutes and foundations

"In collaborative research, sometimes it is stakeholders who lead the way."

There are many examples of industry-led research cooperatives that advance CR. The Pollock Conservation Cooperative Research Center is industry-funded, but managed through an academic partner, the University of Alaska Fairbanks, which supports peer-reviewed competitive research grants. Research priorities are recommended by an advisory board that includes industry representatives, university leads, and representatives from a federal or state management agency. Priorities include research to improve biological data and statistical models of stock status, analyses of incidental catch and discard mortality, ecosystem considerations, management strategy, and sustainability of protected species (Criddle, 2019). The Bering Sea Fisheries Research Foundation (BSFRF) is another industry group representing commercial fishing interests, particularly crab. BSFRF has partnered with NOAA in CR related to king, snow, and Tanner crab surveys assessments, and estimates of crab handling mortality (Foy and Goodman, 2019). Research projects are prioritized by a joint agreement between BSFRF and NOAA within a framework set by the North Pacific Fishery Management Council. Cooperative projects include analyses on trawl efficiency in the NOAA bottom trawl survey. Other examples include the Aleutian Longline Fishermen's Association Fishery Conservation Network (Behnken and Sylvester, 2019).

3.6 Cooperative research programs and development agreements

"It came from talking to each other and then working together. Now, the average fisherman is in direct collaboration with enforcement – the guys who were there to shut us down with regulations that we just couldn't follow. We went from complete breakdown to being able to work together."

Several research-based institutions have also developed CR programs to foster direct engagement and collaboration between industry and scientists (Table 1). Examples in the US include North Pacific Research Board (NPRB) and NOAA science center initiatives (Baker et al., 2019b; Chandler, 2019; Foy, 2019). Partnerships between fishing fleets and the science community can bring many benefits, including enhanced data access, information sharing, economic efficiency, and societal empowerment.

NPRB strongly encourages CR with industry (Baker and Smith, 2018; Baker et al., 2019b) and funds research in the North Pacific that addresses stock assessment, gear modification, electronic monitoring of fleet activity, monitoring for marine disturbance, tracking and movement studies, marine mammal depredation on fishing gear, and bycatch reduction. These efforts not only support marine observations, but often address pressing management needs and improve understanding between the research community, management agencies, and industry.

NOAA Fisheries' Cooperative Research Program involves regional partnerships with a broad range of external stakeholders, including state and tribal managers and scientists, fishing industry participants, and academic institutions (Chandler, 2019). Benefits include increased quantity and quality of data, inclusion of stakeholder knowledge in science and management, improved relevance of research to fisheries management, and reduced costs. Other benefits include shared understanding of science, stakeholder buy-in, improved relationships with constituents, and incorporation of industry knowledge, local knowledge, and traditional knowledge in a representative framework (Foy, 2019).

In New England, the Commercial Fisheries Research Foundation was founded and led by members of the fishing community to provide fishermen with opportunities to contribute to the science and management of key fisheries resources (Mercer et al., 2019). The CFRF develops practical solutions to scientific and supply chain challenges, providing fishermen with specialized apps to collect biological and environmental data and developing scientific products (e.g., digital maps of the seafloor) to inform fishery management. CFRF initiatives have been successful in reducing bycatch through conservation engineering, improving data for stock assessments, and growing markets and consumer awareness of underutilized species (Mercer et al., 2019). Research includes fisheries-based research fleets for lobster (*Homarus americanus*), Jonah crab (*Cancer borealis*), quahog (*Mercenaria mercenaria*) and black sea bass (*Centropristis striata*).

3.7 Forums for discussion and engagement

"What I've seen is, you get people in the same room. At the outset, you have a dialogue. Over time, you're exposed to information through some of the same people. And eventually you realize, 'wait a minute, they're actually doing something that makes sense.' Also, 'here's how to improve that.'"

Much of fisheries management occurs in public forums such as local, regional, or national fishery management council meetings (e.g., US regional fishery management councils http://www.fisherycouncils.org/; ICES regional and advisory areas, https://www.ices.dk/) or commissions developed to focus on specific target

TABLE 1 Established platforms for Cooperative Research and Industry-led initiatives in North America.

Framework for Collaborative Research	Description of Collaboration	Relevant References
Alaska Longline Fisheries Association Fishery Conservation Network	ALF-AFCN engages fishers in research and conservation including more than 100 fishermen, 100 vessels, and has successfully implemented 7 fisher-led projects.	Behnken and Sylvester, 2019
Alaska Hatchery Research Project	AHRP aims to ensure hatchery programs are not detrimental to wild salmon and develop trust among stakeholders, including the Alaska Department of Fish and Game, University of Alaska, salmon hatchery operators, and National Marine Fisheries Service.	Sheridan and Templin, 2019
Alaska Seafood Cooperative	ASC launches collaborative initiatives with management agencies to reduce bycatch mortality, including in Pacific halibut, using exempted fishing permits to sort halibut from target catch and expedite release. Processes are refined iteratively, with industry and agencies collaborating to problem solve and improve design.	Oliver et al., 2019
The Commercial Fisheries Research Foundation	CFRF was founded by Rhode Island's fishing community to develop practical solutions to scientific and supply chain challenges (e.g., collect biological and environmental data, digital maps) and implement initiatives to reduce bycatch, improve stock assessment data, and promote consumer awareness.	Mercer et al., 2019
Bering Sea Fisheries Research Foundation	BSFRF is an industry group representing commercial fishing interests and has partnered with management agencies on research relevant to king, snow, and tanner crab surveys, trawl efficiencies in agency surveys and estimates of crab handling mortality.	Foy and Goodman, 2019
International Pacific Halibut Commission	IPHC engages in multiple CR programs, building on interest from industry for data collection, dockside collection programs, and confidentiality agreements. Programs include at-sea sex-marking protocols for commercial vessels, testing of sex-marking methods, and genetic assays to monitor landed commercial catch. CR programs also estimate discard mortality rates in the longline fishery to estimate injury and vitality.	Stewart et al., 2019; Dykstra et al., 2019
NOAA Fisheries Cooperative Research Program	NOAA-FCRP is a nationwide network coordinating regional partnerships with a broad range of external stakeholders, including state and tribal managers and scientists, fishing industry, and universities. Benefits include increased quantity and quality of data, inclusion of stakeholder knowledge, improved relevance of research to fisheries management, and reduced costs.	Chandler, 2019
NOAA Fisheries Cooperative Research Program, Alaska Fisheries Science Center	NOAA-AFSC is engaged in multi-agency research, collaboration with industry sectors and co-production of research with coastal communities. Specific collaborative research includes longline surveys (Malecha and Lunsford, 2019), biometric data collection (Lang and Foy, 2019), tagging and recovery studies (McDermott et al., 2019), logbook programs (Rodgveller and Lunsford, 2019), and collection of opportunistic acoustic data (Barbeaux et al., 2019).	Foy, 2019
North Pacific Fisheries Research Foundation	NPFRF builds collaborations to develop and implement salmon excluders in the pollock fishery to reduce incidental catch. To mitigate bycatch caps and time and area closures, fishermen have developed gear modifications to enable salmon escapement. Funding is provided through industry donations and in-kind support from industry and management agencies.	Gauvin et al., 2019
North Pacific Research Board Investments in Cooperative Research with Industry	NPRB encourages and funds competitive grants for cooperative research with industry as well as community engagement projects. Research in CR has included stock assessment, gear modification, electronic monitoring of fleet activity, monitoring for marine disturbance, tracking and movement studies, marine mammal depredation on fishing gear, and bycatch reduction.	Baker et al., 2019b; Baker and Smith, 2018
Pollock Conservation Cooperative Research Center	PCCRC is an industry-funded research center managed at the University of Alaska that supports competitive research grants and fellowships. Research priorities are recommended by industry and include: improved biological data and statistical models; estimates of discard mortality; habitat and ecosystem considerations; fisheries management strategy and regulatory flexibility; sustainability of protected species; and product value.	Criddle, 2019

species (e.g., International Halibut Commission, https://iphc.int/, Pacific Salmon Commission, https://www.psc.org/). These forums provide a framework for regular meetings including research scientists, fishery managers, fishermen, and community members and representatives. This is intended to 'allow regional, participatory governance by knowledgeable people with a stake in fishery management' (http://www.fisherycouncils.org/). Plans and management measures (e.g., fishing seasons, quotas, bycatch regulations, closed areas) are constituted following public review and discussion of scientific advice.

At the International Council for the Exploration of the Sea (ICES), stakeholders 'sense test' the science, develop ideas for process reform, solicit priorities for the strategic plans, participate in advisory forums, and engage in meetings to guide research programs (Ballesteros and Dickey-Collas, 2021). ICES principles, policies, and strategic plan require stakeholder engagement and identified pathways for participation include expert groups and workshops, consultation or scoping exercises, and participatory research and co-creation of knowledge (Dankel et al., 2016; ICES, 2023).

While these meetings and associated workshops create platforms for fishermen to contribute to management processes, Councils and regulatory authorities determine allocation and limits; other more targeted forums may be more successful in fostering and incentivizing CR projects and innovation. Many other institutions integrate perspectives of fishermen, fishery managers and scientists (Table 1) to determine priorities for research, identify mechanisms for collaboration, discuss ideas on how to improve what is known about fish stocks and marine systems, and determine how to conserve the resource and optimize management.

"In the North Pacific, fishery management and the annual development of stock assessment plans has processes that directly engage industry through plan teams and other processes that enable a back-and-forth with the scientists. This is one avenue for increased engagement. The data are often straightforward but the interpretation is challenging"

4 Discussion – best practices and principles of cooperative research

"So what's the best way forward?"

Initial success is often achieved through finding common ground and staying simple. Longterm success is often achieved by maintaining momentum, carefully examining processes, and repeating what works. Continued collaboration means constantly refreshing and revisiting aims and objectives, and refining the approach. Best practices distilled from multiple regions resulted in a set of principles for effective and sustainable CR (Table 2). Crucial elements focus on how CR should be collaborative, robust, relevant, cost-effective, timely, directed, and involve dedicated and engaged partners. Recognizing expertise and integrating disciplines and perspectives can provide opportunities to build trust. Open communication and exchange maintain integrity and focus. Clarifying roles and responsibilities confirm commitments and mitigate potential conflict. Sharing data and publishing together strengthen relationships, promote transparency, and ensure results are well-positioned to inform management.

"Find success, and from that, benefits flow. Early on, find projects that are small, tractable, maybe pilot work that has a high chance of success. Get a win and get momentum. Over the years, you form relationships; it helps to have that trust."

TABLE 2 Guidelines and Best Practices.

o Understand the management process and its timing
o Avoid conflicts of interests among stakeholders and researchers
o Prepare for people issues and potential conflict
o Identify and recruit strong leaders
o Anticipate unexpected results and new questions
o Develop large sample sizes to ensure robust research results
o Avoid sensationalized reporting of research results
o Strive for transparency
o Acknowledge disagreement early and often
o Share all data and results openly
o Publish results collaboratively

These guidelines and best practices were distilled from multiple sources and presentations throughout the week-long symposium and subsequent discussions. Information is distilled and sequenced here to highlight some of the most important takeaways from professionals and experts with experience designing and implementing cooperative research in fisheries from both science and industry perspectives.

Author contributions

MB: Symposium Convenor, Steering Committee, Presenter, Conceptualization, Writing, Editing. RA: Panel. RC: Panel. KC: Presenter. DE: Keynote Speaker, Panel. RF: Keynote Speaker, Panel. JG: Steering Committee. SG: Keynote Speaker, Panel. LH: Panel. BH: Symposium Convenor. NK: Keynote Speaker, Panel. AM: Presenter. EP: Panel Moderator. MR: Panel Moderator. JR: Panel. RS: Panel. CS: Keynote Speaker, Panel. KS: Keynote Speaker, Panel, Editing. DS: Keynote Speaker, Panel. All authors contributed to the ideas presented here. All authors were invited speakers, panelists, and/or symposium convenors at the 2019 Lowell Wakefield Fisheries Symposium on cooperative research. This manuscript was organized and developed by the lead author (Symposium Chair) and reflects insights and perspectives of listed contributing authors, developed in panel discussions, invited presentations, and subsequent correspondence and exchange. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author DE was employed by Liberty, Nordic Inc. Author MR was employed by the company Bristol Bay Economic Development Corporation.

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Publisher's note

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EDITED BY
Robert Stephenson,
Fisheries and Oceans Canada (DFO),
Canada

REVIEWED BY
Ernesto Jardim,
Marine Stewardship Council (MSC),
United Kingdom
Bianca Haas,
University of Wollongong, Australia

*CORRESPONDENCE
Ashley R. Wilson
awilson@pewtrusts.org

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Management procedure development in RFMOs offer lessons for strategic and impactful stakeholder engagement and collaboration

Ashley R. Wilson[1]*, Shana K. Miller[2] and Grantly R. Galland[3]

[1]The Pew Charitable Trusts, London, United Kingdom, [2]The Ocean Foundation, Washington, DC, United States, [3]The Pew Charitable Trusts, Washington, DC, United States

International and domestic fisheries management bodies are increasingly embracing a management procedure (MP) approach to managing their living marine resources. An added advantage of an MP approach is the opportunity for strategic and impactful engagement and collaboration among resource managers, user groups, civil society and other stakeholder groups in MP development, adoption, and implementation. We consider examples from four regional fisheries bodies (i.e., RFMOs and a multi-lateral body) where stakeholders are contributing to the development of MPs for several stocks to varying degrees. These case studies highlight differing structures and processes for open and transparent stakeholder engagement in management strategy evaluation (MSE) and MP development. We identify that one important difference between sufficient and insufficient stakeholder engagement in these cases is the presence or absence of formalised structures and processes for inclusive and open stakeholder engagement, where there are key roles for stakeholder inputs and feedback during key stages of MSE and MP development. We highlight the benefits of engaging stakeholders from the outset of the MP development process, including designing processes, agreeing on the timelines and workplan for MSE and providing inputs that can lead to the successful adoption of an appropriate MP. We then consider how stakeholder engagement may be improved in other multi-lateral regional fisheries bodies, such as the NEAFC/Northeast Atlantic coastal States management forums, as well as other relevant RFMOs.

KEYWORDS

marine resource management, management strategy evaluation, regional fisheries management organizations, stakeholder participation, dialogue

1 Introduction

A growing number of international management bodies and domestic agencies are embracing a Management Procedure (MP) approach to managing their living marine resources (Punt et al., 2016; Nakatsuka, 2017; Sharma et al., 2020). In this approach, managers adopt pre-agreed harvest control rules (HCRs) that are used to automatically set fishing opportunities based on indicators of stock status, all with the goal of meeting their pre-agreed objectives for the management of the resource (Butterworth, 2007; Rademeyer et al., 2007; Dowling et al., 2015). Importantly, during the development of a robust management procedure (MP), the HCR and reference points are tested using numerical simulations through the process of management strategy evaluation (MSE) in order to choose and adopt an MP that is likely to be successful in the future, across a range of potential biological (e.g., fecundity, age of maturity, or natural mortality), ecological (e.g., mixing of closely related stocks, or booming/busting predator populations), environmental (e.g., water temperature or primary productivity), and anthropogenic (e.g., illegal fishing, effort creep) parameters (Merino et al., 2019). The pre-agreed nature of this approach reduces the political negotiation in traditional fishery management. Such negotiations have contributed to unambitious, non-scientific, and economically costly decisions in several fora over many decades, and these shortfalls have contributed to the aforementioned shift (Hillary et al., 2015).

An added advantage to the MP approach to fishery management is its opportunity for – and reliance on – stakeholder engagement and inputs during the MP development process (Cox and Kronlund, 2008; Mapstone et al., 2008; Feeney et al., 2019; Goethel et al., 2019; Miller et al., 2019). The definition of a stakeholder has evolved through time (Freeman, 1984; Reed et al., 2018), and the term now features in global standards, such as the AA1000 Stakeholder Engagement Standard, which provides a framework to help businesses, governments, and other organizations demonstrate inclusive sustainability-related stakeholder engagement practices (AccountAbility, 2015). The AA1000 highlights that "*Stakeholders are not just members of communities or non-governmental organisations. They are those individuals, groups of individuals or organisations that affect and/or could be affected by an organisation's activities, products, or services and/or associated performance with regard to the issues to be addressed by the engagement.*" Therefore, in the context of fisheries management, stakeholders may be defined as individuals, groups of individuals or organizations who affect and could be affected by decisions/actions on the use, conservation, or management of fishery resources. There is a growing acceptance that it is important to involve the fishing industry in fisheries science, particularly given the unique knowledge that fishers possess (Stephenson et al., 2016) and the value of fishery-dependent data sources on assessment and MSE results (Steins et al., 2022). But within the MP context, "stakeholders" should be considered more broadly and may include fisheries managers, scientists, and numerous other stakeholders such as commercial, subsistence and recreational fishers, indigenous communities, fish processors, vessel owners, seafood companies, retailers, environmental non-governmental organizations (NGOs), and others who rely on fisheries resources or are affected by fisheries. Each of these groups may have different philosophies for the management of their fisheries; development of MSE and adoption of an MP allow these different philosophies to be defined and quantified (Miller et al., 2019). Various typologies have been proposed to categorize stakeholders and the roles they play in marine policy and science (Newton and Elliott, 2016; Ballesteros and Dickey-Collas, 2023).

Successful engagement and collaboration with stakeholders is important because stakeholders can bring additional or unique data and knowledge that is relevant to science and management (Stephenson et al., 2016). How data, knowledge and perceptions are incorporated into science, and how scientific outputs are communicated to stakeholders can impact the relevance, salience, legitimacy, credibility and trust in that science, as well as how that science is overall fed into strategic and potentially impactful management of fisheries (Winter and Hutchings, 2020; Steins et al., 2022).

As demonstrated in several examples across multiple regional fisheries management organizations (RFMOs), including in the four case studies discussed below, the development and adoption of an MP requires substantial stakeholder interaction. Because the dialogue-driven and transparent MSE development process has differed notably from that of political negotiations on fishing opportunities, which are a hallmark of a more traditional approach to management, the shift to the adoption of MPs has indirectly led to new opportunities for stakeholder engagement and collaboration, particularly at the tuna RFMOs (tRFMOs) (Goethel et al., 2019; Miller et al., 2019).

Here, we describe this evolution and provide case studies that highlight examples of good and poor practices in stakeholder engagement and collaboration. By stakeholder engagement we mean the process of involving and seeking stakeholder inputs, including data, knowledge, views, and preferences, into the science and management process. By stakeholder collaboration we mean how scientists, managers and other stakeholders actively work together in the process of MSE and MP development to inform strategic and impactful management decisions. The case studies were chosen based on author involvement in the process, and through these examples we share our experiences as full-time fishery conservationists working on fisheries across the full spectrum of management, from those fisheries still requiring political negotiation to those with MSE-based MPs now being implemented.

2 Stakeholder engagement under traditional management

Under the traditional approach to international fishery management, scientists conduct stock assessments, which they use to recommend catch or effort limits and/or other regulations, and then managers decide whether to strictly follow, modify, or disregard that scientific advice when setting the limits. There is essentially no formal stakeholder engagement at the multilateral level as part of that process, and the individual members of the relevant management bodies vary widely in outreach to their national stakeholders. For example, the United States' approach to outreach ahead of each meeting of the tRFMOs is comprehensive. It consists of advisory bodies comprising commercial and recreational fishers, academic scientists, and representatives from environmental organizations convening to formally advise the delegations to the relevant meetings. While some other governments have similar processes in place, many have limited their outreach to a small number of representatives of the fishing sector (Aanesen et al., 2014; Yates, 2014; Schwermer et al., 2020). A review of the participant lists from RFMO Commission meetings reveals that most delegations to an international fishery management meeting include commercial fishers or their representatives who have a substantial influence on the process (pers. obs.). For example, the delegation from just the European Union (EU) to the 2019 annual meeting of the International Commission for the Conservation of Atlantic Tunas (ICCAT) included more than 115 representatives of the fishing industry (ICCAT, 2019a). Some delegations to the Inter-American Tropical Tuna Commission (IATTC) offer the microphone to representatives of the industrial fishing sector to speak on behalf of their entire citizenry, even in cases when those individuals are not from the country behind whose flag they speak (pers. obs.). Stakeholder engagement under the traditional approach to international management is often inequitable, inconsistent, and generally reserved for each delegation to do (or not do) on its own. Under this approach, some stakeholders may not be consulted sufficiently, or at all.

3 Stakeholder engagement during management procedure development

Stakeholder engagement is a hallmark of MP development through MSE. Unlike the traditional approach where there is a unidirectional flow of information from scientists to managers, who then seek stakeholder feedback, MP development is meant to fully integrate stakeholder input throughout (Goethel et al., 2019; Miller et al., 2019). This iterative process partners scientists and stakeholders at each step. Managers are considered stakeholders alongside industry and environmental organizations, among other interested parties.

There are several key decision points in the MSE process where stakeholders could provide input (Figure 1). Some steps – like choosing management objectives that set the philosophy for how fisheries are managed – should explicitly include input from fishers, environmental organizations, and other stakeholders. Other steps – like designing candidate management procedures (MPs) – could be undertaken by these groups or their delegates, directly, or it could provide opportunity for stakeholders to comment on their preferred options.

Engaging stakeholders in each of these steps requires additional time and communication, but this investment has multiple benefits. The process is more robust by accounting for the unique knowledge of the various sectors, and these groups become vested in the process, making them more likely to support the outcome. Trust and understanding increase, both within and among stakeholder groups, and the bottom-up approach contributes to inclusivity and transparency in fisheries management (Goethel et al., 2019; Miller et al., 2019).

Different fora engage stakeholders in different ways (e.g., written response consultations, interviews, questionnaires/surveys, in-person dialogue). Whatever form they take, these engagement efforts should be convened at the beginning of the MSE process and meet regularly throughout, and they can be both informal and formal. For example, informal efforts can provide a venue for capacity building, brainstorming, and solicitation of general input, while decision-making can occur at more formal sessions that include managers among other stakeholders. Where an MSE is being developed to identify a preferred MP, there should be clearly defined opportunities for strategic dialogue.

4 Case studies using an MP approach

There are several examples where stakeholders have contributed constructively to the development, adoption, and implementation of an MP for internationally managed stocks (e.g., southern bluefin tuna, Greenland halibut, Atlantic bluefin tuna, Indian ocean skipjack tuna, and Indian ocean bigeye tuna). Below we describe four examples from different RFMOs around the world with different approaches and levels of stakeholder engagement during MP development. Two examples have gone through MP development and are being implemented, and two are still undergoing development.

4.1 Atlantic bluefin tuna – good stakeholder engagement

Atlantic bluefin tuna (*Thunnus thynnus*) is one of the most valuable (McKinney et al., 2020), but also controversial and intensely managed, species in the world. It falls under the jurisdiction of ICCAT, a tRFMO that regulates all Atlantic fisheries for tunas, swordfish, billfishes, and pelagic sharks. In 2015, ICCAT committed to developing MPs for eight priority stocks, including Atlantic bluefin (ICCAT, 2015a). The bluefin MSE was already underway at that point, with a dedicated technical steering group established in 2014 (Di Natale, 2015). The development process summarised in Table 1 successfully concluded in 2022 with MP adoption (ICCAT, 2023).

There was considerable stakeholder input in the development process, starting in 2014 with the first meeting of the Standing Working Group to Enhance Dialogue Between Fisheries Scientists and Managers (SWGSM). SWGSM was established as a venue primarily for discussions related to MPs, although ecosystem-based fisheries management has also featured on agendas (ICCAT, 2014; ICCAT, 2015b; ICCAT, 2017; ICCAT, 2018a). There were three SWGSM meetings that covered the bluefin MSE, but since 2018, discussions were moved to meetings of

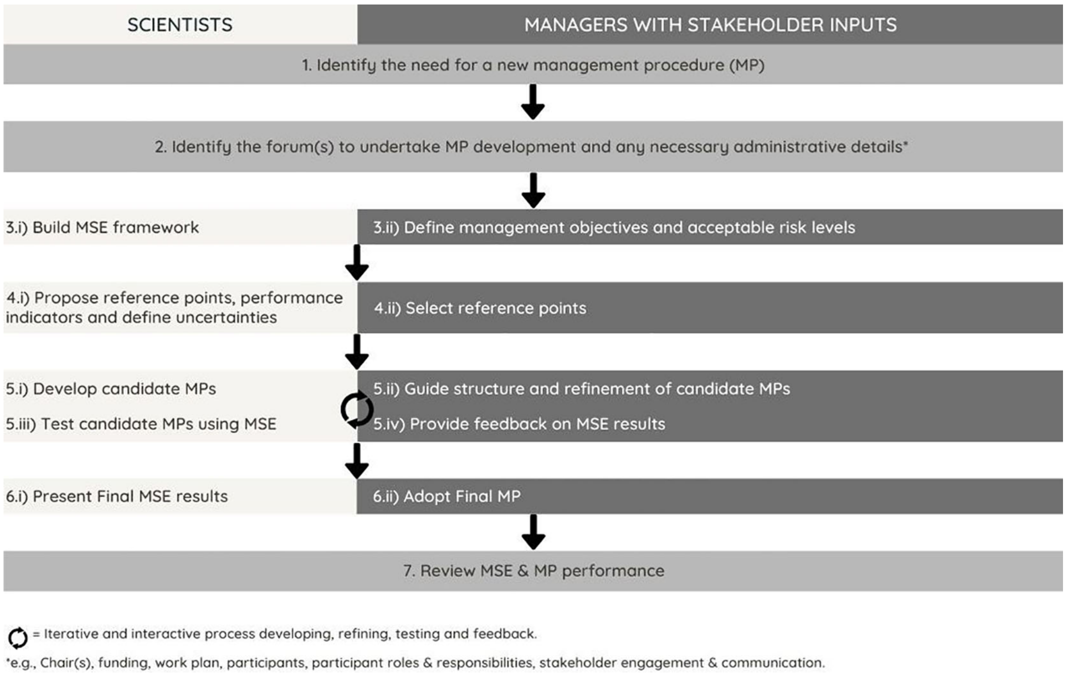

FIGURE 1
Process to develop a management procedure, from idea to adoption, highlighting opportunities for stakeholder input.

Panel 2, the ICCAT species-specific subgroup in charge of Atlantic bluefin. This enabled a more targeted focus on issues pertaining directly to the bluefin MSE. Panel 2 met intersessionally three times in 2021 and four times in 2022 to advance the bluefin MSE toward completion. Stakeholders were encouraged to participate in SWGSM and Panel 2 meetings, either as members of their national delegations or as accredited observers. The most influential stakeholder engagement was in crafting management objectives and setting specifications for the MP, including MP type and management cycle length (ICCAT, 2018b; ICCAT, 2019b; ICCAT, 2022a; ICCAT, 2022b; ICCAT, 2022c).

Both industry and environmental stakeholders also participated in the technical science meetings, again on national or observer delegations. Stakeholders provided input on what uncertainties to include in the MSE, as well as how to weight the likelihood of the various scenarios. This plausibility weighting was achieved via a poll of ICCAT's bluefin tuna species working group, where input from scientists representing stakeholders was considered equally to that

TABLE 1 Number of meetings open to stakeholder input during development and adoption of a management procedure (MP) for Atlantic bluefin tuna by the International Commisison for the Conservation of Atlantic Tunas (ICCAT)

Year	Science Meetings	Standing Working Group to Enhance Dialogue Between Fisheries Scientists and Managers	Panel 2	BFT MSE Ambassador Meetings	Commission Annual Meeting
2014	1	1			
2015	1	1			Adopted measure calling for Atlantic bluefin MP
2016	1		1		
2017	1				
2018	1	1			Adopted conceptual management objectives
2019	4		1		
2020	5				
2021	3		3	1	
2022	4		4	2	Adopted MP

Panel 2 is the ICCAT subidiary body that manages Atlantic bluefin tuna fisheries; BFT MSE, bluefin tuna management strategy evaluaton; BFT MSE Ambassador Meetings were capacity building efforts by ICCAT's scientists to provide information and answer questions about the MSE development.

from government scientists (ICCAT, 2021a). Stakeholders also influenced which abundance indices would be included in the candidate MPs, as well as the general structure of the MPs. Developers consulted regularly with stakeholder groups, and some were funded by stakeholders (e.g., Johnson and Cox, 2021). Stakeholders were welcome to submit candidate MPs for testing, making for a very inclusive process. Careful consideration by the working group's chair ensured that the industry's on-the-water expertise was reflected and stakeholder confidence in the process was secured, while maintaining the scientific integrity of the process.

There was also more informal engagement from stakeholders. In 2021 and 2022, ICCAT scientists selected three "ambassadors," one for each of ICCAT's official languages. These ambassadors hosted open meetings where they provided updates on the process and forthcoming decision points and then fielded questions from the audience. Other stakeholders, including market representatives and elected officials, voiced their views as well through op-eds, webinars, joint statements, and other communication tools.

By the time the bluefin MP was adopted in November 2022, there had been over 20 ICCAT dialogue meetings that brought together scientists, managers, and other stakeholders to discuss and deliberate on the topic. As a result, the MP was adopted and fully implemented immediately without opposition since the stakeholders were familiar with and vested in the approach. This provides a strong example of stakeholder engagement in MP development and is an improvement over the experiences of the previous several decades of traditional management for Atlantic bluefin.

4.2 Greenland halibut – sufficient stakeholder engagement

Greenland halibut (*Reinhardtius hippoglossoides*) is a flatfish with circumpolar distribution in the northern oceans (Chiperzak et al., 1995). In the Atlantic, the Northwest Atlantic Fisheries Organization (NAFO) has jurisdiction over the stock off the coast of the Canadian maritime provinces known as Subarea 2, Division 3KLMNO. The stock has long been depleted (NAFO, 2003), and NAFO adopted a 15-year rebuilding plan in 2003 (NAFO, 2008). Seeing limited recovery success, NAFO scientists opted to develop an MSE for the stock in 2008 to explore an alternate rebuilding strategy (NAFO, 2008).

After the initial MSE framework was developed, NAFO convened a dialogue group to engage managers and other stakeholders in the process, the Working Group on Greenland Halibut Management Strategy Evaluation (WGMSE). The WGMSE met three times in 2010, in January (NAFO, 2010c), May (NAFO, 2010a), and September (NAFO, 2010b), to successfully take the MP to adoption in late September of that year. Stakeholder input in these meetings was considerable, weighing in on MP specifications as well as the workplan for completion. However, stakeholder representation and diversity were deficient. While there were managers and industry representatives present for the iterative exchange with scientists throughout the year, no conservation groups or other stakeholders participated.

In 2013, with expanding MSE initiatives for other stocks, NAFO formed the Joint Fisheries Commission-Scientific Council Working Group on Risk-based Management Strategies (WG-RBMS) to serve as a venue for dialogue on MP development and implementation for all stocks (NAFO, 2013). When the Greenland halibut MP was updated in 2017, it was the WG-RBMS that met rather than the WGMSE. The group convened four times, in February (NAFO, 2017c), April (NAFO, 2017d), July (NAFO, 2017a), and September (NAFO, 2017b), prior to adoption in September 2017, another example of considerable stakeholder engagement. During these meetings, other stocks were discussed in addition to Greenland halibut, given the broader focus of the WG-RBMS as compared to the WGMSE. Nevertheless, the series of meetings enabled the dialogue necessary to finalize the revised MSE. As was the case in 2010, stakeholders were limited to national and regional fishery managers and some industry representatives.

4.3 Northeast Atlantic mackerel – insufficient stakeholder engagement

The management of internationally shared fisheries for three productive widely distributed pelagic stocks in the northeast Atlantic (NEA) – Atlantic mackerel (*Scomber scombrus*), blue whiting (*Micromesistius poutassou*) and Norwegian spring spawning herring (*Clupea harengus*) are the responsibility of several NEA coastal States (the EU, the Faroe Islands, Greenland, Iceland, Norway, Russia, and the United Kingdom), as well as the North East Atlantic Fisheries Commission (NEAFC), an RFMO where these States are Contracting Parties and have joint responsibility for the sustainable management of these fisheries in international waters (i.e., the NEAFC regulatory area) (NEAFC, 2006). The governance regime is a complex patchwork, covering a mixture of domestic and international fisheries legislation and policies (The Pew Charitable Trusts, 2022a). A wide range of stakeholders from multiple countries and jurisdictions have direct and indirect interests in the sustainable management of these fisheries resources.

The NEA coastal States have historically established multi-lateral management agreements between the interested fishing Parties for each stock. These agreements often contain a long-term management strategy (LTMS/MP) with an HCR, set annual catch limits, and establish quota-sharing (allocation) arrangements between the Parties (e.g., EU-FO-IS-NO, 2016). However, there is a long history of disputes over the sharing of these fisheries resources between the Parties, often resulting in incomplete agreements. This has led to management issues, such as total annual catches regularly exceeding scientifically advised levels, that put the long-term precautionary and sustainability management of these stocks at risk (Bjørndal and Ekerhovd, 2014; Østhagen et al., 2020).

Using the recent development of a new LTMS for Atlantic mackerel as a case study, the following paragraphs elaborate on each step in the coastal States' process (Figure 2) for developing and

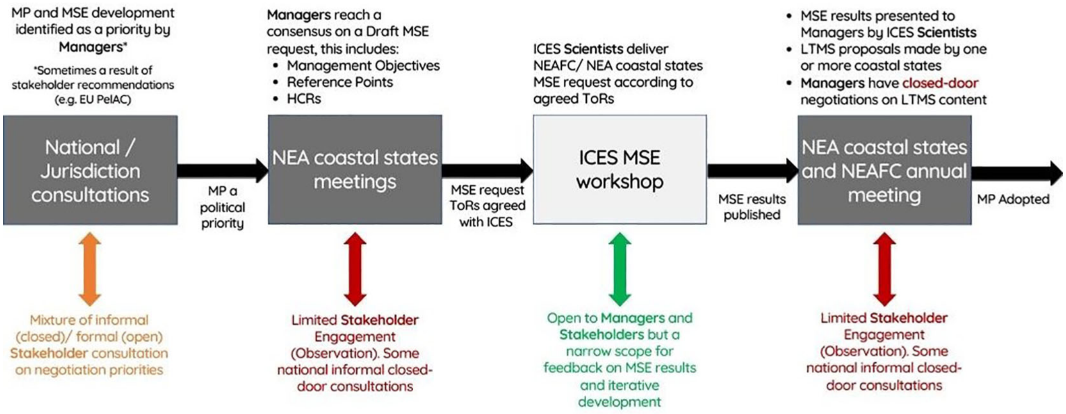

FIGURE 2
The current approach to stakeholder engagement during development of a management procedure (MP)/long-term management strategy (LTMS) by Northeast Atlantic Fisheries Commission (NEAFC) coastal States, color coded by good (green), fair (orange), and poor (red) efforts. MSE, management strategy evaluation; EU PelAC, European Union Pelagic Advisory Council; HCRs, harvest control rules; ToRs, terms of reference; ICES, International Council for the Exploration of the Sea; NEA, northeast Atlantic.

adopting an LTMS, including when and how stakeholders are engaged.

Initiation of a new LTMS usually starts at the national level when a technical imperative arises – for example, a pre-agreed review of an existing LTMS (e.g., every 5 years), or when there are significant changes to the management or the scientific stock assessment that underpins an agreement on an existing LTMS. At the national level, the Parties consult stakeholders in a variety of different ways; openly and officially (formally), and privately (informally) on what priorities and positions to take to coastal States' meetings. In some cases, stakeholder forums such as the EU Pelagic Advisory Council (PelAC) make recommendations to the EU to commission the evaluation of an LTMS (PelAC, 2022). Such recommendations can then be tabled for discussion and decision during coastal States' meetings. In the case of mackerel, the EU, Norway, and the Faroe Islands governments jointly identified the need for a new LTMS and worked to table a joint proposal for an MSE of an LTMS by the International Council for the Exploration of the Sea (ICES) in 2020 (EU-FO-NO, 2019; ICES, 2020b).

Coastal States meetings have historically lacked transparency and comprehensive stakeholder inclusion. Delegations of officials traditionally met privately as a group, with limited stakeholder engagement, to discuss management plans, quota-sharing arrangements, and annual decisions on catch limits. Since 2021 coastal States meetings have slightly improved transparency with stakeholders now officially being able to observe Plenary sessions, but Heads of Delegation meetings still limited to officials for detailed negotiations and decision-making (pers. obs.). However, despite some increased transparency, the scope for active stakeholder engagement and co-production of policy (management objectives, reference points, HCRs, and decisions on trade-offs) as well as scientific requests to ICES remain limited to informal discussions. This contrasts with the above examples, where stakeholder input and feedback in the development of an MP has clearer structures, venues and processes established.

The coastal States and NEAFC do not have an internal scientific advisory structure like some other RFMOs. Instead, they have agreements (Memorandums of Understanding) with ICES, as an external and independent science provider (ICES, 2022). Once politically agreed by coastal States, or NEAFC, ICES receives a request to evaluate an LTMS. An LTMS evaluation is conducted using an MSE framework in accordance with ICES guidelines (ICES, 2013; ICES, 2019; ICES, 2021) and based on the Terms of Reference (ToR) agreed between the requestors and ICES. ICES has clear guidelines for stakeholder engagement in its scientific processes (Dickey-Collas and Ballesteros, 2019; ICES, 2019). According to ICES current guidelines, stakeholders can participate in ICES workshops, including MSEs, by request or invitation.

After ICES received the Special Request for advice on an LTMS for Northeast Atlantic mackerel in 2019, a scoping workshop between managers and scientists was held in January 2020 and was followed by a series of online meetings to conduct the MSE. Only two scientists affiliated with stakeholder organizations attended the online meetings, and no managers or fishers joined (ICES, 2020b). A second dialogue workshop for managers and scientists was cancelled due to the COVID-19 pandemic (ICES, 2020b), and the advice was published in August 2020 (ICES, 2020a). ICES did communicate the results of the MSE to managers and stakeholder observers at NEAFC (NEAFC, 2020), a coastal States meeting (pers. obs.), and the EU Pelagic Advisory Council (PelAC, 2020). Whilst there was scope for discussion of the MSE results at these venues, there was no scope to actively take on feedback and refine the MSE or candidate MPs.

Since ICES produced its Atlantic mackerel MSE and LTMS advice in 2020, the Faroe Islands have produced a proposal for an LTMS (June 2021) to be negotiated during future coastal States meetings. Multi-lateral discussion and national-level stakeholder consultations remain ongoing as of October 2023.

4.4 Pacific saury – early stages of stakeholder engagement

Pacific saury (*Cololabis saira*) is an important part of culture and cuisine in many east Asian communities and is subject to a massive fishery, landing several hundred thousand tonnes each year. It is also notable as a "forage fish" or a fish that forms an important part of the pelagic trophic system, as it is preyed upon by commercially important fishes (e.g., albacore tuna, yellowtail amberjack, etc.) as well as seabirds and marine mammals (Fuji et al., 2021). Growing exploitation of this species was a catalyst in the establishment of the North Pacific Fisheries Commission (NPFC) - an RFMO that manages species in the North Pacific that are not managed by one of the two Pacific tRFMOs. Based on a preliminary stock assessment, scientists concluded in 2019 that the Pacific saury population had reached concerning levels (NPFC, 2019b), and NPFC moved to limit exploitation for the first time (NPFC, 2019a). At that time, the scientists also recommended - and the managers endorsed - a plan to develop MSE for the species as a means to assess the stock status more accurately and began considering the possibility that the MSE could also be used to develop a simulation-tested MP for the species. In 2021, the Commission took further action to reduce fishing for Pacific saury, with a required 40% reduction in the catch, and formally established the Small Working Group on Management Strategy Evaluation for Pacific Saury (SWG MSE PS) (NPFC, 2021).

The SWG MSE PS is a joint effort of the Scientific Committee, the Technical and Compliance Committee, and the Commission and is the first Commission-level meeting beyond the regular, annual meeting of NPFC since this RFMO's establishment in 2015. In the model of the ICCAT SWGSM described above, it is meant to allow for a dialogue between scientists and managers and to include input from stakeholders. The first meeting of the SWG MSE PS took place in early 2022 and was co-chaired by a scientist and a manager. It has met four more times since its establishment. The combined output of these SWG MSE PS meetings has advanced the MP-development process substantially, and the commitment to holding them regularly demonstrates their value. Stakeholders are welcome to participate in these meetings, either as registered observers or as part of Member delegations in some cases, but NPFC has not conducted a formal stakeholder engagement process beyond the working group. As demonstrated in the above cases, such a process (via domestic outreach workshops, "ambassador" meetings, or other fora) is likely to both shorten the length of the development and improve the likelihood that an MP is adopted within the current timeline, something that has only very rarely happened at an RFMO (Pipernos et al., 2023).

5 Discussion

Stakeholder engagement is not a new concept but is generally acknowledged as important to developing fisheries management procedures and more broadly in the context of ecosystem-based fisheries management (Feeney et al., 2019; Goethel et al., 2019). And in addition to the case studies highlighted above, many well-developed fisheries management systems are moving from a traditional best assessment and advice fisheries management framework to an MP-based approach, providing for new opportunities for stakeholder engagement. For example, an MP-based approach has been adopted in domestically managed fisheries ranging from Atlantic herring in the USA (Feeney et al., 2019) to Atlantic redfish (Deith et al., 2021) and Pacific sablefish in Canada (Cox and Kronlund, 2008; Cox et al., 2013), to a host of fisheries in Australia (Smith et al., 1999; Department of Agriculture and Water Resources, 2018), New Zealand (NZ Gov, 2008; Webber and Starr, 2020), and South Africa (Rademeyer et al., 2007; Ross-Gillespie et al., 2019).

In both domestic and internationally managed fisheries, development of an MP has involved an increased component of stakeholder engagement. And while the MP approach to fishery management was not designed to overhaul and improve the stakeholder engagement processes, it is clear from the above case studies that is occurring. That said, there may be some disadvantages and risks associated with participation by more individuals during MP development, such as the time/resources needed to host meetings to iteratively develop an MP or stakeholders' capacity and capability to engage meaningfully in this process. Having mechanisms to ensure due diligence of management and science processes – including audits and monitoring and evaluation – may become increasingly important to ensure stakeholder engagement is effective and leads to improved outcomes (Winter and Hutchings, 2020). This is where principles and standards for stakeholder engagement are helpful. For example, the AA1000 Standard stresses that it is important to understand the difference between good-quality and poor-quality engagement and provides a framework to help businesses, governments, and other organizations demonstrate inclusive sustainability-related stakeholder engagement practices (AccountAbility, 2015).

Whilst overarching governance and scientific advisory structures and processes vary, good MP development process typically engages managers, scientists, and other stakeholders in an iterative and participatory dialogue – from MP initiation to testing via MSE to adoption (Punt et al., 2016; Miller et al., 2019). The development process is valuable from a collaborative science and management standpoint. It offers a useful mechanism for incorporating stakeholder knowledge and feedback in a strategic, process-orientated and outcome focussed way.

We consider that the four case studies discussed above and summarised in Table 2 offer instructive insights and lessons from the different processes of stakeholder engagement used to successfully develop and adopt MPs. Further research using qualitative and quantitative social research methods could be conducted by RFMOs or independent researchers to systematically monitor and evaluate stakeholder engagement in MP development and implementation. Such research could also be used to monitor, evaluate, and compare RFMO governance performance more generally in the future.

The RFMO case studies do, however, highlight that many regional fisheries bodies actively engage and communicate with stakeholders during MSE development and MP adoption.

TABLE 2 Comparison of opportunities to provide stakeholder input at key stages of management procedure development for the four case studies provided here.

Case Study	Stakeholder input opportunities							
	Define management objectives	Determine acceptable levels of risk	Select reference points/ indicators	Define uncertainties	Develop and test candidate MPs	Provide feedback on MSE results	MP adoption	Review MSE and MP performance
Atlantic bluefin tuna ICCAT	Input on conceptual objectives during SWGSM and ICCAT annual meeting. Discussion also during Panel 2 meetings	Inputs during SWGSM meetings Science meetings and ICCAT Panel 2 meetings	Input at Intersessional Science meetings	Inputs on uncertainties and plausibility weighting at Intersessional Science meetings	Inputs provided on CMP structure. Some CMP research & development funded	Inputs provided during Panel 2 meetings - reaction and narrowing CMPs	Inputs via national meetings and ICCAT annual meeting	*x*
Greenland halibut NAFO	Inputs provided during WGMSE & WGRBMS	Inputs provided during WGMSE & WGRBMS	Inputs provided during WGMSE & WGRBMS	Inputs provided during WGMSE & WGRBMS	Inputs provided during WGMSE & WGRBMS	Inputs provided during WGMSE & WGRBMS but limited diversity of stakeholder attendance	Inputs via national meetings and NAFO annual meeting	Scientist only - Review/Evaluation of the MP
Atlantic mackerel NEAFC	No formal input - Defined by managers in MSE request to ICES	No formal input -Defined by scientists - ICES precautionary approach	No formal input -Defined by managers in MSE request to ICES	No formal input - Defined by scientists during ICES MSE workshop (2020)	No formal input - Predefined by managers and ICES in MSE Request	No formal input - MSE open to stakeholders but no feedback loop (iteration)	*x*	*x*
Pacific saury NPFC	Ongoing - Stakeholder input during SWG MSE PS and Commission meetings	Ongoing -Stakeholder contributions made during SWG MSE PS	Ongoing - Stakeholder input during SWG MSE PS and Commission meetings	Ongoing - Stakeholder discussion during SWG MSE PS	Ongoing - Stakeholder feedback on HCRs during SWG MSE PS	*x*	*x*	*x*

Acronyms for working groups are as defined in the text of each case study; x = not yet completed.

In some RFMOs (e.g., NAFO and ICCAT), formal dialogue groups have been established as a vehicle for MP development and for conducting MSEs (The Pew Charitable Trusts, 2022b). We observe that the ICCAT (Atlantic bluefin) and NAFO (Greenland halibut) case studies demonstrate both notable and iterative progress towards the adoption of comprehensive MPs for those stocks using formal working groups. NPFC is similarly positioning itself to have an efficient process with the early establishment of a working group where scientists, managers, and stakeholders can jointly discuss Pacific saury. Whereas for NEAFC, there have been fewer opportunities for formal engagement.

It is notable that dialogue among stakeholder groups, including managers, also provides opportunities to address other outstanding issues that may delay transition to MP-based management. Management of yellowfin tuna in the Indian Ocean Tuna Commission (IOTC) suffers from a long allocation dispute (Holmes and Miller, 2022), and stakeholder engagement will be required to address this issue. Holmes and Miller (2022) argue there can still be benefits of adopting MPs, even without agreed quota allocations, but certainly dealing with both issues simultaneously is difficult. Robustness testing MPs is one mechanism to increase the likelihood that they can still achieve desired management objectives whilst remaining robust to plausible implementation issues like excess catches (Sharma et al., 2020), and designing appropriate robustness tests can be accomplished via two-way dialogue during the MSE process, something that was evident in the case of the Atlantic bluefin (ICCAT, 2021b). Furthermore, having an MP in place to automate the setting of long-term sustainable fishing opportunities should in theory free up negotiation time at decision-making meetings for other fisheries management topics, like addressing sharing/allocation agreements and development of other management measures (Holmes and Miller, 2022).

The Atlantic mackerel case study highlights an example where existing governance structures and processes keep management and scientific interaction in MP development siloed (Figure 2). In the NEA, stakeholder input in MP development, MSE requests, and feedback on MSE results are constrained due to transparency and accessibility barriers at the policy-science interface, where coastal States and ICES interact. Taking lessons from other RFMOs there are a few easy ways to improve stakeholder engagement by augmenting the current management and science processes and introducing formal dialogue groups in the NEAFC/coastal States forums that increase the opportunities for stakeholder engagement. It continues to be important that each coastal State has inclusive and open stakeholder consultations at the national level, while new efforts should additionally be taken at the multi-lateral level to create a more interactive space for active stakeholder input in MSE development and MP adoption.

The addition of a formal working group to serve this purpose for LTMS development could be used to bridge the NEAFC/coastal States management forum, including improved consultation between coastal States managers and ICES scientists. Moreover, this could provide a space for scientists, managers, and other stakeholders to openly discuss the trade-offs associated with different management objectives and decisions once ICES issues its scientific advice. There may also be benefits in terms of improved attendance of ICES MSE workshops if stakeholders are aware and bought into the MSE process from the start – recognizing that ICES MSE guidelines ideally utilize their workshops to collect feedback from managers and other stakeholders on preliminary MSE results (ICES, 2019). It may also help ICES improve the implementation of its stakeholder engagement strategy (ICES, 2023). Figure 3 presents one possible change to the current process via the introduction of a new working group, but further work, utilizing practical examples and guidelines (Goethel et al., 2019; Miller et al., 2019; The Pew Charitable Trusts, 2022b) would be required by managers, scientists and stakeholders to establish a relevant and workable practice.

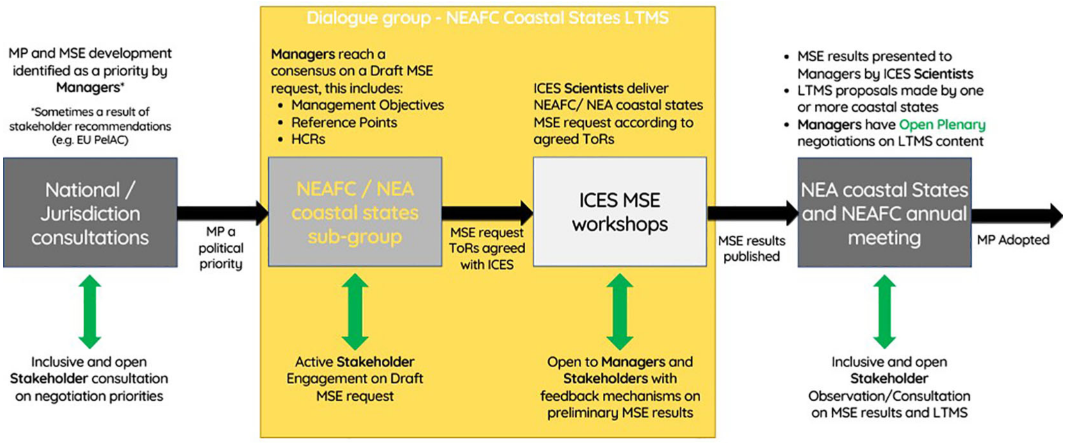

FIGURE 3
A conceptual model for how Northeast Atlantic Fisheries Commission (NEAFC)/ coastal States could improve stakeholder engagement during development of a management procedure (MP)/long-term management strategy (LTMS), via the establishment of a working group to increase dialogue among scientists, managers, and stakeholders. MSE, management strategy evaluation; EU PelAC, European Union Pelagic Advisory Council; HCRs, harvest control rules; ToRs, terms of reference; ICES, International Council for the Exploration of the Sea; NEA, northeast Atlantic.

This is just one example where development of MPs provides an opportunity for improved stakeholder engagement. Other RFMOs are even closer to harnessing these benefits. IATTC and the WCPFC both have fora for discussions among scientists, managers, and stakeholders. IATTC has occasional workshops to discuss its MSE for bigeye tuna, while WCPFC hosted a formal science-management dialogue meeting for the first time in 2022 to review its MSEs for the tropical tunas and South Pacific albacore (WCPFC, 2022). However, neither of these groups is formally established, so they lack the benefits of meeting consistently and having a formal, long-term workplan.

Although the movement toward the use of MSE to develop MPs produces several more touchpoints to engage stakeholders than the traditional approach to fisheries management, these opportunities are not always embraced by RFMOs. In our experience, the main reason for this is almost always capacity. RFMO meeting schedules are already full, so members may reject the addition of new working groups, capacity building efforts, or informal outreach. Extra meetings equate to more time, money and coordination, so some RFMOs have chosen to try to address MP matters within the confines of business as usual. However, due to the specific needs of MP development, specifically related to the iterative dialogue among scientists, managers and other stakeholders, the benefits of stakeholder engagement outweigh the costs – efficiently and consistently gathering the information needed to develop and adopt robust MPs can be less costly than a piecemeal process tacked on to existing meetings with already extensive agendas.

Adoption of MPs that set fishing opportunities has proven to be an improvement in the way that managers and scientists engage a variety of stakeholders in fisheries around the world. Where RFMOs follow the good practices identified above, they are likely to be successful in achieving the buy-in of stakeholders and therefore achieving adoption and implementation of long-term, sustainable management of the fisheries for which they are responsible. And in most cases, this will offer a system with more trust and better results than the regular political negotiation of fishing opportunities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

All authors conceptualized the article and produced the original draft. AW conceptualized and produced the figures. SM drafted the Atlantic bluefin and Greenland halibut case studies. AW drafted the northeast Atlantic mackerel case study. GG drafted the Pacific saury case study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Norway

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Fundação Oswaldo Cruz (Fiocruz), Brazil

*CORRESPONDENCE
Matthew R. Baker
Matthew.Baker@nprb.org

†These authors share first authorship

‡Convenor, ICES Network Session –a new era for science-industry collaboration

§Industry participant (e.g., fisher, fleet manager, industry leader, industry scientist)

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A new era for science-industry research collaboration – a view towards the future

Matthew R. Baker[1*†‡], Nathalie A. Steins[2†‡], Martin A. Pastoors[3‡], Stefan Neuenfeldt[4‡], Andries de Boer[5§], Dirk Haasnoot[6§], Stephanie Madsen[7§], Johan Muller[8§], Kobus Post[9§], Claus R. Sparrevohn[10§] and Mart van der Meij[8§]

[1]North Pacific Research Board, Anchorage, AK, United States, [2]Wageningen Marine Research, Wageningen University & Research, IJmuiden, Netherlands, [3]Pelagic Freezer-trawler Association, Zoetermeer, Netherlands, [4]Danish Technical University, National Institute of Aquatic Resources, Lyngby, Denmark, [5]Rederij W. de Boer & Zonen, Urk, Netherlands, [6]Jaczon B.V., Den Haag, Netherlands, [7]At Sea Processors Association, Juneau, AK, United States, [8]Cornelis Vrolijk, IJmuiden, Netherlands, [9]Zeevisserijbedrijf K. Post BV, Urk, Netherlands, [10]Danish Pelagic Producers Organisation, Copenhagen, Denmark

Direct engagement of the fishing industry in the provision and co-creation of knowledge and data for research and management is increasingly prevalent. In both the North Atlantic and North Pacific, enhanced and targeted engagement is evident. More is needed. Science-Industry collaborative approaches to developing questions, collecting data, interpreting data, and sharing knowledge create opportunities for information transfer and improved understanding of ecosystem interactions, stock dynamics, economic incentives, and response to management. These collaborations require clear communication and awareness of objectives and outcomes. These initiatives also require careful attention to conditions and interactions that foster respect, trust, and communication. Respect is critical and entails acknowledging the respective skills and expertise of both scientists and fishers. Trust is needed to build confidence in the information developed and its use. Communication is essential to maintain relationships and leverage shared insights. To assess current trends and future opportunities related to this type of engagement, we convened a networking session of research scientists, industry scientists, industry leaders, and fishers at the Annual Science Meeting of the International Council for the Exploration of the Sea (ICES) to address the following questions: (1) What are scientific needs that could be addressed with industry-collected data or knowledge? And (2) How can science-industry collaboration be made sustainable? Here we identify opportunities and acknowledge challenges, outline necessary conditions for respectful and sustainable collaborative research, and highlight ways to promote stakeholder involvement in developing science. We address industry concerns and solicit industry advice. We also address challenges to scientists in ensuring standards for scientific data, conflict of interest, and applying information to advise management. The discussions in this session and subsequent correspondence have led to a set of guidelines and best practices that provide a framework to advance further collaboration between industry and research science. We identify opportunities for directed engagement. We also detail potential approaches to clarify expectations and develop avenues for iterative communication and engagement to sustain collaborative efforts over time. The intent is to improve and expand data streams and contextual understanding of ecosystem processes, stock assessment, and socio-economic dynamics to the benefits of science and industry alike.

KEYWORDS

fisheries, participatory research, collaborative research, cooperative research, stakeholder involvement, industry engagement, fisheries management

Introduction

Industry engagement with science in the context of fisheries research has waxed and waned over time and can be sensitive to the timing of prevailing issues related to management (Karp et al., 2001). Presently, there is increasing interest and initiative to promote stronger stakeholder and industry participation in the development of science and directed management of marine fisheries resources (Kaplan and McCay, 2004; Röckmann et al., 2017; Mackinson and Middleton, 2018; Baker et al., In Press). In the past few decades, documented instances of collaborative research in fisheries have grown substantially (Mackinson et al., 2011; Holm et al., 2020; Mackinson, 2022; Steins et al., 2022). Intensified collaborative research involving science and industry is motivated by the longstanding recognition and respect for the knowledge and experience of fishers operating in marine environments (Branch and Kleiber, 2017). This experiential knowledge includes recognition of patterns and processes, understanding of stock dynamics, awareness of environmental effects, and expertise in gear, equipment, and research platforms. Other driving factors include the opportunity to develop data streams with increased spatial and temporal coverage, to access remote areas or unusual conditions, to strengthen and augment existing data, and to test and improve gear or approaches. Additionally, successful management of fisheries requires improved understanding of social and economic dimensions and incentives (Berkes and Folke, 2000; Fulton et al., 2011). Fisheries science is a multidisciplinary domain that encompasses ecological processes, social dynamics, and economic drivers and interactions. At the core of fisheries, both the fishing industry and individual fishers (Figure 1) have direct and valuable knowledge not only about the environments they work in (Johannes et al., 2000), but also choices made and responses to regulation and management. This provides valuable insight to potential tradeoffs in objectives and implications for management actions (Neis et al., 1999; Neis and Felt, 2000; Gutierrez et al., 2011; De Alessi et al., 2021).

In the context of fisheries and marine science, science-industry research collaboration (SIRC) entails engaging industry partners and leveraging industry insight and infrastructure to inform scientific efforts. This might include addressing pressing fishery management needs, improving shared understanding between science and industry, and supporting marine observations. This approach encourages practicality, cost-effectiveness, and the application of results to inform fishery management (Baker and Smith, 2018). Similar to Steins et al. (2020), we define SIRC as collaborative engagement between scientists and fishers, aimed at improving knowledge for fisheries management through both fisheries-related data and fisher's experiential knowledge (Stephenson et al., 2016). As an applied approach, this entails direct industry engagement in problem identification, research design, data collection, analysis, and communication of results (Johnson and Van Densen, 2007).

There are clear direct and indirect benefits to SIRC (Johnson and Van Densen, 2007; Steins et al., 2020). These benefits have been demonstrated across multiple ecosystems and management frameworks. Direct benefits include cost-efficient data collection, enhanced temporal and spatial coverage, increased quantity and quality of the available data, and improved knowledge for fisheries management (Karp et al., 2001; Wendt and Starr, 2009; Lordan et al., 2011; Kraan et al., 2013; Stephenson et al., 2016; Mangi et al., 2018; Bleeker et al., 2021). SIRC also integrates industry knowledge in science and management (Neis et al., 1999; Kaplan and McCay, 2004) and improves the relevance of directed research, ensuring it addresses important pressing fisheries management issues (e.g., stock status, selectivity, gear technology, habitat closures; Johnson and Van Densen, 2007; Stephenson et al., 2016; Baker and Smith, 2018). SIRC also facilitates interest in and opportunities for adaptive management (Johnson and Van Densen, 2007). Indirect benefits include improved relations and engagement between fishers, scientists and managers and increased transparency and communication (Johnson and Van Densen, 2007; Steins et al., 2020). Ideally, this type of engagement, particularly when conducted in an iterative manner and over long timeframes, results in shared understanding of the data, problems, and solutions, and increased trust. Collaborative approaches to analysis and interpretation further this shared understanding and promote acceptance of results. Ultimately, this may lead to buy-in, increased investment of industry in science-based management, and increased legitimacy of the management framework (Hartley and Robertson, 2006; Dörner et al., 2015; Thompson et al., 2019; Baker et al., 2023). Finally, SIRC provides an opportunity for capacity-building and recognizes intellectual property within the fishing industry. This may lead to greater ownership in, understanding of, and appreciation for information produced through scientific research. This is particularly relevant where participatory frameworks exist to evaluate the science used in fisheries management (e.g., ICES, EU Regional Advisory

FIGURE 1
Industry vessels and gear in Dutch Harbor, Unalaska, USA (photos M.R. Baker) and Danish North Sea pelagic fisheries fleet (photo: C.R. Sparrevohn).

Committees, US Regional Fishery Management Councils, Canadian Science Advisory Secretariat, New Zealand Fisheries).

Still, SIRC has inherent challenges that may undermine successful collaboration. These hazards should be explicitly recognized and addressed (Silver and Campbell, 2005; Steins et al., 2020). Scientists and fishers may have different interests, objectives, approaches, and interpretation of results (Kraan et al., 2013; Mangi et al., 2018; De Boois et al., 2021). Absent a collaborative framework that facilitates trust and transparency, collaboration may fail (Ford and Stewart, 2021). Both scientists and fishers need to ensure that expectations are clear, and that respect and communication are maintained. Fishers must remain open to the results of research, wherever those results may lead. Scientists must show how data has been used and ensure results are presented in an acceptable and accessible format. Finally, data and analyses developed through SIRC must meet standards that enable their use and application in fisheries assessment and decision-making (Kraan et al., 2013; Mangi et al., 2018); often this entails addressing perceptions that industry-related science will reflect vested interests (Steins et al., 2020; Steins et al., 2022).

Also, SIRC is easier said than done. How to do it effectively, remains a persistent and relevant question (Reed, 2008; Kraan et al., 2014). SIRC should be, at its essence, a collaboration among equals. The involvement of industry in scientific research should include active participation of industry partners in the full scientific process, including the development of research questions, framing of hypotheses, data collection, data interpretation, and review (Johnson and Van Densen, 2007). Positive developments have been made in this direction (Steins et al., In Press). More specifically, the focus of SIRC and the role of industry in it, is increasingly shifting from passive participation towards active collaboration (Dörner et al., 2015; Mangi et al., 2018). In the former, researchers use fishery-dependent data as an input to models and analyses or use fishing vessels as a platform to collect additional data (Kaplan and McCay, 2004; Mangi et al., 2018). In the latter, industry and individual fishers actively engage in the development of research questions, design of projects, collection and interpretation of data, and communication and application of results (Johnson, 2009; Mackinson et al., 2011; Holm et al., 2020).

To explore mechanisms and foster engagement between research scientists, managers, policy makers, and fishers, we hosted a networking session at the 2021 Annual Science Conference of the International Council of the Exploration of the Sea (ICES, https://www.ices.dk). Presented here are summaries of those discussions. We intend that these discussions better direct collaborative research and cooperation between fishers and scientists. SIRC is a crucial approach to inform ecosystem interactions and change, monitor fisheries stock dynamics, understand socioeconomic drivers and impacts, and facilitate informed and participatory fisheries management. Here, we share lessons learned and best practices and, particularly in relation to ICES, present a view of future success in SIRC. Our lessons learnt are also applicable to other organizations and initiatives involved in SIRC in fisheries.

Framework for discussion on SIRC

Networking session

To further explore mechanisms and approaches to improve SIRC, a networking session (https://www.ices.dk/events/asc/ASC2021/Pages/Network_sessions.aspx; https://www.ices.dk/events/asc/ASC2021/Documents/2021_ANewEra_ASC_network_session.pdf) was hosted as part of the 2021 ICES Annual Science Conference (https://www.ices.dk/events/asc/ASC2021/Pages/science_industry_collaboration.aspx). The four conveners (first four authors of this paper) are all engaged in SIRC in a scientific capacity. Due to the COVID19 pandemic, the conference was held online. A total of 157 individuals attended this session, with 78 active participants contributing information through online polls, recorded chat, and facilitated discussion.

Our networking session actively recruited members of the fishing industry and sought participation from a broad range of experts, including: fishers involved in data collection or knowledge provision; fishing industry representatives; scientists working with fishers; scientists involved in understanding ecological and oceanographic process; scientists involved in assessment and scientific advice; policy makers who utilize scientific knowledge and advice; and non-governmental organizations (NGOs) involved in creating engagement with industry for sustainable development. Participants included researchers, policymakers, and fishers from more than 14 nations engaged in fisheries and/or fisheries research and management in the northwest Atlantic, northeast Atlantic, and northeast Pacific. Industry representatives represented pelagic trawl and bottom trawl fleets as well as at-sea and shore-based processing sectors in Europe and North America. In our first two polls, the 78 actively contributing participants identified themselves as primarily research scientists (78%), followed by fishers or fishing industry representatives (10%), policymakers (5%), NGO representatives (1%) or other (6%; Figure 2). A majority of participants (66%) had some experience in SIRC projects, ranging from occasional (35%) to full-time (5%). Approximately a third of participants (34%) had no prior experience (Figure 3). Most expressed interest in future opportunities

We anticipated addressing several topics in the networking session and set of thought-provoking statements were introduced to the participants in and prior to these discussions (Table 1). Online polls were provided in advance and at the beginning of the networking session. A short inspirational video on SIRC experiences in The Netherlands, with perspectives from fishers, scientists and NGOs, was also made available prior to the session (https://youtu.be/FsfBEBbpvck).

In addition to plenary discussions, two thematic breakout sessions were held as part of the networking session, each focused on one of the following two questions:

Breakout 1: Are there specific scientific needs that could be addressed with industry collected data or knowledge?

Breakout 2: How can science-industry collaboration be made sustainable?

For each of these two 10-minute sessions, participants were randomly divided in four subgroups, each facilitated by one of the four convenors for the session. Following each of the breakout sessions, the full set of participants reconvened for a plenary summary and discussion. A closing plenary session discussed ways forward, related to leveraging industry data and information contributions within the ICES context.

In the following sections we share ideas developed in these discussions. All quotes used in this manuscript are extracted from session discussions and reflect either the perspectives and insights provided by fishers and industry representatives (i.e., skippers, fleet managers, owners, and industry leaders) or scientists working in collaboration with the fishing industry – all are listed here as authors.

Defining terms and questions

This ICES networking session focused on science-industry research collaboration. In reviewing the outcome, it is useful to define terms

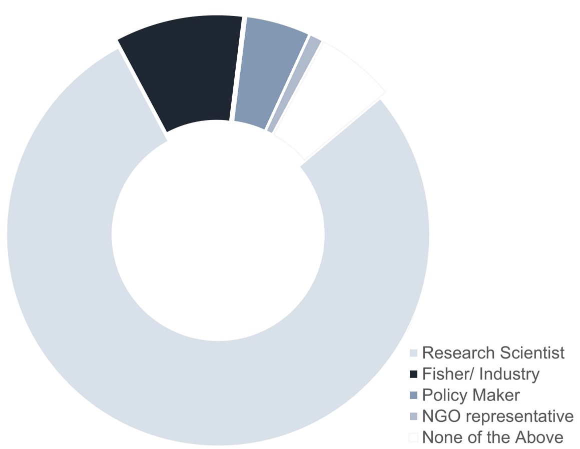

FIGURE 2
Participant affiliation. While many participants noted that multiple categories were appropriate, participants were limited to select only one (NGO – nongovernmental organization).

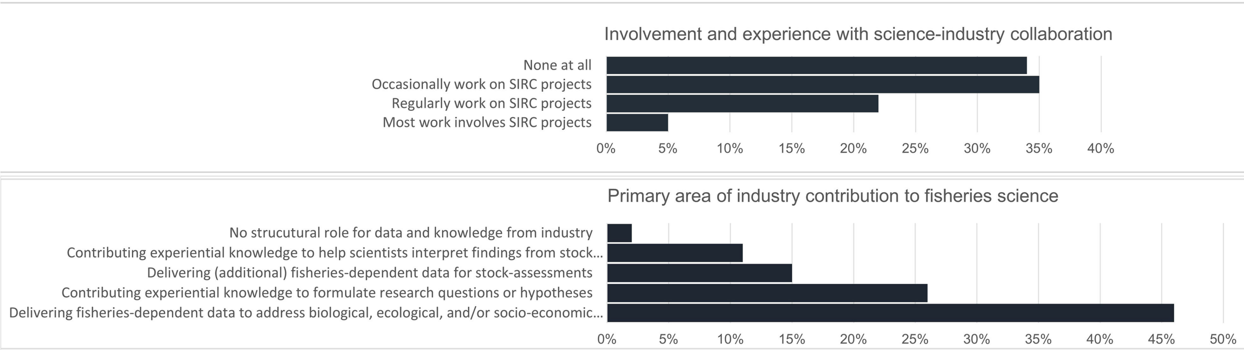

FIGURE 3
Survey poll I (SIRC – Science Industry Research Collaboration).

(Oxford English Dictionary, 2023 https://languages.oup.com/google-dictionary-en/).

net·work/netwrk/
 1. a group or system of interconnected people or things.
ses·sion/seSHn/
 1. a period devoted to a particular activity.
sci·ence/sīns/
 1. the intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment.
in·dus·try/indstrē/
 1. economic sector concerned with the development and processing of raw materials and manufacture of goods.
research/risrt/
 1. a careful study of a subject, especially to discover new facts or information about it.
col·lab·o·ra·tion/klabrāSH()n/
 1. the action of working with someone to produce or create something.
 2. traitorous cooperation with an enemy.

As defined above, science entails systematic study, not only as an intellectual endeavor, but also as a practical exercise. Collaboration as defined here, provides useful insight to one of the challenges in this type of engagement – collaboration between science and industry may be viewed in favorable or unfavorable terms. In the first instance, it is the action of working with others to produce or create something (e.g., increased knowledge and improved fishery management). Alternatively, it may be viewed as engagement with a group inherently at odds with your own interests and objectives (e.g., conflict of interest).

In truth, there is more common ground than not between scientists and fishers. This includes not only interests, but also approaches and objectives. Scientists and fishers are both interested in learning more about marine systems, marine dynamics, fish behavior, and economic systems. Scientists and fishers are both interested in sustainability, yield, minimizing adverse effects, and maintaining natural resources.

We approach collaboration by embracing the definition in its first instance, while maintaining a sober awareness that interests may not always align. We also argue that agreement is not necessary for effective partnership. Disagreement may be a useful instance to identify where different data streams, insights, or experiences reveal gaps in knowledge and where different perspectives may offer new insights. These differences offer opportunities for more holistic understanding. Disagreement may also highlight where interests deviate and where collaboration is not useful or appropriate. This is important in setting priorities and determining the most productive areas for partnership.

Our first question (break-out 1) addressed what industry could offer to the scientific effort, related to addressing needs, presenting new possibilities, providing additional data, and improving knowledge. More specifically, we asked first whether there are

TABLE 1 Anticipated outcomes and questions posed in ICES Science-Industry Research Collaboration (SIRC) networking session.

Aims articulated in the ICES Networking Session
o Develop an inventory of scientific data needs and develop a framework outlining ways for fishing industry to meet these needs
o Highlight new technologies enabling the collection and uptake of data generated by the fishing industry
o Identify incentives to initiate and maintain data and information streams between industry and science
o Determine how to address concerns related to validation, transparency, and accountability
o Outline how to create efficient feedback mechanisms to transfer knowledge from industry to science and from science to industry
o Determine how to bring in fishers' experiential knowledge into the scientific process in a consistent way
Questions posed in introduction of the discussion session
o What is the appetite and capability of industry to make meaningful contributions to scientific understanding?
o How does that match needs for scientific information to address short- or long-term issues for informed fishery management?
o How to build sustainable partnerships between science and industry and organize industry-science collaboration?
o How to set up frameworks for industry to initiate research?
o How to develop iterative collaborations?
o How to develop and enforce quality control and data standards?
o How to promote transparency and trust both in data collection and in evaluation of data sources?
o How to evaluate the quality and reliability of the data?
o How to develop criteria for the adoption of new data sources?
o How to value and evaluate experiential knowledge?
o How to make industry data 'count' in assessment, advice, science?

TABLE 2 Question I. ICES networking session: A new era for science-industry collaboration.

Central Question of Interest	Are there specific scientific needs that could be addressed with industry-collected data or knowledge?
Primary Discussion Point	What are unique insights and interactions that might be derived from fishery activities?
Secondary Considerations and Inferences	• How might that facilitate broader or higher resolution spatial coverage?
	• What are important differences in sampling vs fishing?
	• How might that enhance access in seasons that are not surveyed?
Primary Discussion Point	What types of acquired knowledge are informative and how might these be applied?
Secondary Considerations and Inferences	• How might those insights be used in a formal context to inform or bound quantitative statistics and models?
	• How might systems be established to collect these insights in a more regular manner?
	• How to incorporate experiential knowledge in consistent ways in the scientific process?
Primary Discussion Point	What is required for science to be able to use industry data or knowledge for scientific analyses or advice to management?
Secondary Considerations and Inferences	• What are the standards that need to be established to ensure reliability or comparability of knowledge inputs?
	• How would management processes and analytical approaches be reformed to accommodate this new information?
	• What are quantitative metrics that could be derived from fishery activities?
	• Are there new methods (e.g., qualitative network models) to integrate qualitative information in quantitative processes?
	• Are there other ways this information might be packaged to inform decision making?
Primary Discussion Point	How do we ensure validation, transparency, and accountability?
Secondary Considerations and Inferences	• What are some of the challenges and opportunities around the generation and provision of reliable data?

specific scientific needs that could be addressed with (or even only addressed with) industry collected data or knowledge. The specific sub-questions posed to discussion participants are detailed in Table 2.

Are there specific scientific needs that could be addressed with industry-collected data or knowledge?

Prior to going into breakout 1, a poll was presented to initiate discussion. In response to the question "*I see industry's contribution to fisheries science mostly in…*". The majority of the 46 participants who answered the poll see industry's role in '*delivering (additional) fisheries-dependent data to address biological, ecological and/or socio-economic research questions*' (46%). This was followed by '*contributing experiential knowledge to formulate research questions or hypothesis*' (26%), '*delivering (additional) fisheries-dependent data for stock assessments*' (15%) and '*contributing experiential knowledge to help scientists interpret findings from stock assessments*' (11%). A minority of 2% did not see a structural role for data and knowledge from industry (Figure 4).

Several themes emerged as part of our discussion on addressing scientific needs using industry-collected information: (1) use of data and knowledge; (2) ways to promote effective collaboration; (4) ways to leverage collaborations; and (4) challenges. We summarize each below.

Use of data and knowledge

Data and Information

"Collaboration leads to greater opportunity to gather data, which we are not able to gather on our own, due to constraints on finances, manpower, seasonality and spatial extent in coverage."

Fisheries science is inherently an interdisciplinary exercise (Larkin, 1978; Smith, 1994; Smith and Link, 2005). Participants noted that SIRC becomes transdisciplinary (Hessels and van Lente, 2008) when fishers become actively involved in the scientific process. Much of the science that informs management depends directly on information provided from the fleet such as statistics on catch volume, spatial maps of effort, observer data and catch samples, and logbook information (Hilborn, 2007). Fishers' knowledge is not limited to biological information, and also includes ecological, economic, social, and institutional and experiential knowledge (Stephenson et al., 2016). In this context, it is useful to adopt the Stephenson et al. (2016) distinction between fisheries observation knowledge (e.g., industry as a platform for collecting measurable data) and fishers' experiential knowledge (e.g., experience and insight on the water).

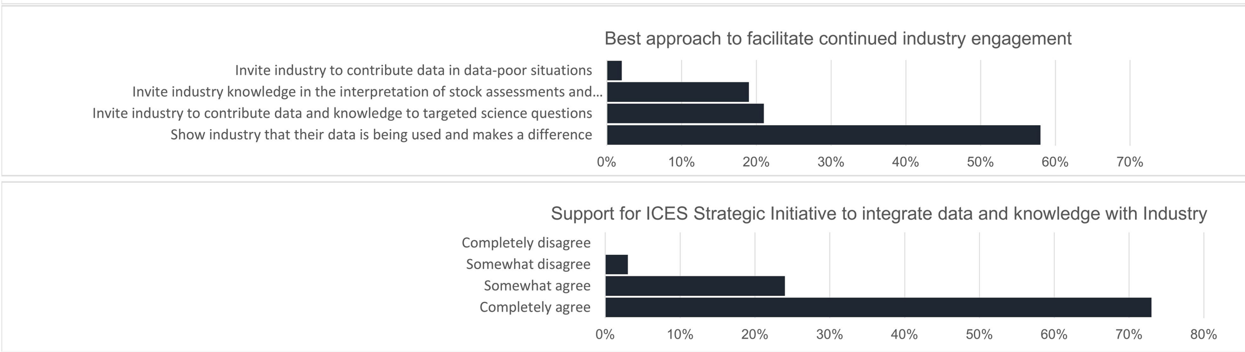

FIGURE 4
Survey poll II.

Fishers contribute information about stock structure through insight on migration and spawning dynamics (Maurstad and Sundet, 1998; Ames et al., 2000), spatial patterns related to size structure and habitat preference (Hutchings, 1996; Maurstad and Sundet, 1998; Neis et al., 1999; Ames, 2004), and effort changes in response to regulatory change (Neis and Felt, 2000).

Many challenges to effective fisheries management relate to the constraints on government-run sampling efforts that are often season-specific or otherwise limited in both duration and temporal coverage (Thorson, 2019; Bleeker et al., 2021; Gonzalez et al., 2021), constrained or influenced by gear performance (i.e., selectivity, Cadrin et al., 2016; Kotwicki et al., 2017), or otherwise unable to access all viable or relevant habitats (i.e., availability, Punt et al., 2014; Baker et al., 2019a). Many of the data needs identified in our discussions reflected these recognized limitations to scientific surveys and sampling. Discussions on where industry data might be most useful identified the need for additional information on specific habitats, broader temporal and spatial scopes, fine-scale life history detail on populations, data on nontarget species, and the better archival, use and application of opportunistic data (e.g., acoustics data, bathymetry, observational data). Vessels collect considerable observational data which can be used. Other ideas for data and information needs included opportunities to better characterize physical oceanography, mechanistic processes and marine ecosystem interactions, climate change, fleet dynamics, socio-economic data, and information on fishery priorities, culture, and way of life. A list of data and information needs identified in our session are outlined in Table 3.

TABLE 3 Data and information needs identified in discussion sections.

Information Needs
o Information on niche level habitats
o Information on non-commercial species for biodiversity metrics
o Improvements and enhancements to temporal and spatial data and sample coverage
o Self-sampling of length-at-age data and maturity data
o Assessment of impacts of fishing on society
o Understanding fisher culture and way of life
o Opportunistic data (acoustic data, climate change data)
o Socioeconomic data and information
o Information on fleet dynamics
o Threat assessment

Beyond data – knowledge, interpretation, context, and validation

"Data and interpretation are two separate things. Often fishermen are worried that the interpretation of the data is wrong because the scientist don't understand the context."

"I get the feeling that some scientists want to have everything in a model. We fishers work out in the natural world. Everything counts and everything has its effect. It is too complex for a model. At least for most models and in most fisheries. This is why working together with fishers and scientists is so important.

Participants also recognized applications for SIRC data and information (Figure 5). One is model validation. Fishery data and information have broad application relevant to testing and validating models. This includes application to fisheries models where additional sources of observational data or experiential information are used to challenge or improve confidence in existing models and insights that might lead to developing new or competing models to better characterize marine ecosystems, stock dynamics, or fisheries economics (Neis et al., 1999; Smith et al., 2007; Bentley et al., 2019). Observational and experiential knowledge are often best applied in stock assessment workshops and fisher management forums where these data and industry insights can be used to improve hindcasts and forecasts. These interactions might also be applied as a way of gaining the industry's trust in these models. Furthermore, fisheries data and information have relevance beyond exploited stocks and are also useful to ecosystem models, habitat models, and regional oceanographic models. In all these instances, fisher data and information are often available, but underutilized, and might be applied to test model skill and assumptions.

Context matters. Fishers' knowledge is often labelled as anecdotal (Pálsson et al., 1998; Neis et al., 1999). But there is value in an anecdote (Johannes and Neis, 2007) and fisheries data and fisher knowledge are critical to interpretation. Interpretation of ecological and economic data is inherently challenging. Results may reflect many underlying processes and interactions. Fishers have unique insights on what might be driving trends and what might be important underlying influences on evident observations. This can be useful in interpreting scientific results of stock assessments,

FIGURE 5
Word Diagram compiled from ICES Networking Session Discussion and Chat.

leveraging insights from ecosystem trends, and distinguishing and discriminating between data sources.

An important question that arose was *'how do we and how should we distinguish between [observational] data and [experiential] knowledge?'* And '*how should we apply each*?' Ackoff (1989) distinguishes between data (factual properties), information (processed data), knowledge (answers '*how*' to questions – analysis), understanding (answers '*why*' questions – synthesis), and wisdom (values and the exercise of judgement). Effectively integrating fishers' knowledge, be it observational or experiential, represents a fundamental challenge to established fisheries science (Hind, 2015). Despite a long history and active interest in this area, fishers' knowledge is highly qualitative and has generally failed to become integrated into the fisheries science mainstream alongside approaches that rely primarily on the knowledge of professional scientists (Stephenson et al., 2016; Steins et al., 2022). This qualitative nature, as well as the non-standard format of much fishers' knowledge, contrasts with the systematic quantitative data typically applied to inform assessments. Scientists working in fisheries have therefore found it hard to integrate this knowledge to inform better decision-making (Hind, 2015). Neis and Felt (2000) outline examples of how to move beyond 'fishery-dependent data' or 'fishery-dependent information', to more fully integrate the experiential knowledge of fishers. Comparisons between fishers' observations and data drawn from more traditional scientific sources might lead to greater consensus on stock status and management (Neis et al., 1999).

Scientific research conducted in partnership with the fishing industry not only promotes the co-production of knowledge about stock status and the marine environment, but also leverages fishers' knowledge and experience in decision-making (Wilson, 2003; NRC, National Research Council, 2004). Participants noted that science is not one thing. Multi-disciplinary approaches are needed to most effectively gather knowledge from fishers and apply it to improve fisheries sustainability and management. Moreover, discussion participants noted that experiential knowledge is built over time, and therefore might be particularly useful to understanding change over time. Systems change and baselines shift. Knowledge across generations, often embedded in the frameworks and perspectives that fishers and Indigenous and coastal communities bring to the conversation, is critical to understanding baselines, interpreting change, and providing context for data.

Technical expertise and experience

"It's not only industry providing data, but also knowledge on fishing gear technology, net performance, and external impacts on its performance. We can provide a lot of examples on how just a minor change in the application of the nets will yield much different results."

One of the most obvious areas for the application of fisher and industry contributions to science is in technical expertise and experience on the water. There are many instances of effective recruitment of industry participation in the development and execution of surveys (De Boois et al., 2021). Often these types of collaborations are crucial to resource assessment.

In the US, there are active cooperative research programs, where industry fleets are contracted to engage in research (Karp et al., 2001). This occurs through directed surveys or directed and opportunistic approaches to collect oceanographic data and monitor ecosystems. Those data are used for a variety of purposes. The effort also creates mechanisms for exchange and relationships, which further trust and long-term partnerships in project design, data collection, interpretation, and delivery of results. Similar examples exist in Europe (Bjørkan, 2011; Kraan et al., 2013; Pastoors, 2021) and New Zealand (Middleton and Guard, 2021). There are also many instances of effective collaboration towards the development and improvement of gear (Walsh et al., 2002; Harley and Robinson, 2008; Feekings et al., 2019; Merrifield et al., 2019), assessment of the selectivity of gear (Graham et al., 2007; Baker et al., 2011; Baker et al., 2014; O'Neill et al., 2019), analysis of selectivity in catch and surveys (Rose et al., 2010; Somerton et al., 2011; Veiga-Malta et al., 2019), analyses of management approaches (Smith et al., 2007; Smeltz et al., 2019) and conservation engineering solutions to mitigate fisheries impacts on marine environment (Kaiser et al., 2016; Österblom et al., 2020) or benthic substrates and communities (Rose et al., 2000; Rooper et al., 2011). Additionally, there are many examples of effective collaborative approaches to minimize or reduce bycatch and incidental mortality in protected or non-target species (Gauvin and Rose, 2001; Carruthers and Neis, 2011; Arkhipkin et al., 2021; Kroska et al., 2021; Yochum et al., 2021). There are also examples of effective science-industry collaboration to inform harvest control rules and management planning (Davis, 2008; Heller-Shipley et al., 2021). Experiential knowledge is critical here.

Promoting effective collaboration

Enhance awareness and exchange

"Scientists learn so much from fishermen. Its real-time data when they are out there, and fishermen always have something to say."

Disparities in perceptions about problems and solutions among fishers, industry, fishery managers, and scientists poses a challenge to effective management and may result in misunderstanding and distrust. Stephenson et al. (2016) note different degrees to which information from industry and fishers data and experience are integrated in fisheries assessment and management, and note that "fishers' knowledge is best implemented in a participatory process designed to receive and use it."

Session participants agreed that there is a lot of room for collaboration and that we are under-using existing opportunities. To begin, participants suggested the importance of simply getting fishers and scientists in the same room to discuss issues, mechanisms, and interactions. Another idea was to ensure room for the fishers to test and develop their ideas. Over time that investment develops trust and mutual understanding, and ultimately long-term cooperation. Time together and continuity were both recognized as critical. Participants also articulated the importance of fostering not only professional but also personal relationships.

New avenues for research

"Every day at sea is different. Every year is different. We see climate change is influencing fishing and the ecosystem. The fishermen are also scientists – we work in the ecosystem, we use echosounders, we track temperature, we observe fish behavior. Overall, fishermen are in the lead."

In addition to existing examples of SIRC, session participants noted many new opportunities for collaboration. These are outlined in Table 4.

Leveraging science-industry collaborations

Motivations and incentives

"What is the appeal of collaboration? To make it happen you need people on both sides willing to do it."

Researchers and managers increasingly recognize the importance of stakeholder engagement in fisheries research (Kaplan and McCay, 2004; Johnson and Van Densen, 2007). It can improve the quality and quantity of spatial, temporal, and ecological data, as well as promote skill transfer and provide mechanisms to identify and address differences between industry perspectives (Holm and Soma, 2016). For fishers, participation in research provides an opportunity to participate in, influence, and understand fisheries assessments (Stephenson et al., 1999). Active engagement in research also improves industry and fisher's understanding and appreciation for how information is produced in the context of scientific research and how it is used to advise management (Johnson and Van Densen, 2007; Steins et al., 2020). Incentives matter (Hilborn et al., 2005). Industry incentives for cooperative research include potential benefits of increased catch and fishing opportunities through better information, direct payment for research activities, and increased confidence in the management system (NRC, National Research Council, 2004). Participation requires both willingness and capacity (Mangi et al., 2016). The level of participation will be determined by funding, interest, and the contribution that stakeholders are willing and able to do effectively (Mackinson et al., 2011; Baker et al., 2023).

Session participants suggested that one of the main incentives for partnership is that SIRC leads to greater opportunity to gather data and to address constraints on manpower and seasonality in coverage. Scientists noted that "*we need to know more about industry motivations*". Fishers noted that "*we need to show the scientists how we work in practice*". When asked what would motivate industry to work together with science, the answer was clear: "*use our data*".

It is important to recognize that agreement is not always evident. Often times, the incentive may develop out of disagreement or management failure. A lack of consensus on the status of fish stocks may provide motivation for collaboration (Dobbs, 2000). Stock assessments often rely on spatially-coarse data collected in limited timeframes and differ from fishers' observations; one way to move towards consensus on resource status is to solicit and apply fishers' knowledge.

Insights and attitudes

"In the past, scientists have often approached fishermen as if scientists are the ones that know best. And while the fisherman is providing them information, and they don't need to know the details. It seems it is changing – scientists are approaching fishermen on an equal basis. Both sides can learn from each other."

Relationships are core to collaboration and the attitudes with which each side approaches SIRC are critical to establishing an

TABLE 4 Ideas generated in discussion sessions for new or underutilized opportunities to apply SIRC to marine science.

New opportunities to apply SIRC
o Development of study fleets supported by industry to generate continuous input or mechanisms to leverage opportunistic data collection
o Inclusion of social and economic and ecological information in reports to managers
o Research on the impact of fisheries and management on society and fishing communities, understanding fisher culture and way of life.
o Research efforts to document experiential knowledge and fishers' ecological knowledge
o Methods to identify drivers of change in stock dynamics and fishery effort and distinguish how much is driven by the environment, the fishery, and the management policies. Subtle shits in management (e.g., spatial or temporal closures) restrict effort and therefore influences catch-per-unit effort. That may have nothing to do with the stock dynamics but instead fully reflect management actions. That interaction is key and engaging with industry is the way to understand those interactions.
o Methods to gather knowledge from fishers – we need different types of science and disciplines to be involved
o Methods to integrate interdisciplinary and transdisciplinary approaches (e.g., socioeconomic information and experiential knowledge) into qualitative frameworks and models (e.g., qualitative network models).
o Processes to identify and mitigate conflict of interest

environment for trust, respect, and positive exchange. Some suggestions from network session participants included: a balanced exchange where no one side is *"dominating meetings"*, and environment where everyone feels as though *"you are at the same level"*, *"respect for expertise"*, *"curiosity"*, *"reciprocity"*, and *"trust"*.

Defining roles and responsibilities

"There is a real need for clarity in roles and outcomes. We are knowledge partners."

"When you enter a collaboration, you need to work in an agile way to determine what skills sets you have. And how to best make use of them."

In SIRC, it is important to be clear about roles (*"who will do what – and when?"*). In general, fishers have unique insights into certain areas – they know the grounds, their gear, their capabilities. Fishers are critical to assessing the technical feasibility of research and calculating costs. Fishers are also often best positioned to leverage knowledge of appropriate timing and location for directed efforts. Scientists have expertise in other areas – how a survey needs to be designed, how to collect, compile and format data to be statistically robust and to apply it towards quantitative analysis. Scientists understand the need for consistently and specified protocols and how to assess the statistical power of the observation scheme to ensure that the results will be valid statistically for use in science and management. Fishers have individual experiential knowledge; scientists know how to analyse accumulated information from many fishers together.

Benefits in SIRC arise from recognizing and leveraging these complementary sets of skills. Commercial fishers have practical experience in the marine environment, knowledge of marine organisms and processes, technical expertise, and platforms and resources to facilitate data collection. Industry perspectives and expertise may be important in survey design and gear deployment, technology development, understanding impacts of gear on habitat or nontarget species, hypothesis testing, and understanding information important to informing management. Scientists bring expertise in the scientific method, experimental design, data synthesis and statistics. Integrating complementary skills and knowledge of these two groups has the potential to improve the quality and relevance of research (Baker and Smith, 2018). Working together also furthers understanding between science and industry and promotes industry confidence in the products of the scientific research.

Session participants noted that effective collaboration starts with respect for these different areas of expertise. Participants also noted that it is important to view these collaborations as investments in an iterative relationship that might be extended across multiple projects. The intent of SIRC is to facilitate partnerships to improve and enhance data streams, inform analyses, and improve understanding of marine stocks and environments. The expertise of both fishers and scientists is crucial for making applicable rules and informing sustainable participatory management of living marine resources. Combining approaches and knowledge streams is intended to lead to more robust policy.

Challenges

"When it comes to making it for real, we always end up in the same issues. It's like this … you need a long time series, data need to be standardized and reproduced, the model is not really fit for purpose, it is difficult to combine data…"

One of the challenges articulated in network session discussions was the difficulty in combining data. Fishery-dependent data is limited to where fishery is executed. Similarly, standardized methods applied in surveys mean that gear types do not necessarily cover all areas equally well. It is very difficult to combine data collected in different ways. It is also difficult to analyze data from data sets that are not fit for purpose. One approach is to design new approaches through SIRC. Another is that fishers' surveys can be combined by many fishers putting their data together replicating the footprint of a survey.

Beyond data collection, interpretation of fisher data and information is challenging. It is often difficult to integrate experiential knowledge of fishers into a system that is dominated by models and statistics. Receiving systems will need to be reformed to deal with transdisciplinary approaches (Steins et al., 2022). Also, creating spaces for communication is hard. Timeframes do not necessarily align; funding for industry data collection schemes are often short while science needs long-term time series. Results that are developed are often slow to be integrated. Scientific processes in which fishers are involved are often dominated by scientists, with fishers often seen as a data supplier and not as a partner. Fishers also may not recognize the value in participation or have time to attend.

Additionally, there are legitimate concerns about conflict of interest. Absent a transparent framework, SIRC may be challenged by suspicions about motives of industry to contribute data. SIRC must safeguard scientific integrity and should operate within a transparent and open framework. Participants also stressed that there are legitimate concerns that the results of SIRC may have negative effects for industry. New information may lead to a shift in understanding for the ecosystem or stock. This leads to questions such as: "*What happens if/when fishers data used in stock assessment enhances negative perceptions and or results in reduced quotas? How would industry react?*" Rationalized fisheries may shift incentives for industry and allow for longer term time horizons.

History is important. Whatever is being done in the present builds on the history of interactions and engagement that preceded it. Frustration related to failed collaboration or unacknowledged results may compromise future efforts. This underscores the importance of trust building. Trust may need to be rebuilt over time, particularly if there have been negative experiences in the past.

"Don't forget that history is important. There is frustration with failed collaboration and instances where input was not implemented or incorporated into management perspectives. In many ways this

may have been as frustrating for the scientists as it was for the fishers themselves."

How can science-industry collaboration be made sustainable?

Our second question (breakout 2) aimed to identify the best mechanisms to sustain industry participation in delivering data, information, or knowledge – how do we make the collaborations last? The specific sub-questions posed to discussion participants are detailed in Table 5. Prior to going into breakout 2, a poll was presented to kick off discussions. Participants were asked to select *'the most promising mechanism that facilitates continued availability of industry data and engagement, recognizing this is not a guarantee'*. From the total of 43 respondents to this poll, 21% thought that *'inviting industry to contribute data and knowledge to targeted science questions'* was the most promising mechanism for facilitating continued availability of industry data and engagement (whilst recognising the latter is not a guarantee); 19% selected *'inviting industry knowledge in the interpretation of stock assessments and ecosystem indices'*, 2% chose *'inviting industry to contribute data in data-poor situations only'*; the majority (58%) felt that *'showing industry that their data is being used and makes a difference'* is centrally important (Figure 4).

While the principal desired outcome of industry participation in research is to improve the scientific data and knowledge available to inform effective, participatory, and transparent management and governance. The question remains- How can a deeper, more systematic, and more sustainable engagement of stakeholders be enabled (Mackinson et al., 2011)? Our results shed some light on how to best approach this. The following themes emerged in relation to making industry data contributions sustainable: (1) enabling effective collaboration, (2) promoting collaboration, and (3) facilitating engagement.

Critical components to enable effective collaboration

Relationships and trust

"What is essential? In one word, trust. It is very important for fishermen. And it is also important for scientists. When we work together, we can learn from each other. If you are able to operate on the same level, if you have a sense that scientists will also learn from you, then there is potential for understanding one another."

Trust is very important for success in SIRC. That starts with openness and honesty. Participants, both in plenary discussions and in each individual break-out, noted the importance of communication, trust, and transparency. Relationships are the core to this type of collaboration. There are benefits in building not only professional, but also personal relationships. It was noted that spending social time together is really important. Fishers noted that there is often a stiffness or distance to interactions with scientists. The solution – "*be normal*". It was also noted that scientists have often approached fishers as if they know best and that needs to be changed. This engagement has to be on an equal basis. Learn from each other. Meet on the same level. Respect as each other based on knowledge and experience. Longterm engagement is key; ultimately that leads to trust.

Expectations

"If the result of using the data means less quota, there is a risk. We are not using this data for their benefit only. And this needs to be made clear."

In SIRC, there is a need for clear expectations. All assumptions should be stated clearly, and participants need to understand what questions the research seeks to answer and how the data will be used. This is critical to ensuring realistic expectations. Participants

TABLE 5 Question II. ICES networking session: A new era for science-industry collaboration.

Central Question of Interest	How can science-industry collaboration be made sustainable?
Primary Discussion Point	o What mechanisms or approaches will increase the probability that the collaboration lasts? o What are effective ways to initiate collaborations? o What are the initial conditions necessary for active partnership? o How do we build trust? o How do we develop effective communication strategies?
Primary Discussion Point	o What are ways to effectively ensure iterative exchange and communication?
Secondary Considerations and Inferences	o How do we adapt processes to accommodate different timelines, perspectives, processes, outlooks, incentives? o What has changed in recent times that complicate or facilitate exchange and collaboration?
Primary Discussion Point	o Can science serve the needs for industry? If so, how?
Secondary Considerations and Inferences	o Often this seems to be something motivated by scientists looking to engage industry, when and how do we reverse this? o What are ways industry can highlight opportunities for increased understanding of processes that are data-poor?
Primary Discussion Point	o How do we create efficient feedback mechanisms to promote exchange of data and knowledge from industry to science and from science to industry?

should not expect the research to translate into a specific management outcome nor necessarily expect positive responses. If results of using the data means less quota, industry has to accept this; it is not only about using data to their advantage. Industry participants in this session noted that industry does not have a default expectation for positive or favorable outcomes. The interest is in understanding the reality of stock status. Industry is typically invested in the value of the resource over time; this provides a common ground and common interest to pursue and develop the best available science.

Scientists must also address industry concerns that the data will be interpreted incorrectly by people that are not fishers themselves. Context is important and industry and fishers need to be assured that the use and application of this data will be in a process that includes their input and expertise. The pace and duration of the collaboration should be negotiated and collectively understood. Clarity in expectations on both sides is crucial to positive and effective engagement.

"Data is also just one side of the conversation and interpreting this data can be just as difficult. So we are extremely worried that our data will be interpreted wrongly by people that are not fishers themselves."

Critical components to promote effective collaboration

Engagement

"Fishermen often feel there is a lot of information provided and not much in return. Feedback is essential. When data is collected, provide information on what is collected and how it is used."

SIRC is, by definition, participatory research. That should reflect active engagement on all sides, with both scientists and stakeholders involved in all stages of research planning, development, and delivery. Fishers should contribute to project planning and design. Fishers should be involved in the identification of the problem statement. Industry should also be invited to ask the questions. The development of the research question or hypothesis is an area where fishers' knowledge can contribute significantly to the scientific research process. Those on the water may have different questions and those questions often warrant further exploration. Moreover, this process fosters engagement as it reflects real interest in that research. Science is at its essence curiosity-driven. That applies to researchers and fishers alike. Active engagement in the interpretation of data may provide motivation for further engagement.

Ownership is also important. There should be open sharing of data and products. Give fishers ownership of the data they collect. This improves transparency and trust. It also provides critical information that industry can investigate and use in internal discussions and public forums (e.g., fishery council meetings). It provides industry something they can bring to the table. It gives them a voice.

Communication and transparency

"To build trust, you need communication. That's the only way. You need to meet in person."

There is a need for fishers' voices to be heard and valued. Communication is key. Continuous dialogue is essential. Keep the communication going. A common scenario described in our discussions was that that authorities approach industry and ask for data on this or that. Fishers then comply, gather the data and send it to the management authority. And that's the last they hear of it – there is no feedback on why that data is required or what it is used for. It is important that there is a dialogue at the outset. What is the purpose? What are the results? Moreover, it's important not only to share data, results, and outcomes, but also to identify what works and what doesn't work. Iterative discussions and regular feedback are critical.

Openness and honesty are important. Do not over-promise. Transparency in the process will contribute to the building of trust and confidence in the research. Ideally, in cooperative research, all participants share their findings, including the explanation of how the data have been or will be used. This entails communicating not only the results, but the significance of the results, the meaning of the outcome, the format for presenting the results, and information on how results will be communicated to industry, science agencies, and in publications, presentations, and management forums. Effective communication along these lines builds trust, which can be expected to translate into more effective management.

Critical components to facilitating effective engagement

Frameworks

"We fishers have been trying for decades to reduce discards because having unwanted fish in the trawl affects the quality of the fish we are targeting – crowding the net, removing the slime layer that keeps fish fresh, and making work to sort out unwanted fish. So, it's not that we don't want to fix it, we're just a bit stuck. To tackle it we have scientific partnerships with multiple vessels in the fleet. Fishers would like a bit of room to test and develop things themselves - for example if I'm trying a new net that might reduce discards, but which doesn't comply with the existing rules and I get stopped by the control vessel, I'm in trouble. Fishermen have been innovating on these sorts of questions for decades."

New and modified frameworks are necessary to move forward. New technology can also change how information is collected – "*automation, automation, automation*". Institutional settings that favor recurrent interaction should also be employed. Continuity is very important. Mechanisms to maintain the recurrent interactions between industry and researchers and ensure long-term engagement are key, but can be difficult to maintain with existing modes for research that are project-based. Project-based funding is limited in scope and duration; securing 20 years of funding for collaboration is unrealistic. If there are established relationships, however, the long-term outlook for partnership is often good. Institutional settings that favor recurrent interaction can help here.

One approach to consider is a shift in focus. It is often much easier to collaborate on questions of ecological understanding or ecosystem monitoring, rather than stock assessment, where there is direct economic interest and potential financial consequences. Collaboration might be viewed in this broader context. There is significant documentation of the value of fisheries observations towards ecosystem and ocean monitoring (Gawarkiewicz and Malek Mercer, 2019; Lindeberg et al., 2022). Another approach to consider is a shift in ownership and leadership. At the most basic level, give fishers ownership of the data they collect. At the extreme, give fishers ownership of regulation (e.g., New Zealand). Where fishers manage elements of the fishery, this provides strong incentive to think about what data is required and all other aspects of the management process. In between these extremes, there are frameworks for active consultation and engagement. In the US, one approach has been to engage commercial fishers directly through a steering committee. That brings fisheries scientists, managers, and fishers all in one room together to discuss what the scientists need for stock assessment, data gaps, and the feasibility collecting this information through fishers.

Actionable recommendations

Ways forward

"Roughly 10 years ago, younger scientists arrived in the Netherlands and brought a new view that we have to work together with the fishermen. And this was also what the fishermen thought themselves. And from that time, we started working together. In the past it was always fighting, and always bad results. Since started working together we have had excellent results. Our advisors work together as close as possible with the scientists."

There are both opportunities and barriers to SIRC and industry-led fisheries research (Harte, 2001; Steins et al., 2022). Both deserve further exploration. One approach is the potential for expansion of governance regimes in which fishers both contribute knowledge and actively participate in research and management. Co-management — 'the sharing of power and responsibility between government and resource users' — reflects a potential shift towards decentralization and collaborative decision-making (Berkes et al., 1991). These approaches to governance, where fishers and government managers jointly develop, implement, and enforce management measures are often viewed as a means to promote collaboration and shared stewardship (Hart, 2021; Puley and Charles, 2022) and to improve efficiency and legitimacy in the management of fisheries (Charles, 2009; Pinkerton, 2018).

Other approaches maintain distinctions between resource users and resource management, but increase engagement. Co-management is gaining increased attention worldwide and is at the core of many fishery governance discussions (Campbell and Salagrama, 2001; Linke and Bruckmeier, 2015). Engaging stakeholders in research and decision-making on European marine issues is endorsed at high levels because agreement of stakeholders is believed to be essential for any management plan to succeed (Mackinson et al., 2011). Incorporating fishers' information and knowledge generates buy-in, because the results are more likely to be viewed as practical and reasonable and therefore legitimate. These commitments and principles are also reflected in US fisheries management (Karp et al., 2001; Hare, 2020).

Until recently, the North Sea Stock Survey collected data on fishers' perceptions of the status of fish stocks through a voluntary annual survey; the aim was to provide a means for fishery scientists and managers to incorporate fishers' knowledge into their assessments (Johannesen, 2010). The Netherlands set up a dedicated multi-annual grant scheme 'Partnerships Science and Fisheries' as part of its national implementation of the European Maritime and Fisheries Fund with the specific objectives of promoting SIRC. This has led to joint development of research questions and innovative methodologies for data collection by fishers to address knowledge gaps in important data-poor commercial fisheries (Quinn et al., 2016; Cope et al., 2023), such as *nephrops* (Bleeker et al., 2021) and turbot and brill (Schram et al., 2021) in the North Sea. In Pacific Canada, governing agencies increasingly employ collaborative forms of decision-making in fisheries management to improve decision quality and legitimacy. Results indicate that an incentive to participate, consensus decision-making, and independent facilitation were key to ensuring effectiveness (Davis, 2008). These types of initiatives and this momentum towards enhanced and improved SIRC has the potential to have positive effects on resource use and sustainability, social benefits, and ecological outcomes (Sen and Nielsen, 1996; Whitehouse and Fowler, 2018).

"Industry should also be invited to ask the questions. Collaboration should not only target science. Those on the water may have different questions and those questions often warrant further exploration."

Strategic Initiative – towards a more structural approach in ICES

"Recently there have been new elements incorporated into the [ICES] stock assessment process, including ecosystem and socio-economic profiles, where ecological, economic, and social information is included in a side report. We are still trying to determine how that information will flow into the decision-making system. At the same time, there has been a profound shift in the ecological system. So we have new conditions on the water and new systems and processes in management. Those are the times where we need to focus to rebuild and strengthen trust and transparency."

Fisheries are increasingly recognized as systems with ecological, economic, social, and institutional aspects that require interdisciplinary approaches to science and participatory governance (Stephenson et al., 2016). Decision-making benefits from more holistic approach to information integration, leveraging data from fishers, scientists, management and often coastal communities and other stakeholders. Trust, communication, and a sense of partnership between stakeholders are critical to success (Johnson and Mccay, 2012; Holm and Soma, 2016).

The use of data and information from SIRC or industry-led research is an important topic of discussion within ICES (Dickey-Collas and Ballesteros, 2021). ICES is unique as a marine science organization, which also develops science and advice to support the sustainable use of marine resources. The institution serves and advises national and regional (EU) institutions and facilitates a framework within which scientists work together to provide the scientific basis for management advice. For nearly 120 years, ICES has approached fisheries management with an emphasis on integrity, transparency, and independence, but also an awareness of the need for accountability and an adaptive and flexible approach (Stange, 2010; Cvitanovic et al., 2021). Despite a history of ambiguity related to stakeholder involvement in ICES (Wilson, 2009), the current ICES mission considers stakeholder engagement to be a critical component, necessary to improve decision-making and ensure coherence and reliability in policy-relevant science (Dickey-Collas and Ballesteros, 2021). In recent decades, there has been consistent movement within ICES to open-up to stakeholders and to encourage an institutional transformation of ICES towards engagement and increased participation (ICES, 2019; ICES, 2020; Dickey-Collas and Ballesteros, 2021; ICES, 2021).

Following the breakouts, our closing plenary session discussed how to further promote to industry data and information contributions within the ICES context. ICES is currently hosting several separate workshops to develop guidelines for industry data and stakeholder engagement (e.g., Workshop on Science with Industry Initiatives 2019, Workshop on Standards and Guidelines for Fisheries Dependent Data 2021, Workshop on Stakeholder Engagement Strategy 2021, Workshop to Evaluate the Utility of Industry-derived Data 2022). Network session convenors suggested that ICES could benefit from a more structural approach, involving the stock assessment working groups and experiences from scientists and industry outside Europe. One way forward would be to set up an initiative on the integration of industry data, knowledge, and information. Participants were asked to respond to this idea through a poll and expressed their interested in participating in such an initiative. A majority of participants (73%) fully agreed with the statement that '*Setting up an ICES (Strategic) Initiative tasked with how to integrate data and knowledge from industry, involving experts from outside Europe, is much needed*' (Figure 4). Several participants also expressed their explicit interest in such initiative, including the chairs of ICES Working Groups (WG) on Maritime Systems (WGMARS), Social Indicators (WGSOCIAL), Economics (WGECON), Shipping Impacts on the Marine Environment (SHIP), Technology Integration for Fishery-Dependent Data (TIFD), and Integrated Ecosystem Assessments (IEASG).

Discussion

Several important considerations emerged from our discussions. One was how to define knowledge and understanding (Jenkins, 2004). Knowledge is more than data, but what? Another was how to best develop data quality controls to enable use in management. In defining knowledge, we draw on observations in Steins et al. (2022). Data include metrics and measurements that are products of observation, while knowledge provides context (Ackoff, 1989; Rowley, 2007). Scientific knowledge builds on systematic processes of accrued observation and experimentation and models and analysis (Hessels and van Lente, 2008). Fisher Experiential Knowledge includes the knowledge held by individuals, sectors, and communities and a process of producing and assembling that knowledge through observation, trial, and application. It includes associated socio-economic, cultural, and technological experience, often accrued over generations (Neis and Felt, 2000; Hind, 2015; Stephenson et al., 2016). Experiential knowledge also includes Traditional Ecological Knowledge, Indigenous Knowledge, and Local Ecological Knowledge with a focus on communities with histories of engagement in subsistence, recreational or commercial fisheries (Chan et al., 2019; Cooke et al., 2021). Solutions included ensuring that data or final reports follow regulatory standards and be peer-reviewed before their use in science and management. Also, interpretation was highlighted as a critical area for collaboration; including fisher knowledge here may provide insights not considered by scientists. Validation, transparency, and accountability are important to ensure the generation of reliable data. Finally, protocols and standards are necessary to identify, assess and manage potential conflict of interest in data and information provision, particularly where that data and knowledge might affect the integrity of science advice and influence management (ICES, 2023). Necessary steps include flagging possible conflict of interest at data entry points and subsequent evaluation of the potential impact.

Another important consideration was how to define collaboration. Often this requires a shared vision. Many objectives may be shared (e.g., maximize harvest, maintain healthy populations, optimize use, benefits and utility). But does the type of collaboration and framework (e.g., mandated, voluntary, compensated or contracted) matter and what is its influence the type of data and output? And what are the main incentives to initiate and maintain data and information streams between industry and science? How do we create efficient feedback mechanisms, both from industry to science and from science to industry? How do we to bring in fishers' experiential knowledge in a consistent way into the scientific process?

Many questions remain. What is the outlook for the future? How might we better leverage experiential knowledge? How do we shift the framework so that industry is positioned to ask the questions? How do we ensure industry and more importantly fishers have a voice at the table? Are there means and mechanisms to provide research funding for both industry and science? Where are the opportunities for industry to employ scientists? Fisheries organizations are increasingly hiring scientists to lead independent data-collection and research initiatives as well as represent industry perspectives and science in participatory management discussions (Peterman, 2009; Pastoors, 2016); this trend is anticipated to increase in future (Mackinson et al., 2011). Finally, under what conditions is it appropriate or even best that fishers direct and control the research and management system? What are the necessary preconditions to ensure enforcement of the regulations they propose?

Our networking session was held in the context of ongoing initiatives within ICES designed to open science to new forms of data and knowledge and improve stakeholder involvement. Its aim was to contribute to these ongoing discussions. Historically, SIRC has focused on catch sampling and surveys, gear and selectivity research, biological and catch information, and evaluation of assumptions and interpretation of results in Management Strategy Evaluations (Walsh et al., 2002; Johnson and Mccay, 2012; Kraan et al., 2013; Dörner et al., 2015; Wijermans et al., 2020; De Boois et al., 2021). New applications of Fisher Experiential Knowledge include observational knowledge of environmental effects and reporting of ecological change, perspectives on seasonality and life history (Bryan et al., 2021), species and ecological interactions (Bentley et al., 2019), alternative explanations for scientific observations (Murray et al., 2008), validation of survey data (Rand et al., 2022), enhanced assessments of habitat (Doherty et al., 2018), and informed assessments of the effects of regulatory and environmental change on fishing communities (Wijermans et al., 2020; Murphy et al., 2021). Experiential knowledge is also critical in research design, including ensuring more comprehensive and informed approaches to temporal, spatial and technological scales relevant to fisheries (Steins et al., 2022). Even when fishers' knowledge is directed towards stock assessment, experiential insights may enhance these analyses, linking stock dynamics to phenomena at a broader spatial and temporal scales, including considerations of shifting effort, ecological patchiness and change over time, historical context, and changing fish ecology.

Participants saw clear benefits but also challenges to industry contributions the scientific process. We argue that the lessons learned in SIRC may extend beyond use in applied fisheries research with relevance for industry and science engagement in the wider field of marine science (Steins et al., 2020). The discussions here are part of a broad and ongoing dialogue including other forums for coordinated exchange between scientists and fishers to determine best practices and lessons learned (Baker et al., 2019b). Such venues and opportunities should be supported to continue maintain these conversations.

We recommend the establishment of an ICES Strategic Initiative on Science Industry Research Collaboration (SISIRC) to coordinate the separate workshops on this topic, bring different expert groups together and learn from good (and bad) practices from expert groups that already have experiences in relation to collaborating with industry and using observational or experiential knowledge from fisheries. Further, coordination and learning from ongoing work is not only important in ICES, but also as part of movement towards more collaborative and transdisciplinary science more generally.

Ethics Statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MB: Conceptualization, Data, Writing, Editing, Session Convenor, Co-lead author. NS: Conceptualization, Data, Editing, Session Convenor, Co-lead author. SN: Conceptualization, Data, Session Convenor. MP: Conceptualization, Data, Session Convenor. AB: Contributed Ideas and Content. DH: Contributed Ideas and Content. SM: Contributed Ideas and Content. JM: Contributed Ideas and Content. KP: Contributed Ideas and Content. CS: Contributed Ideas and Content. MM: Contributed Ideas and Content. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author DH was employed by the company Jaczon B.V. Author AB was employed by the company Osprey Group. Author KP was employed by the company Zeevisserijbedrijf K. Post BV. Authors JM and MM were employed by the company Cornelis Vrolijk.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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