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GHOTI

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Opportunities to improve fisheries management through innovative technology and advanced data systems

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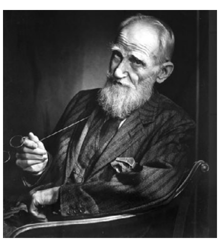
Abstract

Fishery-dependent data are integral to sustainable fisheries management. A paucity of fishery data leads to uncertainty about stock status, which may compromise and threaten the economic and food security of the users dependent upon that stock and increase the chances of overfishing. Recent developments in the technology available to collect, manage and analyse fishery-relevant data provide a suite of possible solutions to update and modernize fisheries data systems and greatly expand data collection and analysis. Yet, despite the proliferation of relevant consumer technology, integration of technologically advanced data systems into fisheries management remains the exception rather than the rule. In this study, we describe the current status, challenges and future directions of high-tech data systems in fisheries management in order to understand what has limited their adoption. By reviewing the application of fishery-dependent data technology in multiple fisheries sectors globally, we show that innovation is stagnating as a result of lack of trust and cooperation between fishers and managers. We propose a solution based on a transdisciplinary approach to fishery management that emphasizes the need for collaborative problem-solving among stakeholders. In our proposed system, data feedbacks are a key component to effective fishery data systems, ensuring that fishers and managers collect, have access to and benefit from fisheries data as they work towards a mutually agreed-upon goal. A new approach to fisheries data systems will promote innovation to increase data coverage, accuracy and resolution, while reducing costs and allowing adaptive, responsive, near real-time management decision-making to improve fisheries outcomes.



Ghoti papers

Ghoti aims to serve as a forum for stimulating and pertinent ideas. Ghoti publishes succinct commentary and opinion that addresses important areas in fish and fisheries science. Ghoti contributions will be innovative and have a perspective that may lead to fresh and productive insight of concepts, issues and research agendas. All Ghoti contributions will be selected by the editors and peer reviewed.

Etymology of Ghoti

George Bernard Shaw (1856–1950), polymath, playwright, Nobel prize winner, and the most prolific letter writer in history, was an advocate of English spelling reform. He was reportedly fond of pointing out its absurdities by proving that 'fish' could be spelt 'ghoti'. That is: 'gh' as in 'rough', 'o' as in 'women' and 'ti' as in palatial.

KEYWORDS
electronic monitoring, electronic reporting, fishery-dependent data, information systems, mobile technology, transdisciplinary management

1 | INTRODUCTION

Achieving effective fisheries management is increasingly important as overfishing threatens fish stocks globally, reduces biodiversity, alters ecosystem functioning and jeopardizes the food security and livelihoods of hundreds of millions of people worldwide (Golden et al., 2016; Jackson et al., 2001; Pauly, Watson, & Alder, 2005; Szuwalski, Burgess, Costello, & Gaines, 2017; World Bank 2009). Fisheries management is a complex socio-political process, and there is no silver bullet to improve global fisheries; however, access to accurate, consistent data about how a fishery is doing, and what, where and how much of a species is being caught is a fundamental component for establishing effective fishery management, regardless of the fishing sector or management system (Beddington, Agnew, & Clark, 2007). Rapidly changing ocean conditions due to anthropogenic climate change and natural climate variability have forced the need for higher resolution spatial and temporal fisheries data over shorter timescales to address growing uncertainty about stock status and to allow managers to adjust reference points as the environment changes (Pinsky & Mantua, 2014; Szuwalski & Hollowed, 2016). This requires more precise data collection, faster and more advanced reporting, processing and analysis, and more efficient mechanisms to disseminate the results to enable near real-time responses (Wilson et al., 2018). However, the ecological characteristics of fished stocks make data collection difficult, time-consuming and costly due to their relative invisibility in the oceans, wide distribution and mobility across jurisdictional boundaries, and complex interactions within marine ecosystems and the physical environment.

The specific nature of data needs and management goals vary across fishing sector (i.e., industrial fishing, small-scale fishing [SSF] and recreational and subsistence fishing), data availability (i.e., data-rich vs. data-poor) and management type (i.e., top-down, decentralized and informal), but fishery-dependent data are required to effectively manage *all* fisheries. In the most data-rich scenarios, a long time series of fishery-dependent, fishery-independent and other essential fishery information are used to fit dynamic population models to assess stock status. Data-poor fisheries—the >80% of global stocks that lack adequate data for a formal stock assessment (Costello et al., 2012)—need to expand data collection and analysis (and/or create a pathway to formalize and share local knowledge) to understand and track landings and stock dynamics for effective assessment and management, but often lack resources and capacity to do so using traditional tools and techniques (Dowling et al., 2016). A critical lesson that has emerged from syntheses of global fisheries information is that well-managed fisheries, particularly those guided by formal stock assessments, are in better condition than poorly managed fisheries that lack comprehensive assessments (Costello et al., 2012; Mora et al., 2009). Ultimately, fishery data are necessary to support effective management and maintain the sustainability of fished stocks and the economic and food security of the users dependent upon it (Pauly et al., 2005).

Recent developments and emergent technologies—which often leverage the ubiquity of mobile phones and tablets and the growing accessibility of cloud-based computing for data storage and artificial intelligence for analysis—have the potential to contribute to fishery-dependent data systems by expanding or streamlining data collection, automating and empowering the data processing and analysis, and facilitating the communication of results to relevant stakeholders. Electronic reporting and on-board passive sensors like cameras and GPS (colloquially known as "electronic monitoring" systems) can improve the efficiency and/or capacity of data collection. Artificial intelligence methods, like machine learning and computer vision, can be used to rapidly analyse data, and integrated processing and analysis of large quantities of near real-time, georeferenced data can enable management at more relevant spatial and temporal scales. Technology can also be used to expand the distribution and accessibility of data to fishers, allowing them to optimize their fishing based on the best available information and transforming one-way flows of information (from fisher to manager) into a cooperative, mutually beneficial cycle of data collection, synthesis and sharing. Fishers, whose livelihoods depend on understanding ocean dynamics, are usually the first to notice changes on the water, making the thousands of vessels operating at sea the logical first line of defence in tracking changing stock dynamics and environmental variability. Yet, despite the proliferation of efficient, cost-effective technologies and the potential for technology to address data needs in fisheries management, utilization of high-tech fishery-dependent data systems remains the exception rather than the rule.

Here, we provide an overview of the current status and challenges of technologically advanced data systems in capture fisheries in order to understand what has limited their adoption, and propose a solution to guide greater use of technology to improve fisheries outcomes. For tractability, we limit our discussion of data systems to fishery-dependent data collected and/or used on vessels or at the point of landing or first point of sale in industrial, SSF, and recreational and subsistence fisheries. We begin by providing a brief overview of conventional fishery-dependent data systems, followed by a review of the applications of fishery-dependent data technologies. We suggest that the slow uptake of technology in fishery data systems is due to cost and limited access to capital, legal barriers and institutional shortcomings that stifle innovation, and ongoing lack of trust and cooperation between managers and fishers. Ultimately, we propose that a transdisciplinary approach to fisheries management—which emphasizes collaboration between fishery stakeholders and the creation of direct data feedbacks—could promote the uptake of technologically

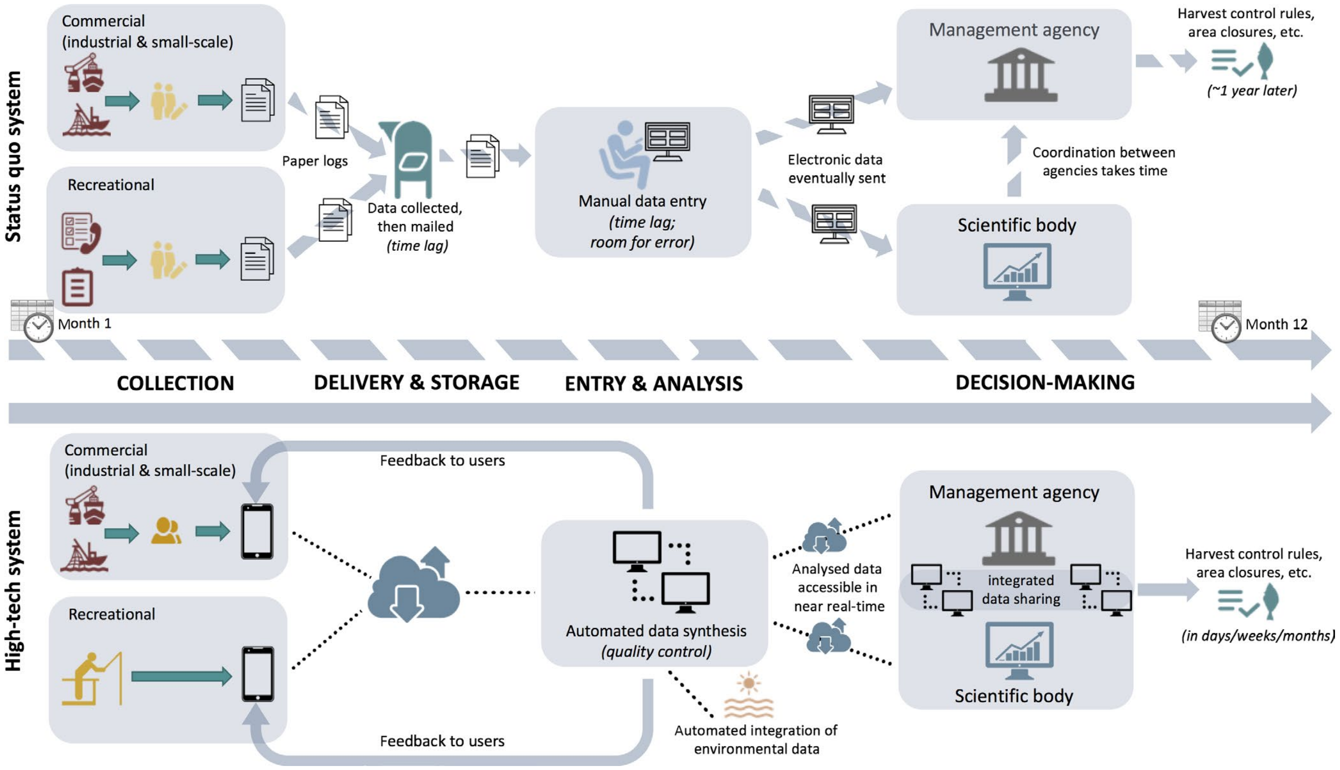


FIGURE 1 A conceptual diagram of status quo (top) and high-tech (bottom) fishery-dependent data collection systems [Colour figure can be viewed at wileyonlinelibrary.com]

advanced data systems by ensuring that all fisheries stakeholders benefit from better data. A new approach to fisheries data systems will promote innovation to increase data coverage, accuracy and resolution, while reducing costs and allowing adaptive, responsive decision-making to improve outcomes across all fishing sectors.

2 | CONVENTIONAL FISHERY-DEPENDENT DATA SYSTEMS

In all fisheries sectors and across all institutional structures, data collection may be conducted by a variety of fisheries stakeholders, including fishers, fisheries managers, fish buyers and/or processors, or even third parties such as consumers or non-profit agencies. Such data are recorded via logbooks and vessel trip reports, on-board observers, landing records, port sampling or dockside surveys, point of first sale, telephone surveys or experiential knowledge, and can be recorded at the site of capture, landing, sale or even later by survey (Figure 1). After data are physically collected, they may make their way through a time- and resource-intensive system of data delivery and storage, entry and analysis after which they may be interpreted and assessed by a scientific body and/or management agency to guide management decisions (Figure 1). The process of moving and processing data from the point of collection into management decision-making is often slow or non-existent, with time lags regularly exceeding the pace of rapidly changing ocean conditions and their impact on fish stocks (National Research Council 2000).

The particularities of fishery-dependent data collection systems vary by fishing sector, data availability and management institution, but most current systems share a need for improving the way in which data can both inform management and improve fishing behaviour and outcomes at appropriate and refined spatial and temporal scales. Data systems in industrial fisheries with top-down management often rely on self-reported paper-based logs and/or on-board observers. Adequate observer coverage can be prohibitively expensive (Kindt-Larsen, Dalskov, Stage, & Larsen, 2012), and manual data recording may lead to issues with data accuracy and reliability, given that multiple values are often important (e.g., location, gear, species, length/weight, by-catch, effort). Paper-based data systems are cumbersome and suffer from quality control and assurance issues due to legibility, problems with standardization in data collection (e.g., species ID codes), aggregation of species into generic groups (e.g., elasmobranchs), transcription errors and misreporting (Lowell, Mustain, Ortenzi, & Warner, 2015; Lowman, Fisher, Holliday, McTee, & Stebbins, 2013; Will, Campbell, & Holmes, 2014). Failure to record data at spatially and temporally relevant scales can be problematic for entire fishery sectors. For example, the Northwestern Hawaiian Islands lobster fishery, which began in 1976, was officially closed in 2000 because of increasing uncertainty in the assessments of stock status due to a lack of data at relevant spatial scales and hyperaggregation (e.g., species pooling) of the data (Botsford, DiNardo, Fogarty, Goodman, & Hampton, 2002).

In data-poor SSFs, fishery-dependent data collection systems are unlikely to be automated, standardized or centralized, resulting in a general lack of coverage in global fishery data repositories such as the FAO (Chuenpagdee, Liguori, Palomares, & Pauly, 2006; de Graaf et al., 2011; Pauly & Zeller, 2016; Salas, Chuenpagdee, Seijo, & Charles, 2007). Information about historical catches and trends within a given SSF may instead be transferred via local knowledge, which can be difficult to standardize and translate into quantitative measures or management actions (Hind, 2014). Insufficient resources for data collection and ineffective data collection systems have resulted in a paucity of basic indicator data including total catch, number of vessels and CPUE for many of the world's SSFs, including large regional data gaps for all SSFs in the South Pacific, central America and West Africa (de Graaf et al., 2011). Where landings data do exist, it may be reported as total landings of all catch rather than landings by species (de Graaf et al., 2011), which may be useful for understanding regional trends in catches and food security, but may not be effective at guiding stock assessments and management interventions.

Fishery-dependent data in both recreational and subsistence fisheries are scarce (Post, Persson, Parkinson, & Van Kooten, 2008; World Bank, FAO, & WorldFish Center, 2010). If data are collected, routine mail-in or phone surveys, or onsite roving and access creel (i.e., angler) surveys may be used to provide important recreational fishery-dependent data, but each of these data collection methods is expensive (Connelly, Brown, & Knuth, 2000; McCormick, Whitney, Schill, & Quist, 2015), often biased (Connelly et al., 2000; McCormick, Quist, & Schill, 2013; Tarrant & Manfredo, 1993) and not well supported in most locations (Post et al., 2008). Limited information about stock status, and an inability to record fishery-dependent data at appropriate spatial and temporal scales, has led to substantial problems including disputes between recreational and commercial fishery sectors and fishery collapses. For example, failure to collect and process data with sufficient timeliness led the Gulf of Mexico red snapper (*Lutjanus campechanus*, Lutjanidae) recreational fishery to operate unabated, with the retrospective realization that it had exceeded its quota every year from 2007 to 2013. In response, commercial fishers filed suit against the US National Marine Fisheries Service (NMFS; Guindon et al. v. Pritzker, 2014), claiming that NMFS failed to both restrict catches after quota had been reached and use the best scientific information available, among other things. Several Canadian recreational fisheries targeting Salmonids, Percids, Esocids and Centrarchids experienced stock collapses which went unnoticed by fishery scientists, managers and the public due to inadequate monitoring and assessment (Post et al., 2002). In many countries, subsistence catches are key to food security and may comprise a substantial portion of total catch; however, more often than not, subsistence fisheries lack centralized data collection systems altogether, and their precise contribution to total catch is not well resolved (World Bank, FAO, & WorldFish Center, 2010). There is enormous untapped potential for the more than 10% of the total population in developed countries fishing for recreation (Arlinghaus, Tillner, & Bork, 2015) and the for the many subsistence fishers around the world to collect and utilize fishery-dependent data to support better fisheries outcomes.

3 | CURRENT APPLICATIONS OF FISHERY-DEPENDENT DATA TECHNOLOGIES

Relatively recent technological innovation in fishery data systems has the potential to address many of the shortcomings of current approaches to fisheries data collection and management. Data systems that utilize available technologies come in many forms (e.g., hardware and software solutions, mobile phone applications), may be implemented by different fisheries stakeholders or through collaborations between them, and can be used to improve outcomes at multiple points in the supply–management chain, from improving efficiency on the water and access to markets, to driving scientifically sound regulation. Although implementing new data systems and establishing new data infrastructure will likely be a technical, institutional and bureaucratic challenge for fisheries managers and informally managed fishers alike (Beaulieu et al., 2016), improved data systems can increase the temporal and spatial resolution (i.e., near real-time, georeferenced catch and landings), volume and diversity (e.g., length data) of data collected, while also improving efficiency and automation in both collection and data analysis, standardization, verifiability, flexibility, transparency and availability of data. Technologically advanced fisheries data systems can also facilitate traceability of catch for fisheries certification programs, reduce the cost of data collection, and provide a means to enhance communication and cooperation between fishers and/or managers to reach common goals.

We review three categories of existing fishery-dependent data collection technologies to highlight opportunities to improve fisheries outcomes: electronic video monitoring (also called remote electronic monitoring, hereafter EM), traditional electronic reporting (ER) and mobile computing. We then describe emerging technologies and promising areas of technological advancement including artificial intelligence and machine learning in other fishery-dependent data systems.

3.1 | Electronic monitoring

Electronic monitoring systems are camera systems designed to record catch and discard practices for shore-side or at sea auditing. By recording information about gear, haul (target catch, incidental catch, by-catch and discard), catch handling, processing and/or fishing effort (location and time fished), EM systems were developed to enhance on-board human observer programs or as a cost-effective, less biased alternative that can improve monitoring and surveillance through increased coverage. Across different fishing sectors, EM hardware may look very different: large camera systems (video or still) mounted aboard vessels to census effort and landings have been used in industrial fisheries and some SSFs, while still cameras hand-held by operators to capture images of weight, size and identity of landed species have also been used in SSFs, and cameras set up to record fishing activity from shore have been deployed to log nearshore fishing effort in recreational and subsistence fisheries (Greenberg & Godin, 2015; Keller, Steffe, Lowry, Murphy, & Suthers, 2016; Powers & Anson, 2016).

TABLE 1 Electronic monitoring trials/programs conducted globally

Location	Species	Gear	Trial year(s)	Used in management	Sector	Platform/ camera	Compliance goal	References
Australia NT	Tuna, billfish	Various	2009–2010	No	C	AMR	Sort, weight	Piasente et al. (2012)
Australia NSW	Various	Recreational	2011–2013	No	R	ANSO		Keller et al. (2016)
Australia WA	Sharks	Gillnet	NA	No	C	Mobotix Q24	Sort, weight	Evans and Molony (2011)
Canada BC	Halibut	Longline	2002	Yes	C	AMR	Sort, weight	McElderry, Schrader, and Illingworth (2003)
Canada BC	Groundfish	Hook and line, trap	2008–2009	Yes	C	AMR	Sort, weight	Stanley et al. (2009)
Canada BC	Groundfish	Hook and line	2006–2010	Yes	C	AMR		Stanley et al. (2011)
Canada BC	Freshwater	Recreational	NA	Yes	R	Timelapse		Greenberg and Godin (2015)
EU Denmark	Various	Various	2008–2009	No	C	AMR	Sort, weight, discard	Kindt-Larsen et al. (2011)
EU Denmark	Various	Longline, purse seine, trawl	2010–2011	No	C	AMR	Sort, weight	Dalskov et al. (2012)
EU Denmark	Cod	Gillnet	2010–2011	No	C	AMR	By-catch	Kindt-Larsen et al. (2012)
EU Denmark	Cod	Gillnet, purse seine, trawl	2008–2014	No	C	AMR	Discard	Ulrich et al. (2015)
EU Denmark	Demersal	Purse seine, trawl	2014–2015	No	C	Anchor lab K/S	Sort, weight	Mortensen et al. (2017)
EU Germany	Cod	Trawl	2012–2014	No	C	AMR	Sort, weight	Götz, Oesterwind, and Zimmermann (2015)
EU Netherlands	Various, cod	Purse seine, trawl	2012–2014	No	C	AMR	Sort, weight	van Helmond et al. (2015)
EU Scotland	Demersal	Purse seine, trawl	2008–2014	Yes	C	AMR	Discard	Needle et al. (2015)
EU UK	Demersal	Trawl	2013	Yes	C	AMR	Discard	Roberts, Course, and Pasco (2014a)
EU UK	Cod	Gillnet, trawl	2013	Yes	C	AMR	Sort, weight	Roberts, Course, and Pasco (2014b)
EU UK	Crab, lobster	Trap	NA	No	C	Kodak Playsport	Sort, weight	Hold et al. (2015)
Multiple	Tuna	Purse seine	2011–2012	No	C	AMR	Sort, weight	Ruiz et al. (2014)
New Zealand	Various	Set net, trawl	2003–2004	No	C	AMR	By-catch	McElderry, McCullough, Schrader, and Illingworth (2007)
US Alaska	Halibut	Longline	2002	No	C	AMR	By-catch, sort, weight	Ames (2005); Ames et al. (2005)
US Alaska	Halibut	Longline	2002 and 2004	No	C	AMR		Ames et al. (2007)
US Alaska	Rockfish	Trawl	2009	No	C	AMR	Sort, weight	Bonney, Kinsolving, and McGauley (2009)
US Alaska	Halibut	Trawl	2014	No	C	AFSC	Sort, weight	Wallace et al. (2015)
US Atlantic	HMS	Longline	NA	Yes	C	Saltwater, Inc.		NMFS (2015)
US Gulf of Mexico	Red snapper	Recreational	2012–2015	No	R	Bosch Mic		Powers and Anson (2016)
US Northeast	Groundfish	Gillnet, longline, trawl	2010–2013	No	C	AMR	Sort, weight, discard	Pria, McElderry, Stanley, and Batty (2014)
US West Coast	Groundfish	Trawl	2008	No	C	AMR	Sort, weight	Pria et al. (2008)

Note. AMR: Archipelago Marine Research, Ltd.; C: commercial; HMS: highly migratory species; R: recreational.

In industrial fisheries, EM systems comprise of some combination of closed-circuit television (CCTV) cameras, a GPS, a hydraulic pressure sensor and/or a rotation sensor to indicate fishing start times and to commence recording, and a control centre. EM trials have been conducted across a variety of industrial fisheries around the world to verify compliance with catch sorting and weighing regulations, discard bans and quota and interaction requirements for protected species, and for full reporting of fishing and on-board processing mandates (Table 1). Trials have shown that EM can provide precise, verifiable, cost-effective fishery-dependent data and promote adherence to quota regulations for protected species (Hold et al., 2015; Needle et al., 2015; Sylvia, Harte, & Cusack, 2016; Ulrich et al., 2015; van Helmond, Chen, & Poos, 2015). In 2015, the Atlantic pelagic longline fishery became the first US fishery to implement a fleet-wide EM program to verify the accuracy of bluefin tuna by-catch (Sylvia et al., 2016). Following extensive trials (Ames, 2005; Ames, Leaman, & Ames, 2007; Ames, Williams, & Fitzgerald, 2005; Pria, McElderry, Oh, Siddall, & Wehrell, 2008; Wallace, Williams, Towler, & Mcgauley, 2015), the U.S. West Coast groundfish bottom trawl and non-whiting midwater trawl fisheries and all Alaskan fisheries using longline and pot gear formally approved EM to replace human observers in April 2017. In Canada, British Columbia's hook and line groundfish fishery has required 100% EM coverage since 2006, and has lauded the use of video data for its ability to reduce bias in catch estimates to audit other catch accounting systems (Stanley, McElderry, Mawani, & Koolman, 2011; Stanley, Olsen, & Fedoruk, 2009).

A recent push for greater adoption of EM has come from the Western and Central Pacific Fisheries Commission (WCPFC), which manages tuna and other highly migratory fish stocks. EM systems have been recently trialled in seven (Australia, New Zealand, Fiji, Cook Islands, Federated States of Micronesia, Republic of the Marshall Islands and Palau) of the 26 member nations; however, trials have largely been on a small number of vessels (2–5, with exception of Australia, which implemented an EM program on 75 vessels across three types of gear) (WCPFC, 2017a). Across all industrial fisheries, EM data are rarely used for fisheries management (Wallace et al., 2015), but the recent endorsement of EM by at least one regional fisheries management organization (RFMO; WCPFC, 2017a) could change the global uptake of EM.

The utility of EM has also been noted in SSFs where large fleets, small vessels, low enforcement and high costs of paying people to monitor fishing activity have undermined the feasibility of implementing traditional monitoring programs including on-board observers (Bartholomew et al., 2018). In SSFs, EM systems may pair a camera with a GPS unit with power supplied via solar panels (Bartholomew et al., 2018) or use standalone mounted or hand-held cameras; still photographs may be preferred to balance data collection with data storage requirements. In Peru's small-scale elasmobranch gillnet fishery, a trial provided proof of concept that EM can be an effective tool to record the identity and quantity of shark and ray target catch, as well as pinniped by-catch; however, EM images were less successful at accurately capturing sea turtle and cetacean by-catch (Bartholomew et al., 2018). In partnership with The Nature Conservancy in Indonesia, on-board Crew Operated Data Recording System (CODRS) are being used to photograph, measure, identify and geo-reference all fish caught from participating vessels. To date, data have been analysed to generate length-based stock assessments for multiple species of snappers, groupers, emperors and other landed finfishes across several Indonesian Fisheries Management Areas (P. Mous, 28 September 2017 personal communication). Overall, improvements in surveillance have been noted for SSFs in Thailand, Malaysia and Morocco following the implementation of EM programs (Pitcher, Kalikoski, Pramod, & Short, 2009). Despite these success stories, EM programs have not been implemented at scale in SSFs. Many SSFs have thousands of vessels, making full coverage EM challenging (Bartholomew et al., 2018).

Electronic monitoring-like systems have also been tested in recreational and subsistence fisheries, where dockside or other shore-based camera systems can cost-effectively record fishing effort based on landings information, vessel activity or effort around a specific feature (e.g., an artificial reef) (Greenberg & Godin, 2015; Keller et al., 2016; Powers & Anson, 2016). Greenberg and Godin (2015) used dockside cameras to show that large reductions in the length of the red snapper recreational fishery did not lead to commensurate changes in fishing effort, revealing an important weakness with the fishery's management strategy. Beyond trials, large-scale EM as described may simply not be feasible in recreational and subsistence fisheries, where countless individuals operate with limited to no oversight.

3.2 | Electronic reporting

Electronic logbooks (hereafter ELBs) are the most common application of ER in industrial fisheries, but use of formal ELB systems in SSFs and recreational and subsistence fisheries are not well documented (but see Section 3.3). ELBs are a self-reporting tool more akin to paper-based logbooks, and therefore may be less difficult to integrate into a fishery than EM (Lowman et al., 2013). ELBs allow fishers to digitize fishing catch information and are coupled with GPS to enable users to record precise spatial and temporal effort and catch data in near real-time (McCluskey & Lewison, 2008). Some ELB systems may also have a built-in mechanism to alert vessels to cease fishing or leave certain fishing areas when catch limits have been met (Chang, 2011). ELBs have been widely adopted by some management agencies, particularly within the industrial sector. For example, all EU fishing vessels >15 m are required to carry ELBs to record landings and discards. However, although several US vessels have ELBs, they are generally used to verify compliance with regulations and not for direct estimates of catch (Cahalan, Mondragon, & Gasper, 2014; Kauer et al., 2018).

Instead, to improve the temporal resolution of fishery-dependent data, US industrial fisheries have favoured electronic landing receipts (also called fish tickets and e-tickets), which are used as a record of purchase between fish processors and fishers to record landings information via an online submission form. E-ticket landing reports contain information about the date and duration of fishing for each trip, gear type fished, area fished (designated fishing zone), weight and condition of purchased landings by species, for both processed catch and unprocessed catch discarded at the plant, which are recorded by the processor and submitted electronically to a fishery management agency. By transitioning a paper-based fish ticket system to an ER form, fisheries agencies have improved the accuracy and timeliness of commercial landings data for several species in the United States (NOAA 2017). Alaska's crab fishery was the first to adopt electronic fish tickets in 2005, followed shortly thereafter by groundfish and halibut. Use of e-tickets has allowed Alaska's fisheries management agencies to effectively cut significant costs incurred by printing and disseminating huge quantities of paper tickets, reduce errors in catch accounting by streamlining the data entry process, consolidate landings data and improve data transparency by housing all e-ticket data on a single server available to all fisheries management agencies (Carroll, 2006). In order to ensure that harvest data are quickly available to fishery managers and law enforcement, e-tickets were recently mandated for all commercially caught sablefish in the US West Coast catch share fishery to carefully monitor adherence to annual catch limits (NOAA 2017).

Regional fisheries management organizations may again play a role in expanding use of ER globally. Following trials between 2013 and 2017, the WCPFC officially encouraged use of ER for catch and effort data in 2017 (WCPFC13) and for observer data in 2018 (WCPFC14) with suggested, but currently voluntary, data standards, specifications and procedures for purse seine and longline catch/effort accounting (WCPFC, 2017b). All observer data from WCPFC's Pacific Island member countries are currently transmitted via an ER system in accordance with the WCPFC ER standards, while the Republic of Korea and Chinese Taipei currently report all or most fleet data via ER systems that do not fully adhere to agreed-upon data standards (WCPFC, 2018a). Several countries have expressed concerns over implementing any fleet-wide ER system, including costs, legal frameworks and technical trainings (WCPFC, 2018a), and longline ER coverage for catch and effort data peaked in 2016 and has since declined (WCPFC, 2018b), potentially foreshadowing challenges with future large-scale adoption of RFMO-wide ER.

3.3 | Mobile computing

The global proliferation of mobile technologies has fuelled a revolution in fishery-dependent data system advancements and opportunities. The portability and ubiquity of smartphones and tablets has led to a growing recognition of their potential import in the collection of data for all fisheries sectors (Gutowsky et al., 2013; Lorenzen et al., 2016; Papenfuss, Phelps, Fulton, & Venturelli, 2015; Venturelli, Hyder, & Skov, 2016). Mobile technologies including smartphone/tablet applications (apps) can collect, store and analyse large quantities of real-time or near real-time fishery-dependent data, while capturing the spatial and temporal dynamics of catches (reviewed in Venturelli et al., 2016). By allowing for two-way, near real-time information transfer, mobile apps can also be used to effectively change fisher behaviour on the water to ensure compliance with quota and protected species regulations, and/or connect and engage fishers through data-sharing and social networks.

In the US West Coast groundfish fishery, the *eCatch* app, a smartphone/tablet-based mobile logbook developed by The Nature Conservancy, allows fishers to share real-time information about the location and amount of by-catch species with each other and fishery managers to ensure compliance with overfished species quota and facilitate real-time adaptive management (Kauer et al., 2018; Figure 3). Similarly, NOAA's *TurtleWatch* online platform has successfully reduced sea turtle by-catch in Hawaii's pelagic longline fishery by providing fishers with a map updated with near real-time information about the predicted thermal habitat of loggerhead (*Caretta caretta*, Cheloniidae) and leatherback (*Dermochelys coriacea*, Cheloniidae) sea turtles (Howell, Kobayashi, Parker, Balazs, & Polovina, 2008; Howell et al., 2015).

Mobile technologies may be key to addressing data deficiencies in data-poor SSFs, with apps and online forms allowing users equipped with smartphones and tablets to easily record and analyse fishery-dependent data at the point of catch, landing, processing and/or consumption. In a SSF sea cucumber fishery in Japan, the combination of an iPad-based digital diary and a GPS unit allowed fishers to contribute real-time information about fishing effort and the location and quantity of their catch to an online server, where pre-programmed software immediately performed data processing and data analyses, sharing results with the fishers in near real-time (Saville, Hatanaka, Sano, & Wada, 2015). Information available via these high-resolution data streams led the fishery to voluntarily curtail fishing efforts to avoid exceeding overfished species quota several weeks before the end of the official fishing season (Saville et al.,2015). Integrated online reporting systems that record data at multiple points along a fishery's supply chain may also improve traceability and provide support for fishery's seeking seafood certifications. In the Maldivian pole-and-line skipjack fishery, Fisheries Information System (FIS)—an online tool that links fishing vessel licence information and catch certificates to catch data recorded at the point of landing, sale and export—has been adopted to ensure adherence to EU IUU regulations and Marine Stewardship Council certification standards (Kearns, 2016). Use of mobile apps by buyers has also increased the spatial and temporal resolution of fishery-dependent information. For example, *OurFish* is a point of purchase mobile apps that has been used in SSFs in Belize, Honduras, Indonesia and Myanmar that allows buyers to record a suite of relevant information—species, catch date and location, weight—using a picture-based form. Data from the *OurFish* app serve as a form of digital bookkeeping for fish traders, information is privately shared with the fishers so individuals can track their landings through space and time, and data are electronically submitted to government fisheries agencies and other stakeholders (Irby, 2017).

The recreational fishing sector has experienced a particularly rapid expansion of a diverse and competitive industry devoted to the development of angler apps that can accurately record spatially

TABLE 2 Recreational angler apps for recording fishery-dependent data available for use on a mobile device

App[a]	Price[b]	Installs[c] (thousands)	Development location
Angler's Fishing Log	Free	5–10	US, New York
Anglers	Free	100–500	China
Anglers' Log - Fishing Journal	Free	1–5	Canada
Angling iQ	Free	10–50	EU, Iceland
Anglr	Free	1–5	US, Pennsylvania
Beissindex Pro Angeln	Free	10–50	EU, Germany
BlueTipz	Free	5–10	US, Wisconsin
Catchability	Free	1–5	Australia
CCA Florida Star Tournament	Free	1–5	US, Florida
Chesapeake Catch	Free	0.5–1	US, Maryland
ConnectScale	Free	1–5	US, Tennessee
Dr. Catch	Free	10–50	EU, Germany
drophook Fishing App	Free	1–5	US, Florida
Fangstjournalen	Free	1–5	EU, Denmark
Fatsack Outdoors	Free	5–10	US, South Carolina
Fish Rules	Free	50–100	US, Florida
Fish Rules	Free	50–100	US, Florida
Fish trace	Free	1–5	EU, Germany
Fish4all	Free	1–5	New Zealand
Fishaholics	Free	>1	US
FishAngler	Free	10–50	US, Florida
FishBetter	Free	1–5	US (multiple locations)
Fishbrain	Free/5.99/mo	1,000–5,000	EU, Sweden
Fisherman Watch	Free	100–500	Russia
FishFriender	Free	1–5	EU, France
FishHunter Pro	Free	10–50	Canada
Fishidy	Free/0.99	100–500	US, Wisconsin
Fishing Crew	Free	10–50	US, Texas
Fishing diary (FDP Software)	Free	10–50	EU, Sweden
Fishing Diary (GreatSkyLand)	Free	10–50	China
Fishing diary (La Bellota Soft Ltd)	Free/0.99	10–50	EU, United Kingdom
Fishing Friend	4.55	1–5	EU, Germany
Fishing Journal	Free	1–5	EU, France
Fishing Log (Devling)	Free	10–50	EU, United Kingdom
Fishing Log (MP Fish)	Free	100–500	Russia
Fishing Points	Free	500–1,000	EU, Austria
Fishing Trip Log	Free	10–50	US, Florida
FishingMobile	Free	100–500	US, Michigan
FishMemo	Free	5–10	EU, Lithuania
FishOn!	Free	0.5–1	US, Florida
FishPredict Angler Log	Free	1–5	US
Fishtrip	Free	0.5–1	EU, Denmark
FishWise	Free	100–500	US, Michigan
GoFishing!	Free/1.99	0.5–1	US, Wisconsin
GoFree Hooked	Free	10–50	US, Oklahoma

(Continues)

TABLE 2 (Continued)

App[a]	Price[b]	Installs[c] (thousands)	Development location
HookitandBookit Fishing	Free	1–5	EU, United Kingdom
IAngler by Angler Action	Free	1–5	US, Florida
iAngler Tournament	Free	1–5	US, Florida
iDfish	10.76	1–5	Australia
iFish	Free/2.79	>1	US & Canada
iFishing	2.49	100–500	Canada
IGFA mobile	8.99	>1	US, Massachusetts
iGHOFish	Free	0.5–1	US, Florida
iSnapper	Free	0.5–1	US, Texas
Lure Fishing Log	Free	10–50	China
MFP Fishing Log Journal	Free	1–5	Canada
Mijn VISmaat	Free	50–100	EU, Netherlands
Musky Hunter LITE/PRO	2.99/9.99	500–1,000	US, Wisconsin
My Fishing Advisor	5.99	10–50	US, Wisconsin
My Fishing Companion Lite/Pro	Free/2.49	50–100	US, California
My Fishing Diary	Free	0.5–1	Montenegro
My Fishing Mate Pro Australia	2.07	10–50	Australia
Pro Angler	Free	10–50	US, Florida
Release Mako	Free	1–5	US, Maryland
River Monsters Fish On!	Free	5–10	EU, United Kingdom
Ryboszukacz	Free	10–50	EU, Poland
SAMI	Free	1–5	US, Texas
Schonzeiten Bayern & Fangbuch	Free	1–5	EU, Germany
ScoutLook Fishing	Free	50–100	US, New York
Tails n' Scales	Free	0.5–1	US, Mississippi
Дневник рыболова	Free	1–5	Russia
Клёвая рыбалка	Free	100–500	Russia
Рыбы России	Free	100–500	Russia

[a]Only apps that allow the collection of fishery-dependent data are presented (apps that list fishery rules or species ID only were not considered). [b]Price listed as lite/pro version where relevant. [c]Only apps with a minimum of 500–1,000 installs as of the time of writing are reported in this table; there are tens (possibly even hundreds) of additional angler apps with <1,000 installs, some of which are discussed in the text (e.g., OurFish).

and temporally explicit fishing effort and harvest data, information about discards, and weight and/or length of species caught (Jiorle, Ahrens, & Allen, 2016; McCormick, 2017; Papenfuss et al., 2015; Stunz, Johnson, Yoskowitz, Robillard, & Wetz, 2014; Stunz, Yoskowitz, Fisher, Robillard, & Topping, 2016; Table 2). The explosion of angler apps presents exciting opportunities to address data scarcity issues in the recreational sector (Venturelli et al., 2016). For example, recreational fishers from around the globe have logged more than 3.7 million catches with data on where, when, how and what was caught on the *Fishbrain* app (www.fishbrain.com), although there are no records of any of these data being used to inform fisheries management. However, in the U.S. common snook (*Centropomus undecimalis*, Centropomidae) fishery in Florida, angler app data were used to inform a stock assessment in a context where there is no commercial fishery or commercial data stream for the target species (Muller & Taylor, 2013).

3.4 | Emerging technologies and new data systems

Artificial intelligence, specifically machine learning and computer vision applications, is the next frontier in fishery data systems. With large quantities of image-based fishery-dependent data collected via EM and mobile technologies, technology that automates catch identification (ID) and measurement (length and mass) via morphological characteristics is needed across all fishery sectors. Automated data processing including image analysis has the potential to greatly reduce data storage requirements via post-analysis compression, enable collection of length composition data that could be used to infer weight of discarded species, and minimize time between data collection and management action. By coupling innovative hardware (e.g., a conveyor belt attached to a computer vision system) with machine learning software tools, researchers have shown that automated ID and length/mass recording are possible (reviewed in Miranda & Romero, 2017; Shafait et al., 2016). The *CatchMeter* system is one of the earliest fisheries-specific automated data collection tools developed to document catches (ID and measure seven species) in the Barents Sea groundfish fishery (Svellingen, Totland, White, & Øvredal, 2006; White, Svellingen, & Strachan, 2006). More recently, the *CatchMeasure* system (U.S. patent US 9367930 B2) uses photogrammetry to identify, measure and estimate a total weight of the fish catch recorded by EM in a multi-species finfish fishery in the Northeast United States. *CatchMeasure* uses a set of dual cameras to take stereoscopic images that characterize (ID) and measure landed fish. The EM Innovation Project is a collaboration between the Alaska Fisheries Science Center, several federal and state agencies, and the College of Electrical Engineering at the University of Washington to automate length measurement and species ID for multiple Alaskan fisheries using computer vision technology (Wallace et al., 2015); ultimately, the goal of the collaborative effort is to produce open-source software and hardware to automate EM data processing. In Australia, morphometric analyses combined with machine learning was used to discriminate between cryptic shark species, including hybrids, caught in the Offshore Net and Line Fishery in the Northern Territory with greater accuracy than other ID methods (Johnson et al., 2017). However, despite >20 years of interest, and expanded capacity available through new cloud computing options that enable virtually unlimited storage capacity and expand computer processing speed, there is no indication that automated catch ID has been deployed in a fishery or used by a fisheries management agency.

Rather than working to improve existing technological inefficiencies in fishery-dependent data systems, recent efforts have proposed new fully integrated fishery information systems that synthesize and streamline multiple fishery-relevant data inputs and produce reliable forecasts to facilitate dynamic, real-time, adaptive ocean management (Dunn, Maxwell, Boustany, & Halpin, 2016; Hobday et al., 2014; Lewison et al., 2015; Maxwell et al., 2015). For example, a web-based integrated Fisheries Information Management System (*iFIMS*) assimilates multiple layers of fishery data (e.g., vessel register information, vessel day schemes, crew registers, fish aggregating device tracking, port sampling, *eForms* ELB information) to enable participating fisheries and/or managers that are members of the Parties to the Nauru Agreement (PNA) to track vessel and location-specific catch data in near real-time (Karis, Lens, Kumasi, & Oates, 2014). By requiring *iFIMS* for all longline and purse seine vessels wishing to fish in the EEZs of PNA countries, the Pacific Islands Forum Fisheries Agency—the management body in the region—has been able to monitor more fishing events, readily update stock assessments, and decreased manpower needed to process and store paper logs given electronic data available in near real-time with refined spatial resolution at a fraction of the cost of other monitoring methods (Aqorau, Cullen, Mangal, & Walton, 2017).

To date, fully integrated fishery information systems have been used in data-rich contexts to take advantage of existing data streams, but their utility in data-poor and/or unmanaged fisheries, where technology can effectively create a new data system where one did not previously exist, has not yet been realized. Fishery information systems that synthesize multiple sources of fishery-relevant data also create a value proposition to fishers—by using the best available data science to reveal where and when to fish to maximize efficiency and yield while minimizing risks, users are motivated to contribute to the data collection process.

4 | CHALLENGES LIMITING TECHNOLOGICAL INNOVATION AND UPTAKE

The application of emerging fishery-dependent data technologies across multiple fisheries sectors has shown that innovation can lead to improved efficiencies for the fisheries management process. Why then are technologically advanced data systems not widely integrated into fisheries management? We have identified four major challenges that have prevented the uptake and integration of new fishery-dependent data technologies across all fisheries sectors: (a) upfront costs and insufficient access to capital, (b) legal and bureaucratic barriers; (c) failure to implement data collection standards; and (d) lack of trust and buy-in from fishers.

First, the resources needed to adopt new hardware and software for data collection have been identified as a major barrier to the uptake of new technologically advanced fishery-dependent data systems, in terms of prohibitive acquisition and installation costs and human resource needs new technologies may demand (Sylvia et al., 2016; WCPFC, 2018b). The switching cost associated with adopting new technology may be high relative to the status quo, despite potential long-term savings. With EM in industrial fisheries, for example, initial purchase and installation costs average >$13,000 US per vessel (Sylvia et al., 2016), and additional costs will accrue for maintenance, repair and the employment of technicians to analyse collected data (McElderry, 2008; Sylvia et al., 2016). However, over time, EM costs are generally lower than monitoring alternatives such as on-board observers (Ames et al., 2005; Dalskov et al., 2012; Evans & Molony, 2011; Kindt-Larsen, Kirkegaard, & Dalskov, 2011; Needle et al., 2015; NOAA 2015; Piasente et al., 2012; Sylvia et al., 2016). Within the WCPFC, where EM and ER are encouraged, several countries have noted that fleet-wide implementation is unlikely given associated initial costs, while other member nations better suited to invest in fleet-wide systems have asked for training programs to better understand available technologies and their utility, for which additional resources would be required (WCPFC, 2018b). In SSFs in low-resource contexts, success with EM may only be possible through third-party partnerships that provide funding to enable hardware implementation and data analysis (e.g., CODRS in Indonesia). However, even when start-up costs are available via third-party investment (e.g., *OurFish*), if new data systems are not supported by fisheries management agencies, then the cost of investing in innovation and development may be so great that it prevents widespread and/or sustained use. Even mobile apps, which incur minimal hardware and software costs for users, may be prohibitively expensive for developers to improve and update without institutional support. Point 97's *Digital Deck* was a promising suite of mobile apps developed to record and track fishery-dependent data from the point of landing to market. These mobile apps were trialled in SSFs in Lombok, Indonesia (Thuesen, 2016), the US Virgin Islands and the Solomon Islands (Tripp, 2013); however, despite successful trials, a lack of adequate investment and uptake by fisheries management agencies resulted in an unsustainable business model for the tech provider, and the developer ultimately went bankrupt.

Second, legal and bureaucratic barriers have prevented the adoption of high-tech fishery-dependent data systems, particularly in industrial fisheries with top-down management institutions. For example, until recently, in Alaska's groundfish fisheries, all federally permitted vessels >18 m were legally required to complete and submit *paper* logbooks specifically (Cahalan et al., 2014). For ELBs to be widely adopted, paper log mandates will need to change; absent that change, ELBs may continue to be used in just a small handful of US fisheries (Palmer, 2017). The legal constraint for paper, as opposed to ELB data, has ultimately caused the adoption of high-tech fishery-dependent data systems to lag behind other nations (Cahalan et al., 2014). Data confidentiality issues, including the identity and near real-time location of fishers and vessels, and potentially even imagery of individual fishers (e.g., with EM), may require new legal frameworks which may be slow to adapt to rapidly changing technologies (Kindt-Larsen et al., 2012). Confidentiality issues are important, and legal and institutional systems inherently reflect present norms and ethics and are therefore resistant to change by design, particularly in well-functioning, top-down management systems. Overcoming this barrier therefore represents a significant challenge to creating pathways for new fisheries data technologies. In SSFs and subsistence fisheries lacking a formal management structure, fishery norms may be similarly dictated by long-standing traditions, and, like other types of change, the adoption of new technologies may be viewed as a threat to an established way of life and even the food security of associated communities (Eayrs, Cadrin, & Glass, 2015). When data are collected in SSFs, they are rarely synthesized and used by government fisheries management agencies (Chuenpagdee et al., 2006); without a clear mandate by fisheries agencies to accept third-party data, there is rarely an incentive for managers to accept and utilize industry collected data. Moreover, the types of data being collected may not align with government standards and may not clearly support existing harvest strategies, creating further institutional challenges in the uptake and use of new data streams (Wilson et al., 2018).

Third, fishery-dependent data technologies that are not guided by technical and performance standards for collection and processing of data may not be used by managers or supported at fishery-wide scales. For example, a lack of agreed-upon data collection guidelines and standards for angler apps has largely obfuscated their utility in fisheries management (Venturelli et al., 2016). A failure to align angler app development with the needs and standards dictated by a fisheries management agency resulted in the development of many redundant apps, which led to user recruitment and retention issues, and ultimately bankruptcy by many app developers (Venturelli et al., 2016) (Table 2). Without clear data standards, concerns over self-reporting and/or avidity bias may prevent managers from considering app data as a legitimate data source. At the same time, developers may be discouraged from investing in the creation and upkeep of new technologies that are disregarded by management agencies. While data collection standards are needed to encourage greater adoption of new technologies, standards that are implemented from the top-down may be met with resistance from fisheries with working systems in place. Despite substantial effort to create data standards for ER systems by the WCPFC, several countries have yet to adjust current ER systems to adhere to new standards, further acknowledging that the likelihood of changing their existing systems is low (WCPFC, 2018a).

Fourth, a significant problem limiting the success of current fisheries data systems is the lack of trust and buy-in from fishers, which leads to a disconnect between the collection and application of fishery-dependent data. Top-down data systems often lack feedback between data collectors (i.e., fishers) and data users (i.e., managers), thereby creating a black-box of fisheries data that may disincentivize fishers to provide accurate data (Eayrs et al., 2015). Fishery-dependent data collection is a non-trivial task, the burden of which falls primarily on the fishing industry. Yet despite their necessity in the data collection process, fishers are unlikely to directly benefit from the acquisition of better data, and in many cases, fishers are denied direct access to their data, potentially reinforcing a resistance to change (Eayrs et al., 2015). Technology can automate and streamline data collection and its use and visualization, thereby alleviating the burden of collecting data and incentivizing accurate data collection. However, fishers are often suspicious and unsupportive of the prospect of expanding data collection capacity, for fear that "trade secrets" may be revealed, and because data may be used as a means to discredit a fishery or impose additional restrictions (Eayrs et al., 2015; Mangi, Dolder, Catchpole, Rodmell, & de Rozarieux, 2015). Limited adoption of EM, for example, has been credited to a lack of support from fishers, who have raised concerns over loss of privacy, control and agency following installation of the monitoring technology (Mangi et al., 2015; Plet-Hansen et al., 2017). Similarly, one of the largest identified challenges to implementing ELBs is resistance from fishers, who may be opposed to recording exact fishing locations or unmotivated to change current logbook recording methods (McCluskey & Lewison, 2008). If collected data have no value to fishers and/or cannot benefit their fishing operation, then participation in data collection programs and uptake of new data technologies will be met with resistance (Eayrs et al., 2015).

5 | LOOKING TO THE FUTURE: A TRANSDISCIPLINARY APPROACH FOR HIGH-TECH DATA SYSTEMS TO INFORM FISHERIES MANAGEMENT

Addressing each of the challenges identified above will require bridging the gap between existing and emerging high-tech fishery-dependent data systems and their use in fisheries management. As computing power increases and innovation improves existing hardware and software, costs for systems may come down. For example, data storage costs were once important considerations that are rapidly being alleviated by widely available and increasingly affordable cloud storage options. Public/private partnerships may be needed to provide capital and expertise to develop, implement and analyse the output from high-tech data systems in fisheries with limited economic resources (e.g., many SSFs and subsistence fisheries) (Bush et al., 2017). Legal barriers preventing adoption and use of fishery-dependent data technologies will likely need to be addressed with legislation, which can be a slow and tedious process. Data standards will also need to be developed to ensure that innovative data systems have utility to fisheries managers. While opportunities to address these first three identified barriers to greater adoption of high-tech fishery-dependent data systems are tractable, overcoming issues of trust and lack of buy-in from the fishing community are the most ubiquitous and daunting challenge identified throughout all fisheries sectors and across all management types (Eayrs et al., 2015; Mangi et al., 2015; McCluskey & Lewison, 2008; Plet-Hansen et al., 2017), and it is the challenge we aim to tackle in this section. Specifically, we propose the adoption of a transdisciplinary management approach that focuses on collaborative problem-solving among stakeholders, including fishers and managers, to facilitate innovation and implementation of technologically advanced fishery-dependent data systems.

Transdisciplinarity is a collaborative effort undertaken by a diverse group of stakeholders to address a shared question or problem and work towards a common goal (Rosenfield, 1992). In a transdisciplinary framework, stakeholders work jointly to (a) define a shared problem that will address their individuals needs (see Section 5.1); (b) develop a methodology to address the problem by defining specific objectives and target outcomes within a shared conceptual framework (see Section 5.2); (c) determine an agreed-upon solution through an iterative process that facilitates learning and adaptation (Ciannelli et al., 2014) (see Section 5.3). The key to a successful transdisciplinary approach to fisheries management is the early and equal participation of all stakeholders to collectively identify a problem and work together to find a solution (Ludwig, 2001; Roux, Rogers, Biggs, Ashton, & Sergeant, 2006). The inclusion of diverse stakeholders and insistence on equal participation from the very beginning of the process is what differentiates transdisciplinary approaches from other forms of collaborative management (Stokols, Misra, Moser, Hall, & Taylor, 2008). Working with different stakeholders and requiring agreement at each step before moving to the next allows for adaptation throughout the transdisciplinary process, thereby ensuring that outcomes meet stakeholder needs (Virapongse et al., 2016).

Transdisciplinary management is difficult and time-consuming, and requires different skill sets than those that are usually cultivated among fishers and managers. Limited human resources, institutional biases and challenges associated with communication across sectors (e.g., multinational fisheries with many actors and nested governance structures, such as RFMOs) can hamper the success of a transdisciplinary engagement (Virapongse et al., 2016). But, by specifically addressing and reconciling challenges associated with conflicting stakeholder worldviews, the need to manage for change and adaptability, and scale mismatches (e.g., between needs identified by managers and fishers) (Virapongse et al., 2016), a transdisciplinary approach has a greater chance of producing meaningful, lasting solutions and is an investment in cooperative relationships that will pave the way for future management efforts (Cundill, Roux, & Parker, 2015; Eigenbrode et al., 2007; Harris & Lyon, 2013; Reyers et al., 2010). Ultimately, we suggest that a cooperative, transdisciplinary management approach to innovate and expand fishery data systems can create a transparent, participatory process that can increase the likelihood of widespread adoption of new and existing technologies, foster stakeholder buy-in, enable data-informed management decisions and build, repair or reinforce relationships among fisheries stakeholders.

5.1 | Identify relevant stakeholders and establish a shared goal

For any given issue in fisheries management, there are multiple stakeholders involved (i.e., different fishing sectors, managers, processors or even consumers), each with a unique perspective on a shared problem. For example, in an industrial tuna fishery, the problem of by-catch manifests differently for different fisheries stakeholders: for fishers, by-catch creates inefficiencies by reducing target catch and may result in fines or threaten fishing operations; for managers, by-catch may be seen as a problem for regulations on protected or vulnerable species; and for processors and sellers, by-catch may undermine efforts to certify or market a product as sustainable. Thus, while the specific concerns and needs may vary across fishery sector or stakeholder, a transdisciplinary process allows the collective group to recognize commonalities and coalesce around shared goals (Figure 2). Importantly, even when an identified goal may have short-term costs for one group of stakeholders (e.g., reducing fishing quotas), the collaborative process and shared decision-making create transparency and a sense of fairness, which may increase the likelihood of compliance (Turner et al., 2016).

As with other forms of co-management, a successful transdisciplinary engagement is most likely to succeed in fisheries with a history of collaboration and trust among stakeholders, which may be more likely in fisheries with bottom-up management structures. Where management is top-down, and management actions are perceived as disenfranchising fishers, mistrust and antagonism may be pervasive, and the success of the transdisciplinary process may be less certain. However, in low trust situations, involving brokers—for example an NGO, or an administrative entity specifically tasked with managing the collaboration—to facilitate the process of establishing and working towards collective goals can be a means to overcome challenges associated with mistrust (Provan & Kenis, 2008). To get the transdisciplinary engagement off of the ground, time must also be specifically allocated for building trust between stakeholders by

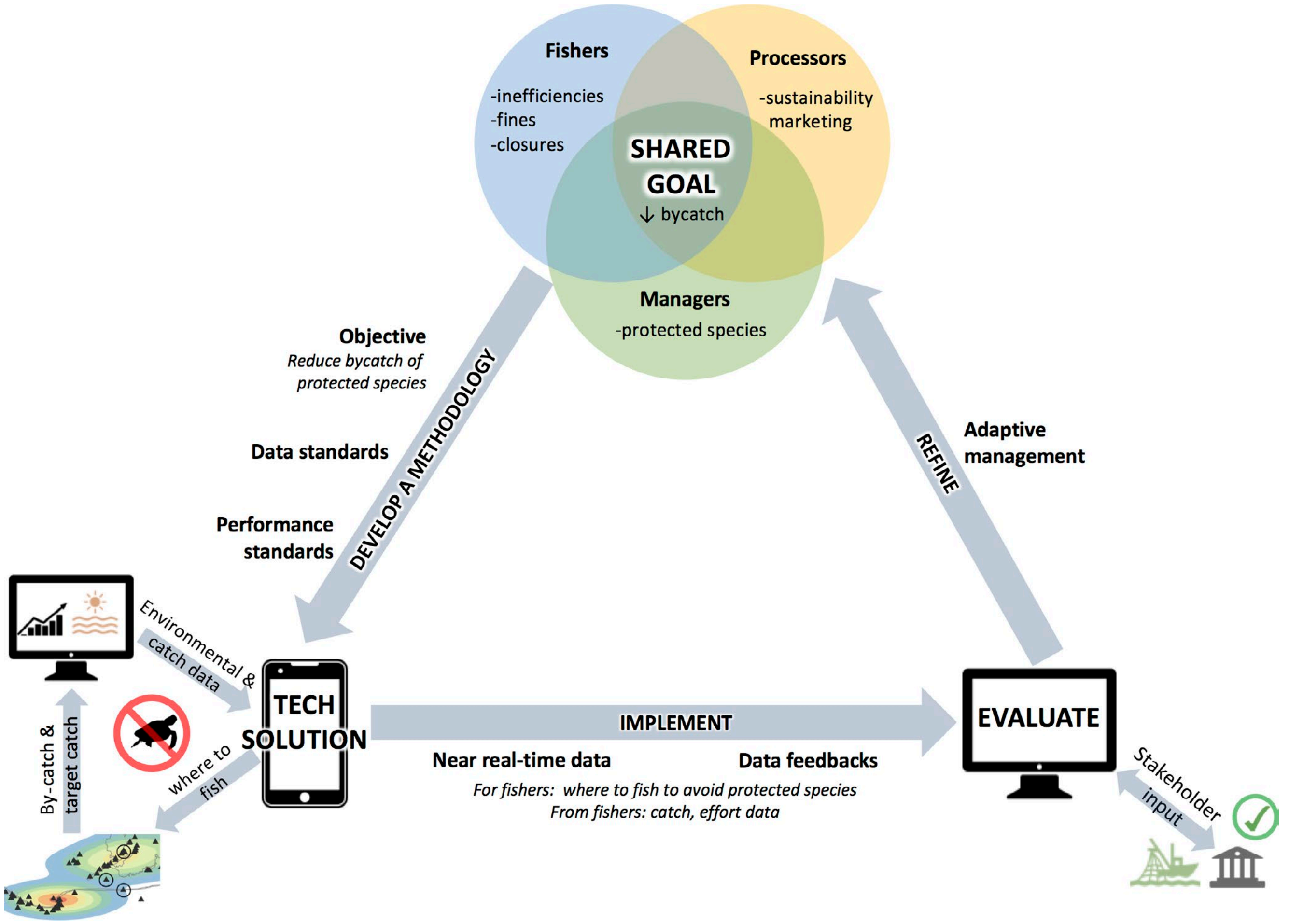


FIGURE 2 A conceptual figure showing the process of transdisciplinary fisheries management as a pathway to the adoption of high-tech fishery-dependent data systems (with the shared goal of by-catch reduction used as an illustrative example) [Colour figure can be viewed at wileyonlinelibrary.com]

managers or facilitators with expertise in collaborative techniques (Virapongse et al., 2016). Once a baseline level of trust has been established, and issues of trust and buy-in preventing wider adoption of high-tech fishery-dependent data systems can be addressed, new data systems can serve to strengthen trust between groups through transparent sharing of information between all stakeholders.

5.2 | Develop a methodology and propose a solution

Once a shared goal has been identified, and the value of technology and data has been clarified, the group must articulate the objective of the new technology in language that recognizes the needs of all stakeholders, and establish clear technical and performance standards for fishery-dependent data collection to ensure that the new technology meets these needs (Figure 2). When objectives are not clearly defined, new technologies may seem superfluous and may never get past the pilot phase (e.g., Table 1). EM program failures, for example, are generally not attributed to problems with systems themselves, but rather as a result of a failure to identify how EM programs can enhance or supplant existing data streams to assist in evaluating whether particular management objectives and goals have been reached (Lowman et al., 2013). At the same time, the inclusion of clearly articulated objectives and technical and performance standards is a critical step to prevent dissatisfying or perverse outcomes for the fishery or the stakeholders. For example, better technology has led to improvements in fishing efficiency in ways that undermine fishery sustainability when standards and objectives have not been set (Sreekumar, 2011; Turner, Polunin, & Stead, 2014).

Within the transdisciplinary framework, the process of finding a solution to achieve an agreed-upon objective is an iterative negotiation—not the result of a top-down decision-making process—in order to address diverse perspectives and values and to ensure buy-in from all stakeholder groups (Roux, Stirzaker, Breen, Lefroy, & Cresswell, 2010). Importantly, the technology tools should not drive the solution if it is not a good fit. It is unlikely that any solution will be mutually and equally beneficial to all stakeholders, but the outcome is more likely to be accepted if reached through this structured, transparent, participatory decision-making process than if the same decision had been made behind closed doors (e.g., failure to adjust existing ER systems to adhere to imposed data standards in the WCPFC).

5.3 | Implement, evaluate and refine

Once a technology is determined to be an appropriate solution to meet a shared goal, a fishery can begin the implementation process. To meet the needs and transparency expectations of all involved, most new fishery-dependent data technologies will need to incorporate feedback mechanisms to grant fishers access to near real-time fishery-relevant information streams and to ensure that the fishing industry is benefiting from its data collection effort. Fishers participating in fishery data collection programs have noted that receiving feedback about collected data is necessary to maintain interest and participation (Prescott, Riwu, Stacey, & Prasetyo, 2016). This can be accomplished through information-sharing programs that use near real-time fishery-dependent data collection tools to effectively expand data access to all user groups (Jensen, 2007; Salia, Nsowah-Nuamah, & Steel, 2011; Saville et al., 2015). A collaborative process can also help to ensure that collected data are shared with fishers in a manner that they can understand and use effectively to guide decisions made on the water (Neitzel, van Zwieten, Hendriksen, Duggan, & Bush, 2017).

Evaluating a data system's efficacy against the agreed-upon objective and data and performance standards is integral to the success of a new high-tech data program (Lowman et al., 2013). An advantage of high-tech fishery data systems is the shortened time lag between data collection and action (e.g., management intervention, chosen fishing location) for fishers and managers alike, which can be institutionalized if arrived at by shared consensus and embedded within an iterative management process (Figure 2). Access to near-time data also can serve to ensure that performance evaluation is timely. The ability to refine the application of fisheries technologies can further safeguard against unintended consequences—such as better fishing efficiency leading to overfishing—of highly temporally and spatially resolved data streams and improved data sharing networks.

5.4 | Examples: learning from fishery data system success stories

Although transdisciplinary management in fisheries is not common, elements of this approach have been utilized in numerous fisheries and have contributed to successful technological innovations and improvements in management. We highlight a few examples where aspects of the transdisciplinary approach are apparent to show the feasibility of and the opportunity for expanding the use of better technology in fisheries management, though none of them could be said to have engaged in transdisciplinary approaches fully.

First, in the British Columbian groundfish EM program, Stanley, Karim, Koolman, and Mcelderry (2014) identified the primary ingredient of success as being collaborative problem-solving between industry and the Department of Fisheries and Oceans Canada. Their shared goal (to improve yelloweye rockfish quota monitoring) led to a joint understanding that addressing the fishery's problems would require compromise and innovation, and through this process, they established EM as a mutually beneficial solution that has been successful and lasting.

The Nature Conservancy's *eCatch* mobile phone app, used on the US West Coast groundfish fishery (Figure 3), was also the result of multiple stakeholders (fishers, managers and NGO) identifying a common goal (reduce by-catch) out of a diverse set of motivating factors (population collapse of protected stocks within the fishery; regulatory consequences for exceeding quota of protected species due to the mixed species nature of the targeting method). The development of an app by a third party allows fishers to share data with each other and with managers to increase efficiency of fishing (less by-catch), reduce risk (fewer negative regulatory consequences) and inform adaptive management via real-time information about where not to fish (Kauer et al., 2018). The fishery also experienced additional benefits when fishery-dependent data available via *eCatch* enabled Monterey Bay Aquarium's Seafood Watch program to conduct an assessment and upgrade the sustainability ranking of 10 species of West Coast groundfish (Kauer et al., 2018).

NOAA's *TurtleWatch* site was created to achieve a shared objective of reducing sea turtle by-catch in Hawaii's pelagic longline fishery. Fishery managers needed to ensure protection of endangered species in accordance with the US Endangered Species Act, and fishers were motivated to improve fishing of target species and avoid potential fines and/or the closure of the fishery given too much sea turtle by-catch. *TurtleWatch* facilitates near real-time data exchange between managers and fishers about the predicted location of sea turtles (Howell et al., 2008, 2015), thereby allowing both fishers and managers to accomplish their shared goal to reduce by-catch, while also providing additional benefits to both groups. In a SSF in Peru, simple high-frequency, two-way radios were used to similarly successfully mitigate sea turtle by-catch for fishers and managers alike (Alfaro-Shigueto, Mangel, Dutton, Seminoff, & Godley, 2012). Radio communication allowed analysts to share real-time information about sea turtle by-catch hot spots to compel fishers to avoid certain areas, while also providing oceanographic and climatic information valuable to the fishers for targeting their catch (Alfaro-Shigueto et al., 2012).

In fisheries with decentralized or informal management, or without management, the recognition of shared problems between fisheries stakeholders, such as fishery inefficiencies and market failures, can motivate collaborative, bottom-up efforts that may utilize technological innovation to find solutions. For example, in SSFs in Kerala, India and the Effutu Municipality, Ghana, standard mobile technology (e.g., text messaging) facilitated information sharing on the water and between fishers and buyers to prevent catch discard due to an unavailable buyer—benefiting both the fishers and the buyers (Jensen, 2007; Salia et al., 2011; Sreekumar, 2011). In each example, win–win outcomes were possible because of collaborative efforts between multiple fishery stakeholders that allowed them to identify a shared problem and then use technology to address it. This cooperation increases the likelihood of buy-in and utilization of the technology, and builds trust between stakeholder groups.

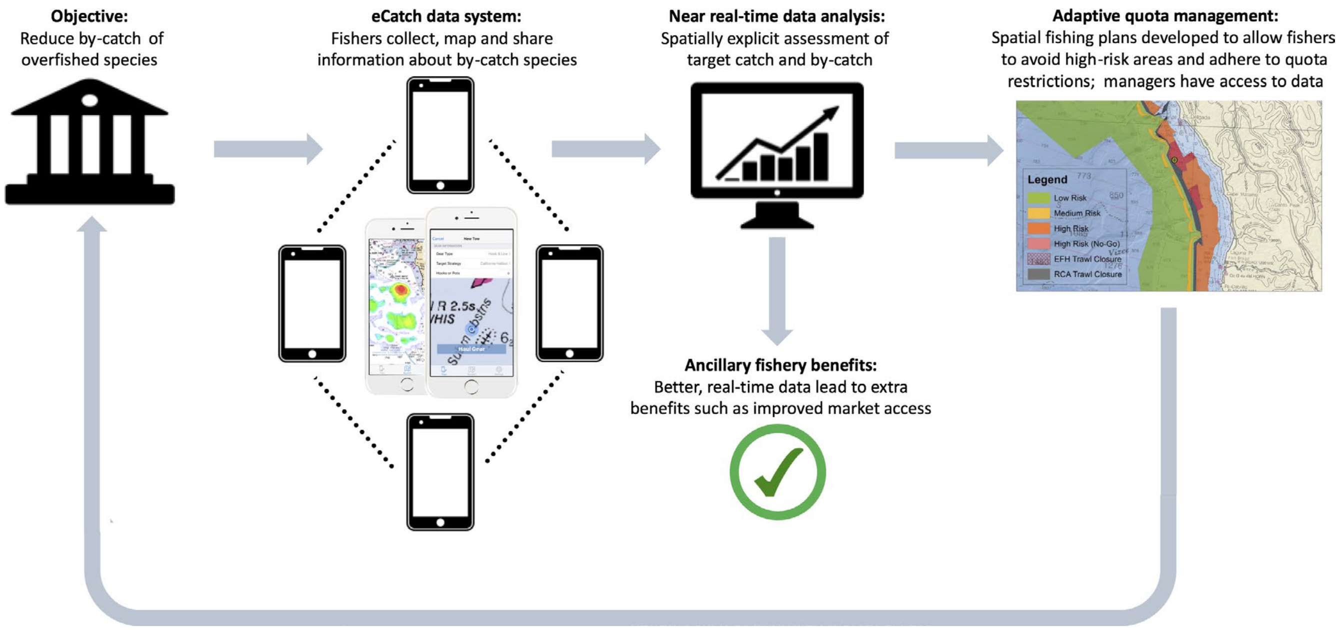


FIGURE 3 A conceptual illustration of a mobile electronic logbook system, *eCatch* (developed by The Nature Conservancy) that allows fishers to securely collect, map and share their fishing information in near real-time with the goal of reducing by-catch of overfished species and facilitating adaptive management [Colour figure can be viewed at wileyonlinelibrary.com]

5.5 | Unintended consequences and risks

Transdisciplinary management approaches help distribute the burden of management across the many stakeholders involved in the resource system. To the extent that a given technology integrates data input through data output (e.g., an app), it can democratize management by decentralizing data collection and analysis and making it available so that fishers or local governance bodies are less dependent on outside experts or a centralized agency. This cooperation can increase the management capacity in informal or decentralized management systems, or any data-poor fisheries that lack the resources to fully manage their fishery. In centralized management systems, the use of technology to collect, analyse and/or distribute data occurs within the hierarchy of the top-down management structure, but decentralizes some of the management process by inviting stakeholders to participate in decision-making. It is important to acknowledge that there are risks associated with the introduction of technologies that allow fishers to gain more agency within a management structure or empower fishers with data in the absence of formal management.

Improved technology may be used to fish more effectively, and rather than supporting sustainable fisheries, it could instead contribute to overfishing. For example, in the Northumberland lobster fishery and a SSF in Kerala, India, information-sharing networks led to sizeable increases in landings, which were unlikely to be sustainable over the long-term (Sreekumar, 2011; Turner et al., 2014).

Communication and information sharing can also undermine cooperative efforts between multiple fishery stakeholders by strengthening the bond between groups of stakeholders at the expense of others. Sreekumar (2011) noted that real-time price information sharing between buyers facilitated by mobile phones in Kerala, India, led to the formation of buyer cartels and collusive price-fixing practices.

Even after working collaboratively and iteratively to define a shared goal and implement an agreed-upon data solution, newly available data may be interpreted differently by different users, or seen as being at odds with observations made on the water, leading to conflict between individuals or stakeholder groups. In the North Sea flatfish fishery, fishermen noted an increase in plaice stock, but catch reconstructions did not corroborate this view, and policymakers and NGOs rejected their claim outright (Verweij, van Densen, & Mol, 2010). Fishers viewed annual decreases to their total allowable catch as putative and unnecessary, leading to controversy and feelings of distrust between fishery stakeholders (Verweij et al., 2010). Feedback, communication and agreed-upon standards for information use and processing may alleviate some of the conflict that can arise as a result of differences in perception and/or interpretation of data (Prescott et al., 2016; Verweij et al., 2010), but perception differences may persist.

As with any management change or technological innovation, there is the risk of unexpected consequences; however, the cooperative decision-making and iterative nature of transdisciplinary collaboration could make it easier to identify these problems and address them within a reasonable time frame.

6 | CONCLUSION

As a growing human population continues to drive up demand for seafood (Hall, Hilborn, Andrew, & Allison, 2013), it will become increasingly imperative to achieve sustainable resource use in all sectors of capture fisheries to safeguard food and livelihood security, and to maintain the ecological integrity of the ocean. There is an exciting opportunity to use technology to vastly improve fishery data systems. New tools can expand data collection, analysis and distribution to achieve more sustainable resource use by empowering fisheries stakeholders with data that are spatially and temporally relevant for fishing and fisheries management. Existing uses of technology in fisheries highlight the vast potential of technology to improve fisheries outcomes across fishing sectors; yet, the relative paucity of innovation and adoption of new technologies suggests that significant challenges have limited support for new technologies in much of the world's fisheries. We suggest transdisciplinary fisheries management as a pathway towards achieving greater buy-in and ultimately uptake of new fishery-dependent data technologies. By working together towards a shared goal, fisheries managers can use fishery-dependent data technology as a value proposition to fishers: by employing tools that streamlines and/or automates data collection and analysis, and returns information to users about where and how to best fish and/or improve market access, the adoption of innovative data systems can improve fishery outcomes for multiple stakeholders.

There is often a steep learning curve associated with the adoption of new technology. Developing and synthesizing information from fishery data systems designed to meet global challenges including rapidly changing ocean conditions due to anthropogenic climate change and natural climate variability may therefore necessitate expanded public/private partnerships to leverage external expertise that may not exist within either management agencies or the fishing industry. At the same time, management institutions need to support the uptake of new and improved data streams. For example, an important advantage of a high-tech fishery data systems is the shortened time lag between data collection and action (i.e., management intervention, chosen fishing location) for fishers and managers alike, which can be institutionalized if embedded in an adaptive management framework. We acknowledge that once established, improved data streams may come with associated challenges such as general information overload and overconfidence in models and resulting analytics. Data alone will not result in more sustainable fisheries, and data itself do not lead to better decision-making, but it is a key component to effective management, no matter the fishing sector or type of management institution. Ultimately, embracing technological advancements in fishery data systems can lead to win–win scenarios in which managers and harvesters experience improved fishery outcomes through better data.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

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