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Digital fisheries data in the Internet age: Emerging tools for research and monitoring using online data in recreational fisheries

Robert J. Lennox[1,2] | Valerio Sbragaglia[3] | Knut Wiik Vollset[1] | Lene K. Sortland[1] | Loren McClenachan[4] | Ivan Jarić[5,6] | Meaghan L. Guckian[7] | Keno Ferter[8] | Andy J. Danylchuk[9] | Steven J. Cooke[10] | Robert Arlinghaus[11,12] | William M. Twardek[10]

[1]Laboratory for Freshwater Ecology and Inland Fisheries, NORCE Norwegian Research Centre, Bergen, Norway

[2]Norwegian Institute for Nature Research, Trondheim, Norway

[3]Department of Marine Renewable Resources, Institute of Marine Sciences (ICM-CSIC), Barcelona, Spain

[4]Department of History and School of Environmental Studies, Ocean History Lab, University of Victoria, Victoria, British Columbia, Canada

[5]Institute of Hydrobiology, Biology Centre of the Czech Academy of Sciences, České Budějovice, Czech Republic

[6]Department of Ecosystem Biology, Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic

[7]Department of Environmental Studies, Antioch University New England, Keene, New Hampshire, USA

[8]Institute of Marine Research, Bergen, Norway

[9]Department of Environmental Conservation, University of Massachusetts Amherst, Amherst, Massachusetts, USA

[10]Department of Biology, Institute of Environmental and Interdisciplinary Science, Fish Ecology and Conservation Physiology Laboratory, Carleton University, Ottawa, Ontario, Canada

[11]Departement of Biology and Ecology of Fishes, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany

[12]Division of Integrative Fisheries Management, Humboldt-Universität zu Berlin, Berlin, Germany

Correspondence
Robert J. Lennox, NORCE Norwegian Research Centre, Laboratory for Freshwater Ecology and Inland Fisheries, Nygårdsgaten 112, Bergen 5008, Norway.
Email: role@norceresearch.no; https://twitter.com/fisheriesrobert

Abstract

Recreational fisheries are diverse in scale, scope, and participation worldwide, constituting an important ecosystem service of marine and freshwater ecosystems. Management of these socio-ecological systems is challenged by monitoring gaps, stemming from difficulties engaging with participants, biased sampling, and insufficient resources to conduct biological or social surveys of fish and human populations. In the Internet age, online data have great potential to make a meaningful contribution to recreational fisheries research, monitoring, and management. Recreational fishers in some countries increasingly use social and other digital media to share their experiences with followers, with most data freely available to web scrapers that compile databases of text (e.g. tweets, status updates, comments), photos, videos and other media that contain information about spatiotemporal activity, sentiments towards catches/experiences, targeted and bycatch species, effort levels, and more. Although the future of recreational fisheries research, monitoring and management will likely involve more digital scraping, uptake is only just beginning and there are several challenges including tool availability/accessibility, sampling biases, and making findings relevant and usable to practitioners. Despite these challenges, we envision fisheries managers will increasingly turn towards online sources of fisheries data to supplement conventional methods. We challenge scientists to work towards continued method development and validation of various digital fisheries data tools and emphasize how biases from the online behaviour of users may complicate interpretations of these data for fisheries management.

KEYWORDS
catch-and-release, culturomics, fisheries management, iEcology, recreational fishing, social media

1 | INTRODUCTION

Recreational fisheries science, monitoring, and management are challenging endeavours that demand consideration of the environment and animals affected by fishing as well as the associated cultural and social dynamics. Fisheries science, therefore, tracks biological aspects of the resources (reviewed in Hilborn, 2003 and Lorenzen et al., 2016) including biological status of target species and harvestable surplus (Forseth et al., 2013), bycatch (Davies et al., 2009; Lennox et al., 2018; Raby et al., 2011), and collateral damage to natural spaces (e.g. pollution, habitat disturbance, damage/stress to species caused by noise or boat strikes). Nature managers must also track the social dimensions of fisheries including catch shares (Abbott et al., 2018; Miranda, 2005), perceptions of management (Quinn, 1992), effort (Dutterer et al., 2020), target and nontarget species (Brouwer et al., 1997), user satisfaction (Birdsong et al., 2021), stakeholder attitudes, perceptions, beliefs and values (Arlinghaus, 2005, Manfredo et al., 2017), and management or behavioural outcomes (i.e. harvest or release; Gaeta et al., 2013). Although some fisheries are highly valued at national scales and funding is available for intensive monitoring, many fisheries are poorly studied (so-called data-poor fisheries; Pilling et al., 2009) and effective management is impeded by monitoring gaps (Arlinghaus et al., 2017; Elmer et al., 2017; Post et al., 2008).

New solutions are being sought to collect fisheries data at spatial and cultural scales needed for effective management (Arlinghaus et al., 2017; Holder et al., 2020). In the digital era, science has great potential to be engaging with nature conservation and management using connected tools (Arts et al., 2015). Individual users can actively archive their data on the Internet either directly using naturalist diary applications (e.g. iNaturalist, eBird) or indirectly by uploading text, photographs, video, or audio files to the Internet. Passive data are also generated by individuals being active on the Internet, compiling page views on sites like Wikipedia and search volumes on browsers such as Google (i.e. Google Trends). When these data are used to identify ecological patterns such as species distributions or interactions, the data are referred to as "iEcology"; when the data are interpreted in the human context of nature–human interactions including attitudes, values and perceptions, the data are referred to as "culturomics". Collectively, fish and fisheries data that are archived and can be accessed for scientific purposes are what we call digital fisheries data. Digital fisheries data have great potential for studying and monitoring social and ecological aspects of fisheries (Jarić, Roll, et al., 2020). Analytical tools for accessing and compiling digital fisheries data from online sources involves systematic mining of the information giving sufficient information to replicate the data access procedures and then using video and image object recognition, natural language processing, and mapping of georeferenced data to analyse the data and draw conclusions (Correia et al., 2021; Jarić, Correia, et al., 2020; Jarić, Roll, et al., 2020; Ladle et al., 2016).

As a growing number of recreational anglers turn to the Internet to learn about fishing, share their personal information about their fishing activities, and connect with like-minded users (e.g. Giovos et al., 2018), the corpus of digital fisheries data is growing and their potential to provide representative samples for science and management is amplifying. Given that the data shared by recreational fishers contain valuable information about various ecological and sociological aspects of a fishery, we submit that these data will be increasingly essential to the jobs of fisheries scientists and managers worldwide in the coming years. In this paper, we review the opportunities we perceive to exist for recreational fisheries to integrate digital fisheries data and discuss how to facilitate the adoption and implementation of digital fisheries data approaches in research, monitoring and management.

2 | ACCESSING DIGITAL FISHERIES DATA

Digital fisheries data is a general term that we adopt to refer to any data available online that are relevant to fisheries. For our purposes, we are focused on digital fisheries data on recreational fisheries. There are four similar disciplines: historical ecology, iEcology, and culturomics. Historical ecology has a similar remit of using archived corpora of media to analyse spatial or temporal trends; as libraries and archives work to digitize newspapers, maps, and photographs, historical ecology will become an increasing source of digital fisheries data about society in general using tools like Google Ngram viewer and Lexis Nexis (Figure 1; Lotze & McClenachan, 2014; Marzin et al., 2014). Individual data may be accessed from users' personally tagged contributions to online websites. Angler-generated data are increasingly common in recreational fisheries as anglers log

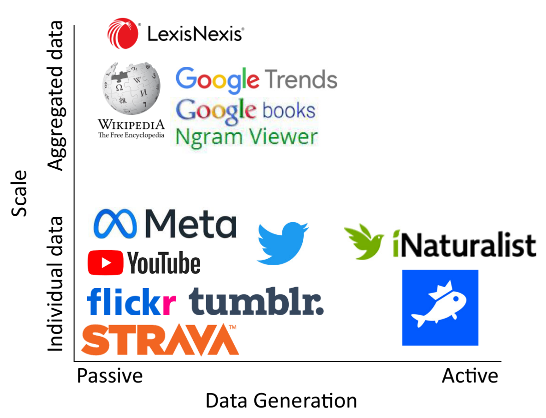

FIGURE 1 Tools that generate potential digital fisheries data. Users will either passively generate the data or actively provide it via dedicated apps. Data affiliated with individuals are available from social media applications and include text, photo, video, or audio files that can be scraped and used to understand fisheries. Contributed data may also be posted on other microblogs, blogs, personal websites, or web forms with user profiles. Actively generated data are provided to applications dedicated to creating checklists or field diaries. Aggregated data are not specific to individuals but describe user volumes or interest metrics based on archived news media or books or based on search metrics from browsers such as Google or services such as Wikipedia

their fishing efforts and catches over time (Gundelund et al., 2020). This active and voluntary contribution of data is explicitly or implicitly generated for scientific use by uploading data to nature applications such as iNaturalist or specialized fishing apps (Figure 1; see Venturelli et al., 2017). However, individuals may unknowingly provide data usable for fish ecology or fisheries social science by posting online (Figures 1 and 2). Digital fisheries data can be gleaned from individuals posting information on blogs, microblogs (e.g. Twitter, Tumblr), personal websites, or online forms (e.g. Shiffman et al., 2017) or commenting on photos on Flickr, Facebook, or Instagram, providing information about fish, fisheries, and their usership (Figure 1). Societal trends can also be gleaned from browser search volume, web page views, Wikipedia word counts, or other volume-based metrics related to online interactions with fish and fisheries topics (Jarić, Correia, et al., 2020). Computer programs can read text, analyse images, or watch videos to quantify data contained in these media and generate digital fisheries data from the worldwide web (Correia et al., 2021). Analytical pipelines for accessing quantifiable data from online sources using reproducible and transparent methods provide digital fisheries data that can be fit using modelling, machine learning, ordination, network analysis, and other tools for testing hypotheses about ecological, social, and economic dimensions of recreational fisheries (Figure 3).

3 | RECREATIONAL FISHERIES MANAGEMENT QUESTIONS AND THEIR POTENTIAL TO BE ADDRESSED BY DIGITAL FISHERIES DATA

3.1 | What are the statuses of fish populations?

The status of fish populations is crucial to manage fisheries and forms the basis of actions including length limits, bag limits, and spatiotemporal closures intended to protect stocks from overexploitation. Digital fisheries data have the potential to provide circumstantial information about the demographic status of fish populations, particularly when considered over long periods of time and when assessed as trend information (i.e. declining or increasing) rather than absolute population status. Leveraging digital fisheries data can be useful for data-poor fisheries where assessment and management are constrained (Arlinghaus & Krause, 2013; Pilling et al., 2009), or to supplement traditional stock assessments that may not have historical context to draw on (van Gemert et al., 2022). Analog analogues of digital fisheries data illustrate how access to historic records can provide information to fisheries management where digital fisheries data are too new to provide suitable examples. For instance, fishing publications have been used to show population declines of sharks in Argentina since the 1970s (Barbini et al., 2015), infer abundance declines of blue groper (*Achoerodus viridis* Labridae) and grey nurse shark (*Carcharias taurus*; Young et al., 2014), and estimate declines in snapper (*Pagrus auratus* Sparidae) populations in Australia (Thurstan et al., 2016). Time series data can also provide insight into how fish

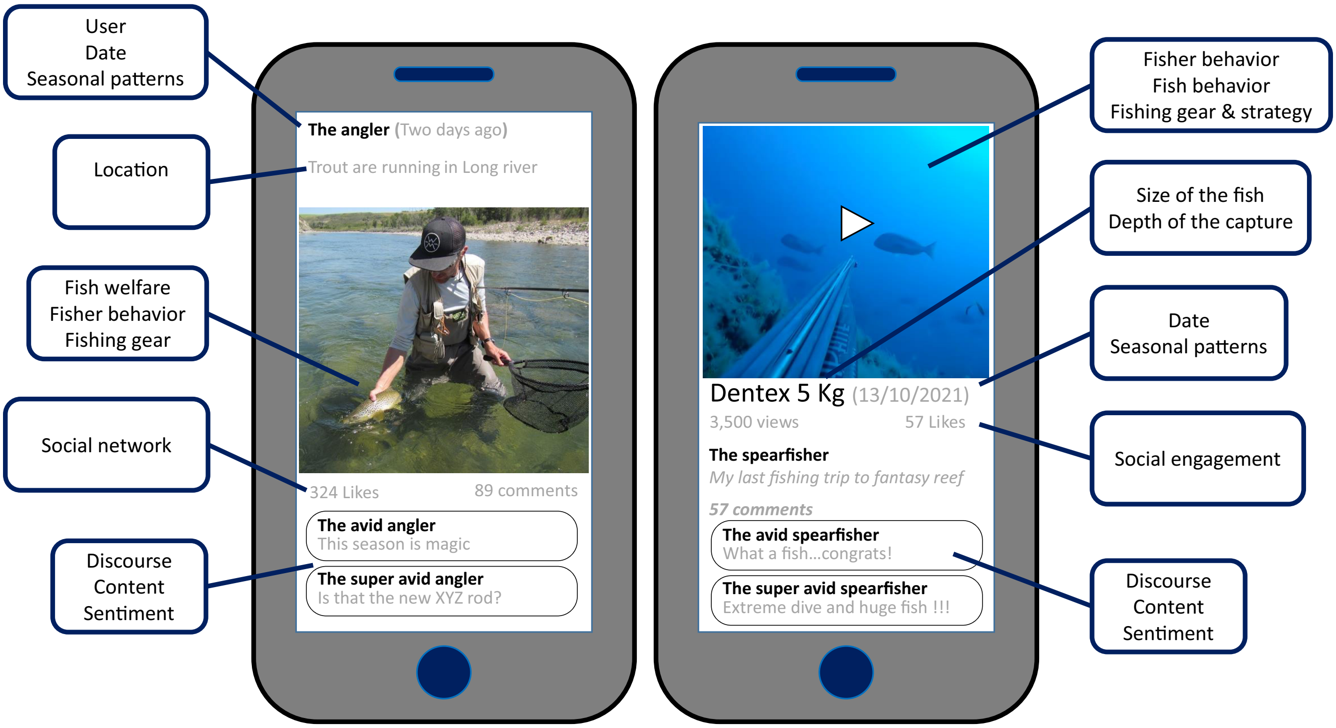

FIGURE 2 Examples of the potential of digital fisheries data. Images of recreational fishers posted and archived online provide information about who, where, when, why and how fish are being targeted and fished. Figure inspired by Toivonen et al. (2019)

size structures have changed over time (e.g. Jiménez-Alvarado et al., 2019; McClenachan, 2009; Rypel et al., 2016). Finally, these records can document community-level changes such as a shift from predatory to omnivorous fish, as observed on the island of Gran Canaria over 70 years (Jiménez-Alvarado et al., 2019).

Many of these existing examples of tracking the status of fish populations with cultural information use library records of photographs that have yet to be digitized. However, they show how broader access to these data via online digitization has the potential to provide valuable historical context for managing fisheries, especially where shifting baselines are affecting present management decisions (Pauly, 1995). At shorter time scales, digital data on blogs and image sharing sites have potential to flag rapid changes in fish populations. Early warning signs that distributions or bathymetric ranges of fish populations are shifting may emerge in social media posts of recreational fishers (Sbragaglia, Coco, et al., 2021). Measuring fish in photographs can provide opportunities for preliminary length-based stock assessment techniques but must account for biases related to size classes of fish that are photographed and posted online as well as shifting baselines of what constitutes a 'big' fish. Early warnings of declines for two species of heavily targeted reef fish emerged from the Australian spearfishing community nearly two decades before protection of those species, alongside documentation of angler concern for the status of these species (Young et al., 2014). In California, analysis of trophy fish records found declines in the maximum size of twelve targeted species since 1966, but stabilization and recovery in response to conservation efforts since 2003 (Bellquist & Semmons, 2016). Fisheries management is still a ways away from operationalizing the use of digital data for tracking the status of fish populations, but there are clearly opportunities to be capitalized on as fishers passively provide information about their catches around the world to websites and social media and actively contribute to angler diary applications (Figure 4).

3.2 | Recreational fishing effort: where, when, why and how are people fishing?

Human dimensions of fisheries are crucial to match demographic status of fish populations to the effort levels dedicated to exploiting those stocks. Digital data can be used to reveal fishing patterns in society by tracking preferences for fishing opportunities and travel priorities. Early research efforts that mined Internet data to infer fishing participation used broad measures of Internet search volume (e.g. Google Trends, Carter et al., 2015; Wilde & Pope, 2013) or posting volume to social media sites (Martin et al., 2014) to reveal general spatiotemporal trends in fishing effort intensity. More recent research efforts have tapped into the digital fisheries data frameworks to analyse photographs or posts on Instagram, Twitter, and Flickr; these social media data have revealed details of national park use by anglers (Sessions et al., 2016; Tenkanen et al., 2017) and seasonal trends in general fishing effort (Mancini et al., 2018; Sbragaglia et al., 2020). Georeferencing public statements about fishing can also be used to map local densities of fishers for managers to use (Monkman et al., 2018a). Search volumes for fishing at certain sites available through Google Trends or similar tools may also have a role

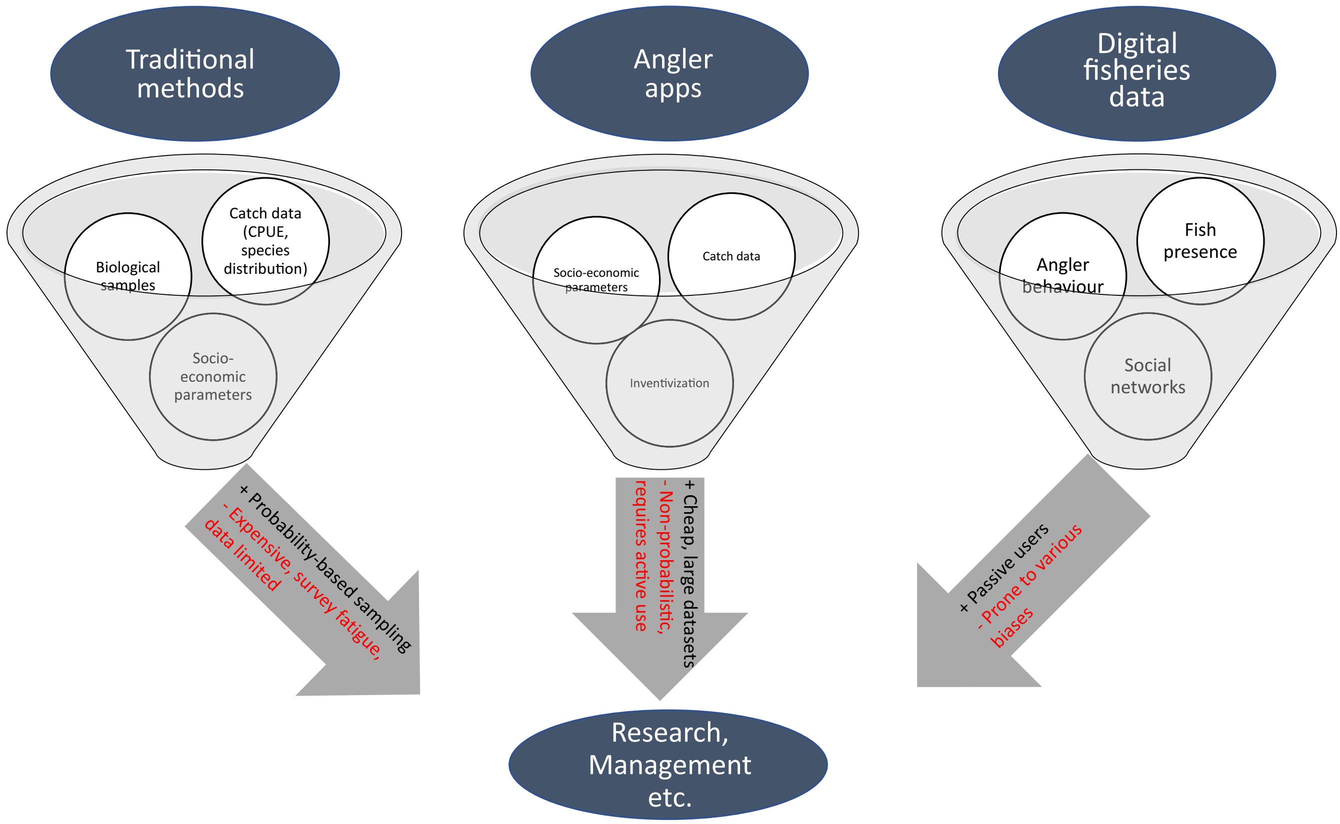

FIGURE 3 Situation of digital fisheries data with other forms of biological and social monitoring of fisheries. Digital data provide some unique benefits to management of these social-ecological systems when consideration of potential biases in the data are accounted for

in gauging interest. Digital data should be preferably used as a relative measure of spatiotemporal use of sites or fisheries by recreational anglers, which is more robust to the nonrepresentative nature of most digital data sources compared to inference on absolute numbers. Developing automated near real-time tools for tracking fishing activities at local scales can be useful to monitor participation rates, hotspots, short- and long-term changes in fishing patterns, and management needs for specific species or waterbodies that anglers are targeting. Prioritizing monitoring or revisions at areas where fishing effort is increasing can be aided by knowledge about where and when anglers are taking trips, for example. Tracking fishing locations using geolocation (e.g. use of protected areas) and angler apps will help identify how mobile anglers exploit their landscape, but must take steps to protect individual privacy and avoid negative narratives about surveillance.

With the data in hand from recreational fishers, using these numbers to estimate general population-level trends from may be tenuous and will require testing of assumptions and validation experiments to check how social media data perform as an indicator of where, when and how people are fishing (Sbragaglia et al., 2020). Biased samples from over-representation of active users and influencers on social media may skew perceptions if appropriate models are not generated. Indeed, Vitale et al. (2021) showed that people sharing catches on digital platforms are more avid, have a higher economic expenditure, higher CPUE when catching something and tend to catch trophy, iconic and emblematic species. Gundelund et al. (2020) showed that digital app users were more committed and specialized than a random sample of fishers. This aligns with what ornithologists have found when hobbyist bird watchers register their sightings on applications: bird abundance data from the citizen science application eBird have undergone scrutiny to understand if, how, and when user checklists could be applied to management of bird populations (e.g. Ruiz-Gutierrez et al., 2021). For fisheries applications, some anglers are very active in recording catches on specific websites either with the intention for the data to be available for research or alternatively for the information to be available to their social network (e.g. iNaturalist; Figure 1). With enough records accumulated, these catch and effort data can be analysed to understand when and why anglers are fishing, similar to the way logbooks have historically been used in recreational fisheries (Vinson & Angradi, 2014). Digital data that specify angling gear have also been found useful to track angler movements, relating these movements to the spread of invasive species (Fricke et al., 2020; Magalhães et al., 2021) and future Internet-of-things connectivity may allow more passive collection about angler activity.

3.3 | What are people catching (intentionally and unintentionally)?

Digital fisheries data can help managers determine what species are being captured by recreational fishers, and to some extent, whether

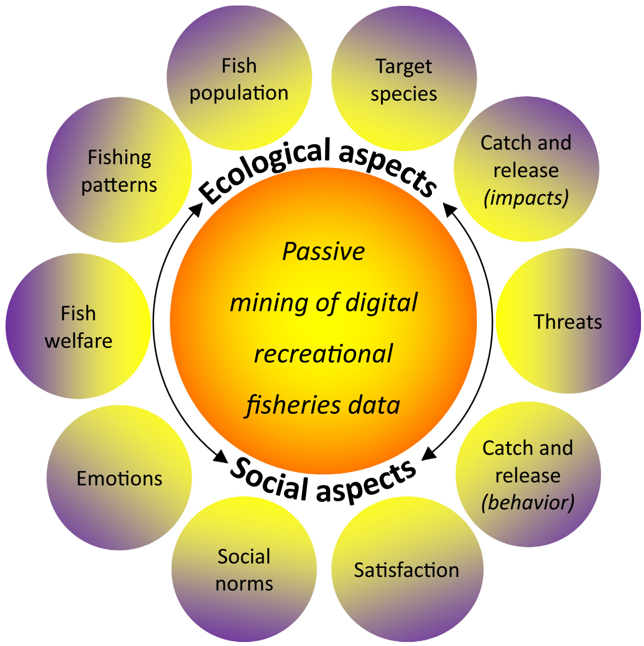

FIGURE 4 Conceptual figure describing how digital fisheries data in the Internet age are acquired by passive mining to study both ecological and social aspects of fisheries. These data can be applied to better understand behaviour and psychology of fishers and the status of the exploited fish populations

the catches comprise target species or bycatch. Traditionally, logbooks would be used as a tool for active monitoring, but passive data can be gathered from the Internet. Forums, blogs, and social media websites such as YouTube and Facebook are becoming increasingly important for recreational fishers and are being used to find information and share fishing experiences (Martin et al., 2012; Sbragaglia et al., 2020). Automated tools may be used to identify species and measure body size of both targeted and bycatch species in photos and videos posted to these social media outlets (Monkman et al., 2019). Managers can turn to digital fisheries data for questions about the exploitation rates on key recreational species such as bass (*Micropterus spp* Centrarchidae), pike (*Esox lucius* Esocidae), salmon (*Salmo salar*, *Oncorhynchus kisutch*, *O. tshawytscha* Salmonidae) and tarpon (*Megalops atlanticus* Megalopidae), can identify interactions with species at risk (e.g. eels *Anguilla anguilla*, *A. rostrata* Anguillidae, Napoleon wrasse *Cheilinus undulatus* Labridae), and can monitor for invasive species (e.g. pink salmon *Oncorhynchus gorbuscha* Salmonidae, lionfish *Pterois sp. Scorpaenidae*) as an early warning system (Jarić, Roll, et al., 2020; Jarić et al., 2021). Managers may notice differences in selectivity or vulnerability of fish species based on location, fishing gear or time of year from large volumes of angler application records or social media posts; for example, Sbragaglia et al. (2020) showed that anglers harvested larger common dentex (*Dentex dentex* Sparidae) than spearfishers, and that spearfishers seemed to have most success in July, when the dentex were located in shallower water and more available. In Libya, fishers posted photographs of invasive lionfish they had captured, which revealed the first instance of this invasive species in that country (Al Mabruk & Rizgalla, 2019). Digital data can provide insights into capture trends across large spatial scales at a relatively inexpensive cost. Surveying recreational fishers around the entire Mediterranean coast would be prohibitive, but mining YouTube data helped identify species targeted by recreational fishing (Giovos et al., 2018). This seems promising, but the rigour required to verify that these data are representative should not be ignored and analysts should diligently document their search strategies for reproducibility. Indeed, more calibrations are needed to identify causal relationships from digital data. Fish community data combined with spatial, temporal, and gear data can be analysed by multivariate statistics to reveal exploitation patterns relevant to management (e.g. different data collection but similar analysis to Filous et al., 2019). Images posted on social media can be used to indicate trends in catches but may have limited resolution on fishers' effort. However, geotagging and path tracking data from apps such as Strava may be useful to calculate how long fishers spend at certain sites, to combine catch with effort level. Linking social media profiles of anglers to estimate metrics such as CPUE will be challenging and largely biased towards specialized individuals, as is often a significant bias with other data collection methods relying on human behaviour (Zhang, 2020).

Knowing which species are captured by recreational fishers is easiest when there is visual evidence in images or videos posted online. However, other types of data from social media can provide insights into social aspects of recreational fishers. Content analysis of the text of posts made to an online discussion forum examined which shark species were captured and released by South Florida's land-based fishery (Shiffman et al., 2017). The study found that many captured sharks belonged to protected species, with no changes in fishing practices following the implementation of legal protection of hammerhead (*Sphyrna* spp. Sphyrnidae) and tiger sharks (*Galeocerdo cuvier* Carcharhinidae). Several studies demonstrated that people share their illegal interactions with protected wildlife online, perhaps anonymously acting under pseudonyms and screen names (Shiffman et al., 2017 and references therein). Digital data can help evaluate whether wildlife protection measures are respected when there are available data on what species are being captured. In some cases, social media posts demonstrating illegal fishing activities have been used to issue fines (e.g. https://barrie.ctvnews.ca/two-anglers-fined-3k-for-catching-endangered-fish-in-closed-season-1.4549955). Furthermore, data mining from social media could help reveal people's attitudes and perceptions to policy changes, such as protection of overexploited species or populations (Monkman et al., 2018a). For example, comments posted by Italian recreational fishers on YouTube suggested that the subject of discussions included fishing techniques, appreciation for the capture, technological aspects and other topics such as pollution and commercial fishing (Sbragaglia et al., 2020). As posts made on social media platforms are archived, it allows for studies of temporal trends on species targeted by recreational fisheries. Although social media data come with limitations (e.g. people's tendency to post their 'best' captures), iEcology can help identify areas for future research and guide management decisions on which areas to prioritize (Shiffman et al., 2017).

3.4 | Are fish being harvested or released?

Effective fisheries management relies on the ability of managers to accurately estimate the proportion of a fish population being removed by recreational harvest and discard mortality. Many recreational fisheries worldwide are open access, meaning anyone can purchase a license and participate in the fishery (Post, 2013). Although license sales can be monitored, the amount of effort expended by a fisher, and the number of fish they capture, is rarely a reporting requirement for participants (McCluskey & Lewison, 2008). Recreational fishers are also a highly heterogeneous group with diverse motivations (Fedler & Ditton, 1994), and many fish that are captured may also be released (Arlinghaus, Cooke, Lyman, et al., 2007). Managers are left with the difficult task of estimating harvest, which is conventionally accomplished by creel surveys (Pollock et al., 1994). Uncertainty in recreational fisheries harvest estimates is common (Cabanellas-Reboredo et al., 2017), and it has been purported that unaccounted harvest in recreational fisheries is leading to the collapse of some fish populations (Post et al., 2002).

Information posted by recreational fishers on social media platforms may help to characterize harvesting behaviours of certain fisher groups. Data mining on YouTube provided estimates on the average weight of common dentex captured by spearfishers and anglers as well as seasonal patterns (Sbragaglia et al., 2020). Computer vision is increasingly powerful and could conceivably identify the species captured, whether fish were harvested or released, sizes of captured fish, and even the time and place of capture via media metadata. Expectations must be tempered, however, because harvest information extracted from social media may not be reflective of the fisheries themselves given that there is likely bias in what a fisher posts on social media (e.g. sharing only positive fishing experiences; Hall & Caton, 2017; Lee-Won et al., 2014). Text and data mining approaches to characterize a European sea bass (*Dicentrarchus labrax* Moronidae) fishery tended to overestimate fisher activity and catch compared to existing survey data (Monkman et al., 2018a). As Gundelund et al. (2020) showed, specialized anglers are over-represented by digital data and these specialists are less harvest-oriented than their counterparts (Arlinghaus, Cooke, Lyman, et al., 2007). Although accounting for sources of bias in social media and other media posts may limit the ability of digital fisheries data to quantify exact harvest numbers, there are a number of inherent benefits to adopting digital data into the toolbox of recreational fisheries managers to understand fish harvest/release behaviours.

3.5 | What is the status of fish welfare?

In many recreational fisheries, more fish are actually released than are harvested (Cooke & Cowx, 2004), and there is a growing emphasis in recreational fisheries science and management on quantifying how fish capture and handling influence the welfare of fish once released (reviewed in Brownscombe et al., 2017). When fish are to be released to comply with regulations (e.g. size limits), because of harvest preferences (i.e. bycatch), or by voluntary catch-and-release, physical injury, and physiological stress related to capture and handling can lead to sublethal effects that impact fitness (reviewed by Cooke & Wilde, 2007), and, when severe, lead to postrelease mortality. For example, tissue damage inevitably occurs when a fish is hooked, with the degree of damage depending on a range of factors, including hook and/or bait type, whether the hook is barbed or barbless, and where on the body the fish is hooked (reviewed by Muoneke & Childress, 1994). Once landed, if an angler lifts a fish out of the water for a photo, air exposure impacts respiration and adds to physiological stress (Cook et al., 2015), that can lead to decreased swimming performance (Holder et al., 2020) and postrelease predation (Danylchuk et al., 2007). Studies that have examined how capture and handling influence the fate of fish following release have also identified how changes in the ways recreational anglers interact with their catch can reduce sublethal effects and postrelease mortality (reviewed in Brownscombe et al., 2017). Although evidence from this line of research has led to the development of science-based best practices for catch and release, they will only be effective at reducing negative effects on fish if recreational anglers effectively learn and adopt them when they go fishing.

The potential effects of fish being caught and handled in recreational fisheries fuels debates on whether fish feel pain (Rose et al., 2014), fish welfare (Arlinghaus, Cooke, Schwab, et al., 2007; Ferter et al., 2020) and the ethics of fishing altogether (Arlinghaus et al., 2012). Digital fisheries data tools, such as scraping (i.e. computer programs reading data from online formats to local data) Instagram and analysing YouTube videos, can be used to assess trends in how anglers are interacting with their catches, the extent of capture and handling practices and whether education and outreach campaigns are being effective at getting best practices to anglers (Martin et al., 2012). These data could prove to be an excellent way to evaluate not only adoption of best practices but also how accurately best practices are used, and how they are perceived and communicated among anglers (Guckian et al., 2018). For example, Italian recreational anglers on YouTube commented on how long a fish has been handled out of the water (Sbragaglia et al., 2020). Relatedly, posts by German anglers regularly fuel debates about the ethics of catch-and-release vs. catch-and-kill. Grassroots efforts aimed at changing social norms about how fish are caught and handled are emerging (Danylchuk et al., 2018), as are broader sentiments about voluntary regulations (Cooke, Suski, et al., 2013). However, what is publicly shared on social media by recreational anglers and available to analysts may not be representative of the scope of angler behaviours, the diversity of captured fish (e.g. they may not post about bycatch) and it may be impossible to discern techniques and tools used (e.g. barbless hooks) from a still image. As such, approaches using digital media data or angler app archives may still need to be complimented by other assessment methods when addressing issues related to fish welfare.

3.6 | What are the needs of stakeholders and their satisfaction?

Fishers often go out fishing to catch big fish, to catch many fish, to spend time with friends and family and to harvest food; satisfaction with the fishing experience is quite important to fisheries sustainability. Recreational fishers share their fishing experiences through fishing reports, comments on social media content, and ratings of specific fishing spots on websites or applications. Accessing and analysing these online data can deepen our understanding of recreational fishers' satisfaction with fishing opportunities and management styles. Satisfaction data can be sought on specialized Facebook groups that are specific to certain fishing sites, areas, species, or techniques. By parsing through posts and comments in these groups, analysts can gather data that provide a general understanding of how satisfied fishers are in specific fishing areas, although the same reservations apply that the social media content is likely biased and not representative. Data analysts and those interpreting or using digital data to measure fisher satisfaction should, therefore, avoid the temptation to overinterpret the data that are provided on social media about the values and satisfaction and not generalize patterns outside of the sampling space. A repeated measures design is, however, a powerful approach in such settings given that the same users are likely to provide input throughout the year and over several years, and the internal consistency provided by tracking the sentiments of frequent users can make it possible to evaluate how satisfaction varies across time or between specific fishing techniques (e.g. angling vs. spearfishing). These data can be applied by fisheries managers to prioritize actions or measures by mapping spatial and temporal trends in fishing satisfaction, allocating efforts to areas that have the potential to provide return on investments in restoration, or other economic measures to address fish or habitat quality.

Tools for using social data to understand user needs and satisfaction include content analysis (Sbragaglia et al., 2020) and sentiment analysis (Sbragaglia, Correia, et al., 2021), which can provide both qualitative and quantitative inference of satisfaction with their fishing experiences. Considering the large volume of digital data available, conducting content analysis on data scraped from social media will not always be feasible. Sentiment analysis, however, provides a text-based solution to analysing comment data using reference dictionaries such as the Saif Mohammad's NRC Emotion lexicon (http://saifmohammad.com/WebPages/NRC-Emotion-Lexicon.htm). The NRC emotion lexicon is a list of words and their associations with two sentiments (negative and positive) and eight emotions (anger, fear, anticipation, trust, surprise, sadness, joy and disgust). There are presently available applications that integrate the NRC emotion lexicon in different languages, such as the 'syuzhet' R package (Jockers, 2017). However, it is extremely important to develop modified versions of such dictionaries tuned to specific recreational fishers' languages, which could strongly differ from standard word associations with sentiments (Lennox et al., 2018; Sbragaglia, Correia, et al., 2021). For example, Sbragaglia et al. (2022) developed a customized dictionary for Italian marine recreational fishers and used it to quantify polarity and sentiments of comments posted on YouTube after watching videos related to catching bluefish (*Pomatomus saltatrix* Pomatomidae), an invasive species in the area of study. These analytical pipelines allow emotions such as joy or anger to be quantified across space and time in different contexts, and support rapid assessment of stakeholders needs.

3.7 | How do social norms influence what is communicated among fishers?

Social norms can be important drivers of human behaviour and are known to influence how fishers interact with animals and their environment (e.g. Guckian et al., 2018). The role of social norms within the context of recreational angling is of particular interest, given that angling behaviour is seldom formally or easily monitored and enforced (Cooke, Suski, et al., 2013). When behaviour is not regulated and/or enforced, individual perceptions about the prevalence of a behaviour (e.g. descriptive norm) combined with perceptions regarding what is socially approved of (e.g. injunctive norm) can exert a large influence on human decision-making and behaviour (Cialdini & James, 2009; Lapinski & Rimal, 2005). The use of social media by anglers to share angling-related information and experiences (e.g. through images) may present both an opportunity and challenge for researchers and managers to glean unbiased data from what is posted. Similarly, such biases may influence the ability to understand (and shift) the norms that operate within angling communities, which can act as the foundation for changing policy and management actions. For instance, as nascent work continues to systematically document how variation in angling behaviour impacts the biological fitness of angled and released fish (Bower et al., 2016; Cooke, Donaldson, et al., 2013; Danylchuk et al., 2014), the conservation potential of catch-and-release fisheries may, in part, be dependent on anglers transitioning to a new norm, including the adoption of scientifically validated best practices (Brownscombe et al., 2017; Danylchuk et al., 2018). Thus, digital fisheries data present an opportunity to understand the norms that currently govern catch-and-release practices and address additional questions, including how exposure to information and imagery shared online may influence anglers' perceptions and attitudes toward best practices and formal regulations. Content analysis and coding of images depicting the culmination of a catch-and-release angling event can be used to understand the types of angling practices (e.g. air exposure, fish orientation, hand location, gear type) that are descriptively normative (e.g. higher prevalence), although yet again concerns remain that the norms revealed online may not be representative. In general, catch and release is more prevalent among more specialized anglers, although some develop into role models and influence others. Observing trends in these influencers can show new developments and alert managers about new technological innovations (Cooke et al., 2021).

Concerns about the proliferation of dry, improperly handled, and air-exposed fish has given rise to the Keep Fish Wet Campaign (Danylchuk et al., 2018), a grassroots movement seeking to transition the norms that govern catch-and-release practices, as well as the online disclosure of photographs depicting the outcome of a catch-and-release angling event. The 'keepfishwet' hashtag promotes the scientifically validated tenet of minimizing air exposure postcatch. One immediate need that culturomics can fulfil is to ascertain the pervasiveness of the campaign and whether images tagged with the 'keepfishwet' hashtag accurately align with the underlying scientifically validated principles promoted by the campaign. Content analysis of angler interactions may also reveal information regarding anglers' willingness to impose sanctions on others' noncompliant or non-normative behaviours or beliefs (Chapman et al., 2018; Guckian et al., 2018). Provided norms are enforced through implicit and explicit forms of social interactions (e.g. rewards, punishment; Cialdini & James, 2009), such interactions may reveal information about what practices are perceived as significant transgressions to warrant social sanctioning and those that are not. More broadly, mapping the digital angling community via social network analysis may allow researchers to highlight information-sharing structures online, characterize clusters of like-minded anglers, reveal patterns of information sharing (and beliefs) among and between identified groups across scales, and identify key network actors. The identification of key actors raises specific questions about the role and impact of social media influencers, including whether and how such individuals may drive engagement with angling-related information and practices. Indeed, opinion leaders have been shown to play a critical role in introducing new norms and behaviours (e.g. practices, gear, policy beliefs; Crona & Bodin, 2010; Nisbet & Kotcher, 2009). Understanding the potential of social misperceptions is important provided it can lead individuals to act in ways that are incongruent with their underlying beliefs (e.g. Geiger & Swim, 2016; Miller & McFarland, 1987; Prentice & Miller, 1996). If only a subset of the angling population engages on social media platforms, how can trends discovered through digital content patterns be effectively married with other survey techniques to provide robust data sets that accurately reflect what is happening with fish stocks and the angling community? Anglers that target different species may even have different social norms related to information shared on social media, potentially influencing the utility of digital fisheries data. Overall, not understanding the social context by which information is shared can skew or misrepresent the broader beliefs and behaviours associated with recreational fisheries and the data that can be mined for ecological and management purposes.

3.8 | How valuable are recreational fisheries?

Ecosystem service valuation is increasingly important in science to quantify the externalities that have traditionally been undervalued when making decisions about development and exploitation (e.g. Miller et al., 2017). Fish provide a gamut of ecosystem services including market and nonmarket values (Holmlund and Hammer, 1999). Provisioning ecosystem services and cultural ecosystem services are the most tangible to be evaluated via social science frameworks and are sometimes assessed by using surveys to quantify the contribution that recreational fisheries make to sense of self, sense of place, mental health, physical health, and nutrition (Cooke et al., 2018; Pretty et al., 2007; Urquhart & Acott, 2014). Such surveys often rely on self-reporting of contingent valuation proxies, especially willingness to pay or on revealed or stated choice surveys to measure the economic value of fishing or site attributes (Hunt et al., 2019). These valuation frameworks seek knowledge about the value of fish and fisheries to inform management about regulatory needs, identify threats that could minimize economic capitalization and catalyse investment in restoration or other actions.

Online data contain the information needed by analysts to begin to estimate the economic value provided by fisheries to society. Digital fisheries data can indeed be extracted from photographs or videos with geotags on social media sites, human mobility data from apps like Strava, or from new media databases such as LexisNexis for historical perspectives. The spatial data from digital fisheries data can then be applied to calculate trip costs and economic contributions by fishers to local economies. For example, photographs posted to Flickr mapped where users travelled to and from to estimate trip costs for different activities and estimate the value of those activities to quantify economic benefits of restoration in India (Sinclair et al., 2018). However, an extra layer of data can be inferred from these data by identifying what fish the people are catching to match to their trip investments and generate cost-benefit analyses. Managers can then apply these data using economic frameworks that promote sustainable fishing practices; for example, if angler utility is best satisfied by travelling long distances with large carbon footprints, efforts should be made to enhance local fisheries value to reduce the footprint of recreational fisheries. Mobility can indeed play a large part in overfishing (Post et al., 2008). It may also be possible to understand how fisheries promote exercise and wellness with spillover benefits to public health. Fisher mobility data from direct tracking have been used by Alós et al. (2020) to observe anglers in experimental contexts, but direct observations may affect behaviour of research subjects. Digital data may not provide the same level of metadata or control as manipulative angler experiments where fishers are provided with trackers, but have the benefit of reducing observer effects when anglers are less aware that their fishing is being analysed (e.g. Monk & Arlinghaus, 2017). Ultimately, digital fisheries data can then be used to assess whether fisheries are being overexploited, whether they are underperforming relative to their potential value, and justify expensive investments in restoration or conservation in order to conserve the resources. Given that the coming decade is the UN Decade on Restoration, better valuation methods will be needed to underlie conservation decision making and using digital data to measure use and estimate value will likely become a key tool for managers to make decisions about recreational fisheries.

4 | KNOWLEDGE NEEDS AND FUTURE DIRECTIONS

As the world becomes ever more interconnected by the Internet, technological development creates new avenues for data collection (Arts et al., 2015). Digital fisheries data will benefit some fisheries but a push forward in this domain will require rigid validations, conservative interpretations, and parallel work with biological and social sciences to avoid biased conclusions. Still, as survey responses decline in many fields, digital fisheries data seem to have great potential to yield passive data on angler behaviour that are increasingly difficult to access (Stedman et al., 2019). The future challenges of using digital data are likely not the availability of data, but rather the opportunities to validate the use of such data in reflecting actual biological, social, and economic statuses and changes across time and space. Notwithstanding, digital fisheries data are increasingly being used to directly test hypotheses about recreational fisheries and are a new tool for science and monitoring alongside several established tools (e.g. angler surveys, stock assessment, telemetry).

Sampling bias is common in ecological survey data as well as in citizen science (Dickinson et al., 2010), a factor that must also be considered for digital fisheries data (Gundelund et al., 2020). Internet access and smartphone use are not equally distributed globally. Willingness to participate also varies and demographic trends in willingness to share must be considered. Vitale et al. (2021) showed that 17% and 31% of anglers share their catches on social media as estimated during onsite and online surveys respectively. Despite uptake of sharing catches not being especially high, the sheer volume of data available for certain fisheries topics can constitute useful corpus for inferring patterns of recreational fishing, including spatiotemporal distribution of fishing, the anglers' motivations for doing so and responses of people to outside influences (e.g. impact of the global COVID-19 pandemic). Active social media users may be alpha users or influencers that dominate conversations; alpha users and influencers probably make more posts than counterparts and their content can, therefore, become dominant when analysing social media data. Individual traits correlate with users' propensity to engage with media (Khan, 2017) with downstream impacts on the quality and representation of digital fisheries data. Sponsored content can also be disruptive when analyzing engagement and information flows. There is much ground-truthing research to be conducted on the nature of recreational fisheries social media and the role of influencers on YouTube, Instagram, Facebook and other platforms in driving demand for fishing opportunities, perception of catches, catch-and-release, and fish welfare via adoption of best practices (Danylchuk et al., 2018). Sampling bias is challenging to account for in the digital sphere, including usership in recreational fisheries, but should be considered by analysts when compiling data and designing analytical protocols. This may also be an opportunity, however, to understand how alpha users form the central nodes in networks of users in social media communities and how the subordinate users respond to posts by alpha users on applications and websites. Digital sources continue to accumulate vast tomes of potential information that can be applied to better understand fisheries and their users, but biases will persist and the temptation to overreach from these samples must be resisted in favour of nuanced and reasonable interpretations that acknowledge the inherent limitations of users' online presences in recreational fisheries (Figure 4).

In line with what exists for well-developed scientific tools, there will need to be standardizations, codes of conduct, and protocols for researchers collecting and using digital data. It is important to gain the trust of users as data protection is a major hurdle and an important social issue in many countries, specifically Europe, which limits the ability to share personally identifiable data for research. Structured search protocols that reduce bias in the selection of keywords by analysts, data archiving with anonymization of personal data (Di Minin et al., 2021; Monkman et al., 2018b), data cleaning to remove bots, accounting for influential individuals in a fishery and self-representation biases, and understanding how the online sample is biased towards certain economic classes, age groups, ethnicities, languages, etc. will be crucial (e.g. Vitale et al., 2021). Consideration of individual identifiability and privacy of users will be paramount (Di Minin et al., 2021; Monkman et al., 2018b), not only especially when dealing with potential illegal fishers (Sbragaglia, Correia, et al., 2021) but also more generally in terms of access to digitally archived individual data. People have a right to know who has access to their personal information as well as where and how those data are stored; they also must have the option to revise their data or withdraw their data from databases (Di Minin et al., 2021). Considering these are emerging areas of research, many researchers are not fully aware of the data policy concerns (Di Minin et al., 2021; Monkman et al., 2018b; Sbragaglia, Correia, et al., 2021). When applied appropriately and with consideration of the potential inherent biases, digital data can provide important insights into recreational fisheries for the benefit of their management.

For now, barriers to using digital fisheries data remain as developers work to overcome some of the bottlenecks in the analysis pipeline. Many machine learning tools are biased or worse, discriminatory. Tools used to assess individual sentiment from written text or image analysis (e.g. body language or facial expressions) from photos will need to be evaluated to determine whether they have been trained to account for diversity. Natural language processing is best developed for the English language, excluding many geographical areas or segments of society when using text-based tools to study global media trends or individual social media posts. Sentiment analysis libraries also have bias due to lexical nuances; Lennox et al. (2020) discussed issues related to species such as "shark" having negative loadings in sentiment libraries that could bias efforts to apply these tools to understand fisheries, for example, by downweighing the satisfaction of anglers catching and mentioning 'sharks' in photo captions. Similarly, Sbragaglia et al. (2022) developed a customized reference library for Italian recreational fishers to reduce the biases associated with misassociations with sentiments and polarity of standard libraries in the context of recreational fisheries.

As issues are resolved and the use of digital fisheries data develops, tools built from these data will not just complement existing methods of understanding patterns in fishing behaviour and catches, but generate new possibilities beyond the present state-of-the-art. Perhaps the most exciting unexplored avenue for recreational fishing with digital fisheries data is the integrated use of multiple data sources to track both biological and social sides of a fishery using data gathered from the Internet that match catches with angler responses. Tracking fish with computer-vision-based mark-recapture, length-based stock indicators for data-poor fisheries, angler surveys to quantify motivations and catch statistics, and online data scraping to identify social networks of anglers, for example, will yield a cross-sectional mosaic of information from the fishery and contribute to efforts to compare results from the digital fisheries data approaches to alternative methodologies. Refining tools for data extraction, storage and analysis are necessary, especially in the field of computer vision and machine learning. We emphasize a need for clear and consistent reporting about data extraction methods and terms used by investigators when compiling databases for reproducibility. Ensuring that methodologies used in different areas are as consistent as possible will be a priority to generate some comparability and provide opportunities for synthesis.

5 | CONCLUSIONS

According to Holder et al. (2020), 100 questions in recreational fisheries entail human dimensions, bioeconomic issues, data acquisition, governance, management, impacts, threats and education components, all of which can be addressed by developing digital fisheries data for science and management. Harvesting digital data available via the Internet will yield a powerful source for fisheries managers to understand where and how people are fishing and to monitor how fisheries are changing over time. Indeed, recreational fisheries are highly dynamic as specialized groups form and new target species are adopted (e.g. microfishing, Cooke et al., 2020). Actively and passively generated digital data contribute to identifying compliance issues, documenting the arrival and spread of invasive species, and providing feedback on policy options. When integrated into more formal analyses, digital data may be useful for assessments, especially when trends over time (e.g. size in the catch) are queried. Indeed, digital fisheries data may be essential to develop as a rapid assessment tool for data limited fisheries. Yet, we have not nearly reached the peak of the digital age in fisheries, particularly as the Internet of Things becomes integrated into fishing rods, reels, and other gear that could provide new data streams (Cooke et al., 2021). The adoption of digital data in recreational fisheries science and management is, therefore, just beginning. Although we do not envision that fisheries in the future will be managed based entirely on data collected and analysed from digital sources, resources for monitoring and regulating recreational fisheries are limited and as anglers continue to seek out new fishing opportunities in remote areas and for obscure species (Cooke et al., 2020), digital data may be increasingly needed to identify and address fisheries issues that emerge more rapidly than they can be addressed with conventional stock assessments and angler surveys. Despite a long road ahead to address privacy concerns and deal with bias inherent to these data, there is clearly a role for digital fisheries data in recreational fisheries that will contribute to filling knowledge gaps and supporting managers with increasingly diverse needs and challenging problems. We see the following as four key steps to using digital fisheries data: 1) informing anglers, 2) learning from anglers, 3) formally assessing fisheries, and 4) regulating fisheries.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

ORCID

Robert J. Lennox https://orcid.org/0000-0003-1010-0577
Valerio Sbragaglia https://orcid.org/0000-0002-4775-7049
Knut Wiik Vollset https://orcid.org/0000-0003-0210-4316
Robert Arlinghaus https://orcid.org/0000-0003-2861-527X

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