Environmental Technology & Innovation 28 (2022) 102865

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Technoscience and the modernization of freshwater fisheries assessment and management

S.J. Cooke [a,*], M.F. Docker [b], N.E. Mandrak [c], N. Young [d], D.D. Heath [e], K.M. Jeffries [b], A. Howarth [a], J.W. Brownscombe [a,f], J. Livernois [g], C.A.D. Semeniuk [e], P.A. Venturelli [h], A.J. Danylchuk [i], R.J. Lennox [j], I. Jarić [k], A.T. Fisk [e], C.S. Vandergoot [l], J.R. Britton [m], A.M. Muir [n]

[a] Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON, K1S 5B6, Canada
[b] Department of Biological Sciences, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada
[c] Department of Biological Science, University of Toronto Scarborough, Toronto, ON, M1C 1A4, Canada
[d] School of Sociological and Anthropological Studies, University of Ottawa, 120 University Private, Ottawa, ON, K1N 6N5, Canada
[e] Great Lakes Institute for Environmental Research, University of Windsor, Windsor, ON, N9B 3P4, Canada
[f] Great Lakes Laboratory for Fisheries and Aquatic Sciences, Fisheries and Oceans Canada, Burlington, ON, L7S 1A1, Canada
[g] Gordon S. Lang School of Business and Economics, University of Guelph, 50 Stone Road East Guelph, ON, N1G 2W1, Canada
[h] Department of Biology, Ball State University, Muncie, IN, 47306, USA
[i] Department of Environmental Conservation, University of Massachusetts Amherst, Amherst, MA, 01003, USA
[j] Norwegian Institute for Nature Research, Høgskoleringen 9, 7034 Trondheim, Norway
[k] Biology Centre of the Czech Academy of Sciences, Institute of Hydrobiology and the University of South Bohemia, Faculty of Science, Department of Ecosystem Biology, České Budějovice, Czech Republic
[l] Great Lakes Acoustic Telemetry Observation System, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, 48824, USA
[m] Department of Life & Environmental Sciences, Faculty of Science & Technology, Bournemouth University, Poole, BH12 5BB, United Kingdom
[n] Great Lakes Fishery Commission, 2200 Commonwealth Blvd., Suite 100, Ann Arbor, MI, 48105, USA

ARTICLE INFO

Article history:
Received 25 June 2022
Received in revised form 4 August 2022
Accepted 4 August 2022
Available online 10 August 2022

Keywords:
Technoscience
Modernization
Fisheries
Resource management
Assessment
Freshwater

ABSTRACT

Inland fisheries assessment and management are challenging given the inherent complexity of working in diverse habitats (e.g., rivers, lakes, wetlands) that are dynamic on organisms that are often cryptic and where fishers are often highly mobile. Yet, technoscience is offering new tools that have the potential to reimagine how inland fisheries are assessed and managed. So-called "technoscience" refers to instances in which science and technology unfurl together, offering novel ways of spurring and achieving meaningful change. This paper considers the role of technoscience and its potential for modernizing the assessment and management of inland fisheries. It first explores technoscience and its potential benefits, followed by presentation of a series of synopses that explore the application (both successes and challenges) of new technologies such as environmental DNA (eDNA), genomics, electronic tags, drones, phone apps, iEcology, and artificial intelligence to assessment and management. The paper also considers the challenges and barriers that exist in adopting new technologies. The paper concludes with a provocative assessment of the potential of technoscience to reform and modernize inland fisheries assessment and management. Although these tools are increasingly being embraced, there is a lack of platforms for aggregating these data streams and providing managers with actionable information in a timely manner.

* Corresponding author.
E-mail address: Steven_Cooke@carleton.ca (S.J. Cooke).

https://doi.org/10.1016/j.eti.2022.102865

The ideas presented here should serve as a catalyst for beginning to work collectively and collaboratively towards fisheries assessment and management systems that harness the power of technology and serve to modernize inland fisheries management. Such transformation is urgently needed given the dynamic nature of environmental change, the evolving threat matrix facing inland waters, and the complex behavior of fishers. Quite simply, a dynamic world demands dynamic fisheries management; technoscience has made that within reach.

Contents

1. Introduction

Inland waters, typically defined by their freshwater composition (Kalff, 2002), support diverse fish assemblages around the globe in habitats as varied as wetlands, ponds, rivers, reservoirs, and lakes (Craig, 2016). Inland fish populations contribute to the structure (i.e., biological diversity) and function (i.e., nutrient cycling, trophic interactions) of freshwater ecosystems (Childress and McIntyre, 2015; Lynch et al., 2016), and their movements and migrations couple aquatic habitats (sensu Ives et al., 2019). They also provide numerous ecosystem services for societies, including supporting nutritional security, livelihoods, recreation, and cultures (Welcomme et al., 2010; Lynch et al., 2016). Inland waters also drive marine ecosystem productivity through anadromy and bulk transport of energy, nutrients, and sediments into estuaries. Unlike marine systems where industrial-scale commercial fisheries predominate, inland fisheries tend to be more small-scale, and include subsistence fisheries (Welcomme et al., 2010; Bartley et al., 2015), as well as vibrant recreational fisheries in industrialized nations (Cooke et al., 2015). Given the many pressures on inland waters (Dudgeon et al., 2006; Reid et al., 2019), including fisheries exploitation (Allan et al., 2005), it is not surprising that freshwater ecosystems are degraded, with freshwater fish populations among the most imperiled biota (Arthington et al., 2016; Harrison et al., 2018).

Given the importance of freshwater fish populations and the threats that they face, inland waters are the subject of intensive assessment (Pitcher, 2015) and management efforts (Arlinghaus et al., 2015). However, many assessments continue to rely on methods (e.g., creel surveys, mail recall surveys) and survey gear (e.g., nets, traps, electrofishing) that are failing to keep pace with the rapid changes in freshwater environments, as well as harvest technologies and strategies. Consequently, the viability of freshwater fisheries continues to be threatened in multiple ways. For example, inland fisheries assessment is inherently difficult given the diversity of ecosystem types, difficulty of sampling in many systems (e.g., winter ice cover, large rivers and lakes), issues with fisheries-dependent surveys (e.g., diffuse fishing effort), and limited capacity in many regions (reviewed in Lorenzen et al., 2016). These difficulties then translate to incomplete, biased, or entirely absent assessment data, which – when coupled with diverse fisheries user objectives, varied and uncoordinated governance systems, and the general lack of awareness about the value of inland fisheries – may lead to poor management decision making (Cooke et al., 2016b). Despite efforts to raise the profile of inland fisheries and develop capacity for assessment and management (e.g., the United Nations [UN] Food and Agriculture Organization [FAO] Ten Steps to Sustainable Inland Fisheries; Cooke et al., 2016a), freshwater fisheries continue to be overshadowed by their marine counterparts (Lynch et al., 2020). While fisheries assessment and management will always suffer from imperfections (Suuronen and Bartley, 2014), technological developments in the last decade offer promise for enhancing fishery assessments globally. Moreover, while history is replete with examples of technological innovations that have benefited assessment and monitoring, this knowledge has yet to be synthesized for application to fresh waters, with most syntheses focusing on marine environments (e.g., Serchuk and Smolowitz, 1990; Eigaard et al., 2014).

To identify how inland fishery assessment and management can be modernized, this paper considers the role of technoscience in this process. Technoscience is broadly defined as cases where science and technology unfurl together, offering novel ways of spurring and achieving meaningful change (Pickles, 1997; Brown and Rappert, 2017). There is a parallel literature on technoscience focused on the blurred boundaries among science, technology, and human bodies (sometimes termed critical technoscience studies; see Weber, 2006; Aronowitz, 2014) that explores medical interventions, cyborgization, sensory augmentation, prosthetics, and gender. The use of the term technoscience in this paper clearly differs from that usage, yet draws on specific insights from that school of thought. Using a team of inland fisheries researchers and fisheries management experts with competence spanning the natural and social sciences on six continents, this paper (i) explores technoscience and its potential benefits for freshwater fisheries assessment and management, (ii) presents a series of synopses that explore the application (both successes and challenges) of new technologies to fishery assessment and management, and (iii), considers the challenges and barriers that influence the adoption of new technologies and conclude with a provocative assessment of the potential for technoscience to reform and modernize inland fisheries assessment and management. This study is timely given the recent emergence of several new scientific technologies that offer much promise to grow the field, but also shown signs of growing pains in their adoption. The work presented here reflects examples informed by hands-on experience combined with evidence synthesis and social science studies.

2. Technoscience - an overview

Sociologists of technology argue that technological development has a reciprocal relationship with society (e.g., Latour, 1990; Johnson and Wetmore, 2021). Technologies are tools that are designed, intentionally and unintentionally, in ways that reflect social values, priorities, and interests (Flanagan et al., 2008). People design and adopt technologies to achieve goals: technologies, thus, are reflections of what social actors think is important. Conversely, technologies shape society: in particular, so-called disruptive technologies directly impact established social arrangements and practices (Postman, 2011; Young et al., 2018). Sometimes, technologies force societal change (e.g., impacts of digital communications on work and commerce), and other times, society pushes back on technological change (e.g., social resistance to cloning, nanotechnology, surveillance technologies). Levels of social acceptance can vary across time and geography, making the relationship between technology and society highly dynamic and variable.

The term "technoscience" extends these insights to address how science informs and enables technology, and how technology enables science—all within the context of iterative societal feedbacks (Fleck, 1993; Channell, 2017; ESTE, 2019). This concept encourages us to think about technology-science-society as a dynamic triad, each influencing the others, sometimes prompting or leading changes, and sometimes lagging or resisting them (Bowman et al., 2017). Technoscience has emerged in environmental and sustainability research and practice (see Benessia and Funtowicz, 2015). In the realm of fisheries, some have argued that management dysfunction is rooted in the inability of managers and decision-makers to embrace science and technology (Serchuk and Smolowitz, 1990). Others have suggested that technological developments have been the basis for improvements in fisheries management despite so-called "technical creep" by harvesters (Eigaard et al., 2014). Midden et al. (2007) suggested that change is best achieved when technology intersects with human behavior. Given that fisheries management is essentially a human enterprise (Hilborn, 2007), technoscience needs to be considered in the context of those who undertake fisheries assessments and management (as individuals and institutions), as well as those who are impacted by those activities (Midden et al., 2007). What is key here is that technoscience can be transformational when barriers to adoption are overcome and when technoscience is not at odds with widespread society values (Parente and Prescott, 1994).

3. Technoscience synopses

Each of the following synopses provides an overview of the technology and its actual or potential application (see Fig. 1), and then considers barriers to adoption.

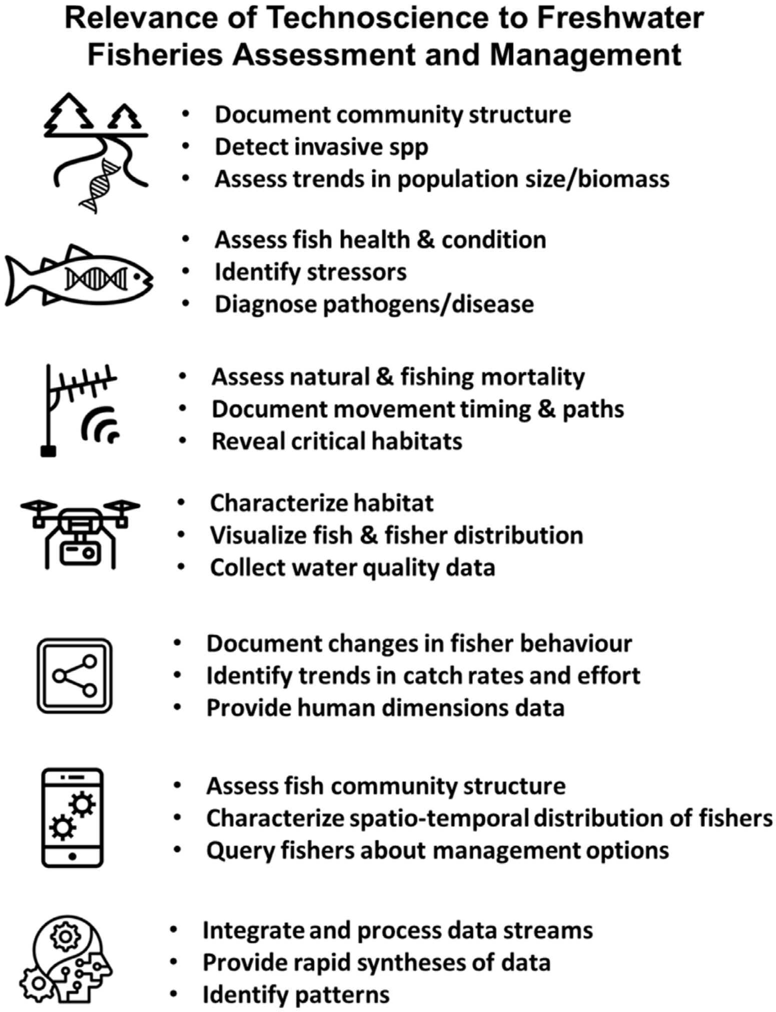


Fig. 1. Schematic demonstrating the relevance of technoscience to the assessment and management of freshwater fisheries.

3.1. Environmental DNA (eDNA)

Advances in genetic methodologies are already contributing to fisheries management, including helping to infer stock structure (Carvalho and Hauser, 1994) and identifying commercial fishery products using DNA barcoding (Kochzius et al., 2010). More recently, the capture and analysis of eDNA is offering a promising and economical alternative and/or supplement to conventional fish survey methods such as netting or electrofishing (Lacoursière-Roussel et al., 2016; Jerde, 2021). Fish shed DNA into the water via mucus, feces, gametes, sloughed off cells, and decomposing remains, which can then be collected (e.g., from filtered water samples) and the species of origin identified. eDNA assays can target individual species via species-specific primers and probes that bind to and amplify gene fragments from only the species of interest, or a community eDNA (or metabarcoding) approach can be used where "universal" primers bind to and amplify all species of interest. The pool of amplicons is then sequenced using next-generation sequencing technology, and the sequence "reads" are identified after comparison to a database of reference sequences (Gehri et al., 2021). eDNA methods are often more sensitive than conventional collection methods for detecting species, particularly at low population densities (McKelvey et al., 2016; Wilcox et al., 2016), making them highly applicable to detecting species of conservation concern and alien species in the early stages of invasion (Jerde et al., 2011; Dubreuil et al., 2022). Important life-history events such as migration and spawning can also be detected (Collatos et al., 2020; Antognazza et al., 2021), and DNA assays can even quantify the relative abundance of numerous species (Lacoursière-Roussel et al., 2016; Yates et al., 2019). However, many abiotic and biotic factors affect eDNA signal strength (Stewart, 2019), and correlations between abundance and eDNA under natural conditions are far from universal (Hansen et al., 2018; Capo et al., 2019) and information such as size structure is unattainable.

Despite its promise and utility to date, challenges to the application of eDNA approaches to fisheries management remain. Indeed, premature application of eDNA prior to validation may have contributed to some of the current skepticism. Given its ability to detect species "sight unseen" (Jerde et al., 2011; Roussel et al., 2015), stringent protocols are required to guard against both false positives (due to contamination or non-specific amplification) and false negatives (due to insufficient assay sensitivity or the presence of PCR inhibitors in the environment). However, Sepulveda et al. (2020) argued that methodological limitations are no longer the problem for management applications when proper field and laboratory protocols are used; rather, the main barrier is the interpretation of eDNA results in a management context. Support structures to facilitate decision-making in response to eDNA survey data are being developed (e.g., Sepulveda et al., 2020; Welsh et al., 2020). They emphasize that reliable interpretation generally requires multiple sampling events. Even when controls show that a positive result is not due to contamination, detection indicates only that the target species' DNA is present in the water sample; it does not conclusively indicate the presence of the live organism itself (Roussel et al., 2015). Establishing thresholds for when to increase eDNA sampling intensity (e.g., in areas where the detected DNA is less likely the result of human activity or transport from upstream), when to conduct conventional sampling, and under what conditions to engage in management actions will help facilitate adoption of eDNA into fisheries management.

3.2. Omics

The potential for genomics, transcriptomics, proteomics, and metabolomics (collectively referred to as "omics") applications in fisheries science and management is substantial. While genomics (and related omics technologies) have been suggested as an approach to develop novel tools for addressing conservation issues in wild fishes (He et al., 2016), the uptake of omics techniques to facilitate real-world fisheries management and conservation decisions is lagging (see Bernos et al., 2020). Under the broad umbrella of omics, genomics addresses processes at the level of DNA, whereas transcriptomics is at the level of RNA, both of which may be relevant to the differential expression of genes in fishes. Therefore, genomics and transcriptomics can collectively measure processes regulating gene expression in fishes, which are critical for characterizing the integrated organismal response to environmental stressors (e.g., Jeffries et al., 2021). Of the different omics approaches, the methods for high-throughput DNA sequencing and RNA sequencing (i.e., next generation sequencing and subsequent sequencing technologies) have been used extensively in conservation biology and management, and are now widely applied to wild fishes and fishes of management concern (e.g., Bernatchez, 2016; Jeffries et al., 2016; Wellband and Heath, 2017; Connon et al., 2018).

The walleye (*Sander vitreus*) is a North American example of an important inland fishery species that has benefited from the use of omics technology to rapidly develop molecular resources. Walleye support commercial fisheries in Canada's Laurentian Great Lakes, as well as the provinces of Manitoba and Quebec, and are a popular recreational species. The transition from genetic to genomic approaches has enabled managers to understand fine-scale differences in walleye populations at a much greater resolution (Euclide et al., 2021a). For example, walleye display some natal homing for spawning, making their fisheries potentially of mixed-stock with small genetic differences between different subpopulations that likely are important for long-term management (Euclide et al., 2021b). Further, DNA sequencing enabled the discovery of a putative chromosomal inversion in walleye of Lake Winnipeg, Manitoba, which may support evidence of genomic divergence despite weak population structure in this system (Thorstensen et al., 2021). This finding is consistent with local adaptation of fishes in the presence of gene flow (e.g., Barth et al., 2019; Shi et al., 2021). Using RNA-sequencing, transcriptomic resources have been developed for walleye, which will facilitate investigations of the physiological responses to common stressors for wild walleye such as temperature and hypoxia (Jeffrey et al., 2020). With many omics approaches able to use non-lethally sampled tissues, they provide opportunities to monitor fish performance and behavior to test for cause–effect linkages between transcriptome variation and fishery-relevant outcome measures, such as survival and movement patterns in the wild (Jeffries et al., 2021).

3.3. Electronic tagging

Over recent decades, the use of various electronic tagging platforms (e.g., biotelemetry and biologging) have grown almost exponentially in their popularity and application to the study of fish behavior and dynamics (Hussey et al., 2015; Matley et al., 2021), including in freshwater environments (Cooke et al., 2013). These tools are enabling the study of fish–environment interactions, documenting space use and movement in rivers, lakes, and wetlands, and revealing predator–prey interactions (Lennox et al., 2021; Matley et al., 2021). Increasingly, these tools are being applied to complex management and conservation problems, such as estimating mortality in the context of fisheries interactions and hydropower (e.g., entrainment), evaluating the success of restoration efforts (e.g., stocking), quantifying fish passage success at fishways, assessing the effectiveness of fisheries assessment methods (reviewed in Cooke et al., 2016c,d), and estimating key population dynamic parameters (e.g., mortality) needed for sustainable stock management (e.g., Harris and Hightower, 2017; Peterson et al., 2021). Given the important role of bioenergetics in fisheries management, there have also been efforts to estimate the energetic costs of specific activities or occupying habitats with different environmental drivers (e.g., flows Cocherell et al., 2011, temperature Madenjian et al., 2018 using electronic tags equipped with sensors Cooke et al., 2016d). Tracking studies occur at spatial scales ranging from localized, high-resolution studies that generate 2- or 3-dimension tracks of fish behavior with sub-meter accuracy (Baktoft et al., 2015) to broad-scale studies that often leverage collaborative tracking networks where telemetry infrastructure is distributed across entire waterbodies or watersheds (e.g., the GLATOS arrays in the Laurentian Great Lakes; Krueger et al., 2018). Importantly, electronic tagging can provide data and insights on fishes through all seasons (Davies et al., 2020), and in northern regions that are extremely difficult to study due to harsh conditions (Marsden et al., 2021).

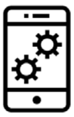
The aforementioned tracking tools have provided unprecedented information on the behavior, survival, and energetics of wild freshwater fishes (Hussey et al., 2015), as well as contributed to their management and conservation (Krueger et al., 2018). Yet, there are also challenges that have impeded the ability to fully realize these benefits for fisheries management (Brownscombe et al., 2019). Although networked tracking systems rely on the use of compatible technologies and shared databases that serve as archives for long-term use (and re-use), not all vendors use the same acoustic transmission protocols, eliminating the benefits of cooperation (Reubens et al., 2021). There can also be apprehension among scientists with sharing data, given fears of "getting scooped" or not having control over how the data are used (Nguyen et al., 2017). An even bigger issue is that electronic tracking generates vast datasets that often take years to analyze. Given that tracking data can be generated on a near real-time basis (Nathan et al., 2022), the inability to analyze and use data shortly after it is collected represents a major lost opportunity. Even when managers are provided tracking data, they may hesitate to use it for a variety of reasons, including small sample sizes (that may not represent the level of variation observed within the broader population), cost (taking funds away from conventional assessment methods), and concerns about tag burden and the representativeness of tagged animals (i.e., their behavior and survival) relative to untagged conspecifics (Young et al., 2018; Brownscombe et al., 2019). Many of these issues can be addressed by having tracking scientists integrate end-user (e.g., manager) input throughout the project process (e.g., study design, implementation, and data analysis) using a co-production model (Nguyen et al., 2019). However, issues still remain with creating workflows and dashboards that will provide managers usable (synthesized) data in a timely manner (Nathan et al., 2022).

3.4. Drones

Over the last decade, uncrewed aerial systems/vehicles (UAS/UAV) and underwater vehicles have grown in popularity as valuable tools for research and management of inland fisheries (Harris et al., 2019). Historically referred to as remotely operated vehicles (ROVs), but contemporarily referred to as drones (herein, the word "drone" is used), these devices offer perspectives that were once only achievable via crewed aircraft for aerial applications (planes, helicopters), as well as submersibles and self-contained underwater breathing apparatus (SCUBA) diving for underwater applications. Moreover, compared to crewed vehicles, drones are relatively cheap, require less training, and have fewer risks to personnel (Perritt and Sprague, 2017; Macreadie et al., 2018). With the proliferation of companies providing consumer and prosumer drones with greater versatility and customization, including longer flight times, vertical takeoff, and landing (VTOL) fixed wing UAS, as well as a wide range of cameras and sensors (e.g., LIDAR), the application of drones for inland fisheries continues to increase. For example, drones have been tested for their use in mapping out spawning activity of salmon (Groves et al., 2016; Roncoroni and Lane, 2019), surveys of the presence and distribution of freshwater turtles (Bogolin et al., 2021), and the detection of invasive aquatic vegetation (Bolch et al., 2021). Drone image acquisition combined with digital photogrammetry is also being used to map above and underwater fish habitat complexity (Kalacska et al., 2018) and for river classifications and hydromorphology (Woodget et al., 2017). Drones are also being tested for quantifying recreational fishing effort (i.e., counting anglers), which has the potential to be more effective and considerably less costly, although at this point it is deemed to largely be complementary rather than a replacement for conventional methods (Fernando et al., 2019; Provost et al., 2020). For larger lakes, autonomous underwater drones, such as gliders, that have increased in application in marine systems, are now being employed as a means to conduct detailed bathymetric mapping and water chemistry (Austin, 2013). Underwater drones are also being tested to deploy underwater equipment such as passive acoustic monitors (Lloyd et al., 2017), and conduct water sampling for eDNA.

Although the use of aerial and underwater drones shows great promise for research and monitoring of inland fisheries, especially as their accessibility, versatility, and practicality continues to increase (e.g., with waterproof aerial drones), many limitations and challenges remain. Since drones enter civil air space, regulations for their use can be complex, require pilot and equipment certification, and differ based on location-specific regulations (e.g., prohibition of drones in national parks; Stöcker et al., 2017; Toonen and Bush, 2018). Additional training and certifications are also needed if the drone is intended to be operated beyond the visual line of sight. Even when in compliance, operators must consider the overall acceptance of the use of drones, since negative public perception could create complications when being applied as a research or monitoring tool (Tobin, 2015; Markowitz et al., 2017). In addition to potentially disturbing humans, it is important to consider how both aerial and underwater drones may impact the behavior of aquatic animals (e.g., due to visual and/or acoustic disturbance; Erbe et al., 2017). A further challenge is the potential need for ground truthing and post-processing of images, whether they be stills, stills captured from video, spectral analyses, photogrammetry, or even the use of machine learning to distill patterns from complex images (Roncoroni and Lane, 2019; Wang et al., 2020).

3.5. Fisher reporting apps



Reporting apps are a technological solution to the problem of limited resources for monitoring diverse and mobile fishers who interact with diverse and distributed resources. Commercial and recreational fishers can use smartphone applications to log and report information about themselves (e.g., age, licence number), their trips (e.g., location, effort), and the fish that they catch (e.g., species, size) (Venturelli et al., 2017; Merrifield et al., 2019). These applications are the most recent evolution of logbooks that began as paper, moved online, and are now available through mobile devices such as tablets and smartphones. Reporting apps can be fisheries-specific or -general, mandatory or voluntary, and issued by agencies (e.g., Denmark's Fangstjournalen, South Australia's Commercial Fishing SA), non-governmental organizations (e.g., California Academy of Sciences and the National Geographic Society's iNaturalist, the Angler Action Foundation's iAngler), and/or for-profit companies (e.g., Fishbrain, MyCatch). Reporting apps are appealing to commercial fisheries as a means of modernizing data collection (e.g., Merrifield et al., 2019; Zhu et al., 2021), and to recreational fisheries as a relatively cheap source of high-resolution, conventional and/or novel data in near real-time and over broad spatial extents (Venturelli et al., 2017). Other advantages include a reduced reporting burden, greater information capture via automation and inference (e.g., species recognition, environmental conditions based on catch time and location), opportunities to create community, and convenient means of outreach, education, and engagement (including citizen science) (Venturelli et al., 2017; Calderwood et al., 2021; Skov et al., 2021). Whereas the literature on reporting apps in commercial fisheries tends to emphasize design (Calderwood et al., 2021) and improved estimates of bycatch and discards (Zhu et al., 2021; Mendo et al., 2022), reporting apps for recreational fisheries is more data-centric. Recreational apps have been evaluated relative to creel (Papenfuss et al., 2015; Jiorle et al., 2016; Gundelund et al., 2020, 2021; Johnston et al., 2022), recall (Papenfuss et al., 2015; Gundelund et al., 2021; Johnston et al., 2022), and gill net surveys (Johnston et al., 2022). Novel applications of data from recreational reporting apps include diseases prevalence (Happel, 2019), invasive species spread (Weir et al., 2022), and climate change (McDonald, 2022).

Reporting apps are only effective if they are used by fishers and produce data that inform management. Gundelund et al. (2021) found general agreement between most survey- and app-based metrics when ∼7% of the anglers in a Danish recreational sea trout fishery used a reporting app. Achieving the appropriate user threshold for a given fishery means overcoming barriers to reporting—namely fisher motivation and the reporting interface. Intrinsic motivators such as prestige, trust, and stewardship are rarely sufficient on their own (Cooke et al., 2000; Wild, 2008; Crandall et al., 2018; van den Heuvel et al., 2020), and extrinsic motivators such as information access, rewards, and fines can have little effect, introduce bias, or be controversial (Cooke et al., 2000; Bradley et al., 2019; Midway et al., 2020). Fishers who are motivated to report via an app but have a negative experience (e.g., because the app is difficult or time-consuming to use, buggy, and/or poorly supported) might report less frequently, less accurately, less often, or stop reporting altogether (Cooke et al., 2000). Ensuring a positive user experience (as well as retaining users in a competitive app market) is a challenge because it requires sufficient and ongoing investment in app design, support, and possibly marketing—all of which are non-traditional roles for most organizations. Whether data from reporting apps are ultimately used in fisheries assessment and management depends largely on real or perceived issues with data quality, an organization's appetite for experimentation and risk, privacy concerns, and operational barriers. Common data quality concerns are that data from reporting apps are unstandardized, non-representative, or otherwise biased (Venturelli et al., 2017; Gundelund et al., 2020). The legitimacy of these concerns under various contexts is largely unknown, owing to a paucity of comparative research and rigorous statistical methods for dealing with non-probability data (Skov et al., 2021). This barrier is exacerbated by organizations that are unable or unwilling to experiment with reporting apps (Serchuk and Smolowitz, 1990; Cvitanovic et al., 2015; Young et al., 2018). Finally, organizations that want to operationalize reporting app data may struggle to do so given the absence of statistics, protocols, and governance frameworks for integrating them into the existing fisheries management system.

3.6. Culturomics and iEcology

The ongoing global digital revolution and widespread adoption of online platforms, including social media, have paved the way for digital tools to inform biodiversity conservation. To wit, conservation culturomics and iEcology are emerging scientific fields that harness rapid development of new digital data and tools (Ladle et al., 2016; Jarić et al., 2020a). Conservation culturomics focus on the study of human culture and engagement with nature (Ladle et al., 2016), while iEcology focuses on addressing broad ecological questions (Jarić et al., 2020a). These fields are providing a valuable opportunity to gain new insights on recreational fisheries and the status of fish stocks, with low sampling costs and broad spatiotemporal reach (Jarić et al., 2020b; Lennox et al., 2022). For example, archived photographs and social media posts contributed by recreational fishers have been used to study the status of fish populations, such as the trends in fish size structure and catch composition (e.g., McClenachan, 2009; Jiménez-Alvarado et al., 2019), or as early indicators of distributional range shifts (Sbragaglia et al., 2021) and biological invasions (Al Mabruk et al., 2020). Internet search volumes (e.g., Google Trends, Wilde and Pope, 2013) and social media activity (Martin et al., 2014) have revealed spatiotemporal trends in fishing effort, while georeferenced data "scraped" from social media provided indices of fishers' site selection (Monkman et al., 2018a). Social media posts can also reveal fishing selectivity and vulnerabilities of fish depending on location, season, and fishing gear (Sbragaglia et al., 2020). Other promising applications include studies of fisher behavior, harvest and release levels, fish welfare issues, recreational fishery value, and stakeholder needs, values, perceptions, attitudes, and satisfaction (Lennox et al., 2022).

Some of the major challenges to the further development of conservation culturomics and iEcology relate to their socio-cultural aspects, data accessibility and reliability, and ethical considerations (Jarić et al., 2020b). Fisher posts featuring individual catches and opinions may be biased towards more active users and specific social groups, whereas catch reports may be biased towards more impressive species and individual "influencers" (Jarić et al., 2020b; Sbragaglia et al., 2020). Digital data are also characterized by uneven spatial coverage, which decreases with distance from shore and water depth, and is mainly concentrated in urban areas and popular recreation sites (Jarić et al., 2020b). Rural, traditional, and Indigenous societies tend to be underrepresented by digital data (Correia et al., 2021). Use of digital data is also complicated by linguistic challenges, temporal instability and decay of online data, limited data access, data-sharing restrictions, limited replicability, temporal limitations bounded by the time spans that are covered by different online platforms, the presence of unreliable data, and underdeveloped analytical tools and pipelines (Jarić et al., 2020b; Lennox et al., 2022). As emerging fields, conservation culturomics and iEcology also face the problem of lack of established frameworks and protocols related to data privacy and ethical issues (Monkman et al., 2018b; Di Minin et al., 2021), though there are general standards for data privacy that can provide guidance, like the European General Data Protection Regulation (aka GDPR). Most fisheries are managed by government bodies which may be held to higher standards regarding privacy and ethics. Because digital data tend to be non-random and vary across users, regions, time-frames, and species, any use of such data requires careful calibration and validation through ground-truthing and triangulation with other data sources (Ladle et al., 2016; Jarić et al., 2020a,b; Correia et al., 2021). Nonetheless, such data could be used to indicate the direction of more focused surveys or as an early indicator of emerging issues.

3.7. Artificial Intelligence

Artificial intelligence (AI) is defined as intelligence demonstrated by machines, which can take the form of problem solving, learning, reasoning, perception, and many other facets of human cognition (Russell and Norvig, 2009). In application, AI generally involves machines receiving inputs, processing them through an algorithm, and producing an output. At the heart of AI is machine learning, which employs statistical models that are focused foremost on optimizing model performance (e.g., the model's predictive accuracy in out-of-sample data). From its conception as a scientific field in the 1950s, AI has become pervasive in society, with widespread applications in diverse industries and sciences (e.g., Google search, self-driving cars, agricultural monitoring and feeding systems). AI is being increasingly applied in fisheries to improve monitoring, practice, and knowledge generation (Jothiswaran et al., 2020; Honarmand Ebrahimi et al., 2021). In their review, Honarmand Ebrahimi et al. (2021) identified three core areas in which AI is applied in 'smart fisheries,' namely ecosystem monitoring, fisheries monitoring, and fisheries policy.

There are numerous ways in which AI is applicable to monitoring ecosystems, including environmental characteristics and fish populations. For example, AI has been applied to oil spill detection and monitoring (Franceschini et al., 2019; Cantorna et al., 2019; Al-Ruzouq et al., 2020) and to predict the distribution of marine litter/debris (Franceschini et al., 2019; Watanabe et al., 2019). AI is also increasingly applied to identify fish species and enumerate individuals from underwater imagery (e.g., Qin et al., 2016; Villon et al., 2018; Jalal et al., 2020). These AI systems can be integrated into remote measurement tools through the use of drones (Meng et al., 2018) or fixed station platforms (Fanelli et al., 2020), providing a means to rapidly inform management. In addition to fish populations and communities, similar AI systems are also useful for monitoring fisheries catch from on-board imagery (Bradley et al., 2019). Combinations of advanced technologies now enable remote monitoring of fish distributions, fishing effort and catch, and rapid data processing to make adaptive and real-time management decisions. However, both Honarmand Ebrahimi et al. (2021) and Bradley et al. (2019) identified distrust in AI by fishers as a major impediment to advancements in smart fisheries. As it continues to advance, AI is likely to be broadly transformative to all aspects of fisheries, including the roles which scientists, policy makers, and resource managers play within knowledge-generation and resource-management processes. However, this will require substantive development of functional systems, as well as buy-in from scientists, managers, and resource stakeholders.

4. The challenges with adoption of technoscience

4.1. Barriers to change/adoption

As the examples above demonstrate, technoscience innovations are not immediately or universally adopted or rejected. Society reacts to technoscience in complex and diverse ways depending on the interests, priorities, and values of different groups, as well as their understanding of the potential impacts of new innovations. This has long been a puzzle for proponents of potentially game-changing technologies such as electric vehicles (e.g., Egbue and Long, 2012). In fields such as environmental management and governance, acceptance and adoption are even more complicated: in these contexts, a core client group (politicians, policy makers, and managers) and broader circle of potentially impacted rightsholders and stakeholders each need convincing. More science and validation is not always the answer—much of what is needed is about understanding how these tools can be applied and associated frameworks for doing so. Existing social-science research on adoption of new evidence and technoscience tools points to substantial barriers among both government decision-makers and rightsholders/stakeholders (e.g., Cvitanovic et al., 2015; Young et al.; 2016). These include a lack of familiarity with new evidence or technoscience tools, reluctance to make risky decisions that deviate from imperfect existing practices, and uncertainty about how new tools and practices might affect the existing balance of interests (Young et al., 2016). This points to the importance of engaging all potential users in extended processes of familiarization with new tools and in-depth consultations about how the tools will be applied in decision making. Relatedly, the scientists involved in developing and testing new methods should be working collaboratively with managers to ensure products and processes are relevant. Co-production of knowledge (e.g., scientists and managers working collaboratively) is regarded as one of the primary means by with uptake of new knowledge can be facilitated (Cooke et al., 2021a). Incremental adoption of new technoscience tools, rather than abrupt or radical breaks with existing ways of knowing or doing, are preferable for building comfort and acceptance across the diverse groups involved in environmental governance (Young et al., 2018). Incremental adoption can take the form of pilot projects, co-production of research and/or application guidelines, and periodic review for lessons learned and best practices (Cooke et al., 2021a; Hinderer et al., 2021).

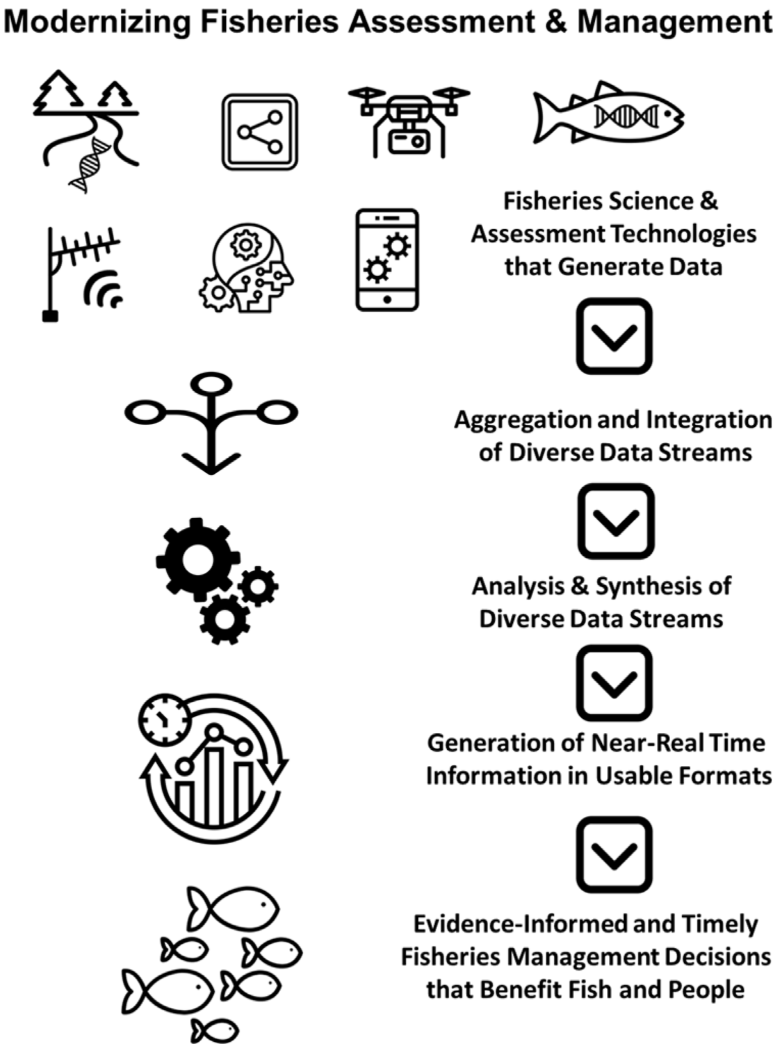


Fig. 2. Schematic of how various technoscience developments can be used to modernize freshwater fisheries assessment and management.

4.2. Need for validation, standardization and understanding limitations

Several perceived, practical, and technological issues affect the adoption of new assessment methods and the use of resulting data in high-stakes management decision. Foremost among these issues is that new methods require quality control and assurance including validation, which helps to achieve reliable results upon which responsible decisions can be based (Peters et al., 2007). Validation provides objective evidence that a method is fit for purpose and that its application is precise (i.e., repeatable and minimally variable) and unbiased (i.e., approaches true value). Analytical method validation is common in chemistry, medicine, and forensics fields (Peters et al., 2007), but fishery techniques such as age estimation (Beamish and McFarlane, 1983), hydroacoustics (Thorne and Thomas, 1984), and eDNA (Jerde, 2021) also require validation. New methods can sometimes be validated using existing methods, but a new approach is often required for validation, and validation can lag behind method development. Additionally, most validation methods have limitations and even validated methods have some level of risk and uncertainty. Fishery managers, therefore, require a clear framework for interpreting results and understanding and communicating limitations. New technological advancements will likely always be viewed with skepticism by managers, stakeholders, and media. As a result, technological and institutional inertia will continue to impede modernization of assessment techniques. However, over-hyping technology can also limit adoption and elevate skepticism. This emphasizes the importance of rigorous and transparent assessment of methods, sharing of limitations, and not exaggerating claims of application.

4.3. Costs

A necessary condition for technology adoption for most organizations is that it must be financially beneficial (i.e., quantifiable evidence for return on investments of time and money with measurable improvements in fisheries and fishery yields; Semeniuk et al., 2022). While new technology should be cheaper or more efficient to utilize, ongoing cost savings must be large enough to overcome what can be significant up-front costs, which include the cost of acquiring new equipment and technology, and human-resource costs of integration and incorporation into training, infrastructure, and best practices. Moreover, the unknown benefits and costs of how using the new technology will evolve in the future runs an additional financial risk when considering new technologies. Access to capital is another potential barrier, especially for public agencies, with budgetary constraints often cited as the primary barrier to new technology implementation (Open Access Government, 2019), especially technosciences, necessitating big-data management and data-accessibility requirements (Semeniuk et al., 2022).

The inherent heterogeneity of potential users can also impede technological adoption in that there needs to be general acceptance across multiple jurisdictions and knowledge holders. Economies of scale are an important cost-determinant, and there may be different legacy technologies in use, some easy and some difficult to replace. Coupled with different mandates (for profit vs. public service), and subject to different administrative constraints and regulations, the use of technosciences in freshwater systems is undoubtedly subject to the same unintended consequences of power, politics, and culture witnessed in marine systems (Jenkins, 2022).

4.4. Keeping up with emerging tools/technologies

The concept of technological innovation is always context specific. For example, for fisheries assessment, innovations such as under-ice gillnet setting tools (Baranov, 1948), the use of electricity for fish capture (Cowx, 1989), or lights (Starck, 1973) to enable deepwater SCUBA (Richardson, 1999), all represent major innovations even though they occurred many decades ago (Lackey, 2005). Yet, because of microchips, other scientific innovations, and human ingenuity, the suite of technological tools available to those engaging in fisheries assessment to support fisheries management has ballooned, making it difficult for managers to keep abreast of new tools. The manner in which fishery assessors and managers keep up to date with emerging tools and technologies should follow the 'diffusion of innovation theory' (DIT), which provides insight on the creation of innovations and how they are then communicated and distributed among users (Rogers et al., 2014). This five step process involves: (1) identification of the attributes that make the technoscience advance attractive (e.g., improved fish detection/capture); (2) its dissemination channels (e.g., journal articles, symposia, workshops, social media, professional networks); (3) identification of the adopters (i.e., those involved in fisheries assessments); (4) the time needed for fishery assessors to develop/integrate the innovation (e.g., as a standardized assessment method); and, (5) the social system in which it spreads (e.g. a specific recreational fishery) (Wejnert, 2002; Cañete et al., 2022). This process emphasizes the need for active engagement by practitioners and managers to ensure that they keep abreast of new innovations. They must then understand how these innovations can be implemented as standardized assessment tools. Notwithstanding, Bradley et al. (2019) highlighted that despite a proliferation of relevant consumer technology for collecting fishery data to achieve more sustainable fishery management, these technologies are rarely implemented. However, the reasons for this more often relate to a lack of trust and cooperation between those exploiting the stock and those managing it, and require more collaborative problem-solving among stakeholders in order to be overcome (Bradley et al., 2019).

The more general adoption of these technoscience advances then raises the potential issue of their leading to greater exploitation of fishery resources (Cooke et al., 2021b; Cañete et al., 2022). For example, the adoption of methods by recreational anglers that increase catch rates directly (e.g., hook, lure, and bait technology) or indirectly (e.g., underwater cameras, fish-finder technology) can increase fishing mortality through improved fish catchability without changes in effort through 'technological creep' (Cooke et al., 2021b; Cañete et al., 2022). Where catch rates are elevated without any apparent advances in angler knowledge and competence, issues might also be raised on the associated ethics and fish-welfare considerations (Cooke et al., 2021b). It is therefore critical that fishery managers remain aware of contemporary developments (as per DIT) to ensure that their management considers technologies for both improving stock assessment and their influences on future exploitation.

5. Modernizing fisheries assessment and management

Imagine a future in which technoscience enables a rethinking of how fisheries are managed—a future that is more anticipatory and relies on near-real time data streams to provide managers with exactly the information that they need to make timely decisions. That reality is potentially within reach in developed countries (assumes financial resources, political support, and value alignment among user groups), although barriers to implementation remain (See Table 1). First and foremost is developing methods for aggregating data from different technologies, which needs to happen at the temporal scale relevant to the management issue (e.g., salmon stock identification using genetics can be done on the order of hours to inform the opening and closing of fisheries; Michielsens and Cave, 2019). The aggregated information must then be provided to fisheries managers and decision makers in a usable format (Fig. 2). For example, simply having

Table 1
Contrasting the characteristics of contemporary and future assessment and management of freshwater fisheries resources.

Characteristics	Contemporary assessment and management[a]	The future of assessment and management[b]
Management style	Largely reactive	Combination of predictive, proactive and reactive
Timeliness	Decisions typically made months or years after the collection of monitoring data given time required for analysis and interpretation albeit this depends on the gravity and social/political context of an issue (i.e., some decisions can be made rapidly while others are made by political entities rather than fisheries managers)	Potential for near-real time decisions using live data that are available online/streamed to desk-top/via apps noting that this is easiest when local/small-scale issues where there is alignment of all resource users and the manager has decision-making authority and social license to do so
Scientific basis for management decisions	Traditional stock assessment based on fisheries dependent and independent information ideally combined with data on fishing effort or other forms of data such as human dimension surveys or habitat/environmental assessments	Diverse data streams that supplement traditional stock assessment, human dimension and environmental data with other information related to the behavior, ecology and distribution, of both fish and fishers and a dynamic environment
Automation	Minimal automation – requires manual entry of data and analysis by stock assessment biologists	Largely automated – using systems that aggregate diverse data streams in real-time[c]
Outputs	Reports often presented as trend-through-time status reports or environmental/habitat assessments	Purpose-built platforms that are underpinned by data and provide managers with the ability to interact directly with data syntheses (e.g., shiny apps), and foster greater interaction between managers and fishers (and other relevant actors)[d]
Relevance	The time lag between data collection and synthesis can make data less actionable given that it may no longer be relevant	Provides managers with live data that can be used for proactive decision making on issues of immediate relevance and based on predicted outcomes
Transparency	Often little transparency given limited access to data that are generated by traditional stock assessment and environmental/habitat assessment methods	Can be easily configured to be open data to allow relevant actors to view data syntheses and thus be engaged with the management process

[a]Note—There are always exceptions.
[b]Note—Additional funding/resources needed to implement the proposed modernization.
[c]Note—Assumes there is information technology and data science support along with stability in technology and process work flows to enable automation.
[d]Note—Trend through time data is always useful for informing management such that it may take time before real time data can be truly embraced given that it needs to be reconciled with data collected over previous years/decades.

a telemetry receiver transmit real-time data on fish detections to the desk of a manager is not helpful given the analytical efforts that would be needed to make sense of the data. There is, therefore, a need for developing automated processes that mobilize knowledge in a form usable by managers, such as an "app" or form of computer dashboard that serves as the interface between raw data and the manager (Fig. 3). Additionally, many of the omics approaches that are used in a fisheries context require significant bioinformatic analyses to identify the main patterns in the data, which may take too long for "real time" actions or fail to provide data in a usable format for managers and decision makers. Using omics to generate targeted tools to screen samples in a more rapid manner and provide relatively simpler data to interpret has the potential to increase the incorporation of omics approaches in fisheries management (e.g., targeted fish stress/health chips; Miller et al., 2014; Semeniuk et al., 2022). Developing such tools requires partnerships among fisheries scientists and managers, data scientists, and programmers. At the end of the day, it will be success stories (such as in Table 1) by early adopters that lead to broader uptake by other individuals and organizations.

With many of these technoscience approaches increasingly generating novel data at individual and population levels, more predictive approaches to support future management decision making may be developed. For example, in the management of alien species, a range of modeling approaches exist for predicting range expansion and thus interactions with native fish populations, including stochastic simulations such as individual-based models (IBMs) (Dominguez Almela et al., 2020). IBMs, for example, have simulated how management control efforts affected the individual movements and population demographics of brook trout (*Salvelinus fontinalis*) (Day et al., 2018) and an invasive sea lamprey (*Petromyzon marinus*) (Neeson et al., 2012), and were used to predict the outcomes of different culling rates and timings in an invading fish population (Dominguez Almela et al., 2021). With increasing data availability on fish movements and population demographics, as well as advances in model design and computing power, fisheries managers will increasingly be able to base their decisions on the simulated outcomes of a range of management scenarios, increasing confidence in the strategy that is implemented (Dominguez Almela et al., 2021). This will be complemented with machine learning approaches that will co-evolve with process-based modeling to address some of the aforementioned challenges with integrating large datasets and ensuring that data are interpretable and are useful in a predictive manner (Razavi et al., 2022).

It has already been mentioned that fisheries management is not a rapidly evolving field (Caddy and Cochrane, 2001), and many facets of fisheries management have changed little in the last decade or two. Indeed, most of the tools, systems, and approaches used today are similar to those used in the 1970s or earlier (Caddy and Cochrane, 2001). A recent analysis of the approach to inland fisheries management in Canada has revealed that, although the goals of inland

Table 2
Examples of how technoscience tools have already been applied in a fisheries management context emphasizing the potential for broader adoption. Note that some of the examples provided are from the coastal marine environment where similar examples do not yet exist in freshwater. Moreover, because these are relatively new technologies there are few papers that describe the actual implementation of these tools by management organizations so it was necessary to include some examples based on press releases or news stories from natural resource management organizations.

Technology	Example applications
eDNA	- eDNA monitoring is being used as an early detection surveillance tool for invasive carp in the Laurentian Great Lakes (e.g., Jerde et al., 2013; https://www.asiancarp.ca/SURVEILLANCE-PREVENTION-AND-RESPONSE/Great-Lakes-eDNA-Monitoring-Program/) and to cost-effectively map the distribution of fish species of conservation concern (e.g., the Range-Wide Bull Trout eDNA Project in the USA—see https://www.fs.fed.us/rm/boise/AWAE/projects/BullTrout_eDNA.html).
Omics	-Applications of omics technologies include the use of transcriptomics to develop and apply biomarkers to monitor the response of wild salmonids to disease or environmental stressors which is being used by managers to determine where management interventions (e.g., regulations that restrict inter-basin transfer of fish) are needed (e.g., Houde et al., 2019).
Electronic tagging & Tracking	-Biotelemetry of tagged walleye in the Laurentian Great Lakes has revealed information on seasonal stock-specific distribution of fish allowing managers to refine cross-jurisdictional fisheries planning and management decisions (Hayden et al., 2014, 2019; Fielder et al., 2020)
Drones	-Aerial drones are being deployed by the UK Environment Agency and the Police Drone Unit for fisheries enforcement in Avon and Somerset areas of the UK to detect (and deter) out of season fishing and illegal nets (https://www.gov.uk/government/news/drones-offer-extra-eyes-to-combat-illegal-fishing-activity)
Culturomics and iEcology	-Fisheries enforcement staff are monitoring social media posts to identify trends in fishing effort to inform patrols and in Florida images posted on Facebook of illegal catches has led to charges (https://www.sun-sentinel.com/news/fl-xpm-2011-08-01-fl-fwc-facebook-poaching-20110801-story.html)
Phone apps	-In Alberta a popular fishing app is being used by Alberta Environment and Parks to obtain information on fishing effort, catch and harvest (Papenfuss et al., 2015)
Artificial intelligence	-Artificial intelligence is being used to automate extraction of data from videos related to fish passage at a variety of facilities including for Pacific salmon in the Pacific northwest providing managers with real time information on run timing and abundance (https://www.newsdata.com/water_power_west/hydro_news/scanners-installed-at-bonneville-dam-to-help-automate-fish-counts/article_ff98ff96-b3b9-11e9-82dc-13510db565ff.html)

fisheries management may have changed over the last 30 years, as have opportunities for change, there is little evidence of widespread change in fisheries management systems (Piczak et al., 2022). In the marine realm, there have been a number of attempts to consider how technology can contribute to sustainable fisheries (see Caddy, 1999; Standal, 2005), yet many of those ideas have yet to be fully realized. Much the same can be said for the synopses above. There are certainly examples wherein data arising from new technologies have informed management, but those examples are piecemeal, and have never been integrated in a coordinated manner leading to true reform in fisheries management. Until such reform happens, fisheries management will continue to be reactive, often at the time scale of years to decades. This is unfortunate, given the possibility of creating fisheries management systems that are much more proactive, where decisions can be made before it is too late, such as characterizing declines in fish populations, detecting and responding to invasive species, identifying disease outbreaks, characterizing range shifts, or identifying changes in fishing effort. It is clear that there will be need for extensive outreach to educate managers, diverse publics, and politicians on assumptions and uncertainty associated with technoscience and any "modernization" of fisheries management systems.

There have been recent calls for international leadership and coordination to realize the potential of technoscience in conservation. For example, Lahoz-Monfort et al. (2019) suggested the need for an entity, such as an international alliance of conservation institutions or a formal intergovernmental institution, to enable the active and targeted uptake of emerging technology with the goal of achieving biodiversity conservation goals; the same is needed for freshwater fisheries assessment and management. The UN FAO has a history of developing fisheries management support tools, often with a focus on countries or regions where technical capacity is limited. The FAO may be well positioned to take on such a leadership role. Professional societies, such as the American Fisheries Society (and their Fisheries Management and Fisheries Information & Technology Sections), are also logical entities that could take on such a leadership role, though this would require an international perspective to ensure global relevance. Proof of concept is needed before one may anticipate broad-scale application. For that reason, it may be logical to consider developing these modernized fisheries management systems in specific regions (e.g., the Laurentian Great Lakes, Europe) where there is already significant interest in the use of technology to inform management. In the short term, having conference sessions or workshops with diverse participants (e.g., data scientists, fisheries managers, technologists) focused on this topic may be a productive way

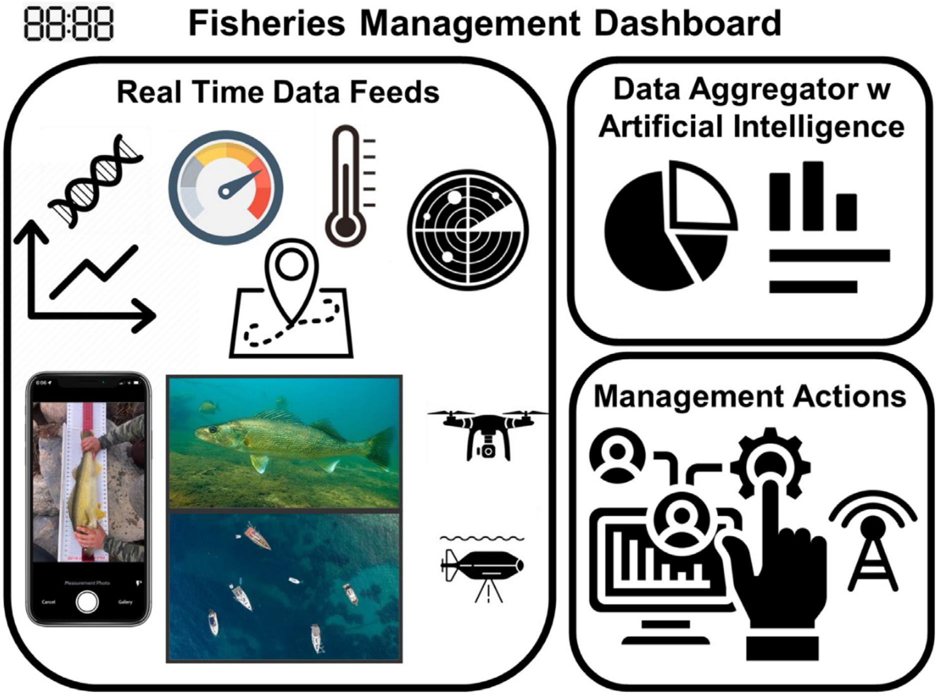


Fig. 3. Hypothetical fisheries management dashboard. Real time data feeds (as described above) come in such as visualized here using walleye as an example (e.g., phone app data from anglers, drone footage of fish and fishers, telemetry tracking data, etc.). Data are aggregated and synthesized to enable managers to make decisions that can be rapidly communicated to enforcement staff, practitioners, and fishers. Such dashboard could be accessible via desktop or tablets.

to bring further attention to this idea and enable collaboration among relevant parties. Ensuring diversity of perspectives including those willing to embrace or drive change will be key to realizing the benefits of technoscience in fisheries assessment and management.

In summary, technoscience innovations are already reshaping the world in many ways. New technologies are emerging that are highly relevant to fisheries science and management, and there is some evidence that the knowledge emanating from those tools is being used in a targeted, but limited and uncoordinated manner to support fisheries decision making (see Table 2 for examples). Technoscience can provide fisheries managers with interpretable syntheses of information that can be used to make better, more timely decisions that benefit fisheries resources and the peoples that depend on them. It is worth acknowledging that management decisions are often driven by social, political and economic factors which are non-technical issues that cannot be solved with new technology or more data. Some management decisions require extensive consultation and may be made by politicians rather than fisheries managers so there are certainly instances in which the "real time" aspects of technoscience emphasized here may not be fruitful. Nonetheless, more data and expediency of synthesis is unlikely to further delay decisions.

6. Conclusion

Using a series of synopses, this paper explored technoscience and its potential benefits for freshwater fisheries assessment and management. Although there are challenges and barriers that will influence the adoption of new technologies, there is certainly great potential for technoscience to reform and modernize inland fisheries assessment and management. Hopefully, the ideas presented here will serve as a catalyst to work collectively and collaboratively towards systems that harness the power of technology and serve to modernize inland fisheries management. Such transformation is urgently needed given the dynamic nature of environmental change, the evolving threat matrix facing inland waters, and the complex behavior of fishers. Quite simply, a dynamic world demands dynamic fisheries management; technoscience has made that within reach. The future is here—if the community of fisheries professionals could only create the structures to realize the possibilities that technoscience has to offer to freshwater fisheries assessment and management.

CRediT authorship contribution statement

S.J. Cooke: Conceptualization, Writing and editing the manuscript. **M.F. Docker:** Conceptualization, Writing and editing the manuscript. **N.E. Mandrak:** Conceptualization, Writing and editing the manuscript. **N. Young:** Conceptualization,

Writing and editing the manuscript. **D.D. Heath:** Conceptualization, Writing and editing the manuscript. **K.M. Jeffries:** Conceptualization, Writing and editing the manuscript. **A. Howarth:** Conceptualization, Writing and editing the manuscript. **J.W. Brownscombe:** Conceptualization, Writing and editing the manuscript. **J. Livernois:** Conceptualization, Writing and editing the manuscript. **C.A.D. Semeniuk:** Conceptualization, Writing and editing the manuscript. **P.A. Venturelli:** Conceptualization, Writing and editing the manuscript. **A.J. Danylchuk:** Conceptualization, Writing and editing the manuscript. **R.J. Lennox:** Conceptualization, Writing and editing the manuscript. **I. Jarić:** Conceptualization, Writing and editing the manuscript. **A.T. Fisk:** Conceptualization, Writing and editing the manuscript. **C.S. Vandergoot:** Conceptualization, Writing and editing the manuscript. **J.R. Britton:** Conceptualization, Writing and editing the manuscript. **A.M. Muir:** Conceptualization, Writing and editing the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

Cooke, Docker, Mandrak, Heath, Jeffries, Livernois and Semeniuk are supported by GEN-FISH, Canada and Genome Canada. Cooke, Docker, Howarth, Heath, and Semeniuk are supported by FishCAST NSERC CREATE, Canada program. Vandergoot was funded by the Great Lakes Fishery Commission, USA (Grant ID #2013_BIN_44024) by way of Great Lakes Restoration Initiative appropriations, USA (Grant ID #GL-00E23010). This paper is contribution 103 of the Great Lakes Acoustic Telemetry Observation System (GLATOS). We are thankful for thoughtful input from several referees.

References

Al Mabruk, S.A., Rizgalla, J., Giovos, I., Bariche, M., 2020. Social media reveals the first records of the invasive lionfish *Pterois miles* (Bennett, 1828) and parrotfish *Scarus ghobban* Forsskål, 1775 from Egypt (Mediterranean Sea). Bioinvasions Rec. 9 (3), 574–579.
Al-Ruzouq, R., Gibril, M.B.A., Shanableh, A., Kais, A., Hamed, O., Al-Mansoori, S., Khalil, M.A., 2020. Sensors, features, and machine learning for oil spill detection and monitoring: A review. Remote Sens. 12 (20), 3338.
Allan, J.D., Abell, R., Hogan, Z.E.B., Revenga, C., Taylor, B.W., Welcomme, R.L., Winemiller, K., 2005. Overfishing of inland waters. BioScience 55 (12), 1041–1051.
Antognazza, C.M., Britton, J.R., De Santis, V., Kolia, K., Turunen, O.A., Davies, P., Allen, L., Hardouin, E.A., Crundwell, C., Andreou, D., 2021. Environmental DNA reveals the temporal and spatial extent of spawning migrations of European shad in a highly fragmented river basin. Aquat. Conserv. 31 (8), 2029–2040.
Arlinghaus, R., Lorenzen, K., Johnson, B.M., Cooke, S.J., Cowx, I.G., 2015. Management of freshwater fisheries: addressing habitat, people and fishes. In: Craig, J.F. (Ed.), Freshwater Fisheries Ecology. John Wiley & Sons, pp. 557–579.
Aronowitz, S. (Ed.), 2014. Technoscience and Cyberculture, first ed. Routledge, New York.
Arthington, A.H., Dulvy, N.K., Gladstone, W., Winfield, I.J., 2016. Fish conservation in freshwater and marine realms: status, threats and management. Aquat. Conserv. 26 (5), 838–857.
Austin, J., 2013. The potential for autonomous underwater gliders in large lake research. J. Great Lakes Res. 39, 8–13.
Baktoft, H., Zajicek, P., Klefoth, T., Svendsen, J.C., Jacobsen, L., Pedersen, M.W., Morla, D.M., Skov, C., Nakayama, S., Arlinghaus, R., 2015. Performance assessment of two whole-lake acoustic positional telemetry systems - is reality mining of free-ranging aquatic animals technologically possible? PLoS One 10 (5), e0126534.
Baranov, F.I., 1948. Theory of fishing with gillnets. In: Theory and Assessment of Fishing Gear (Translated from Russian by the Ontario Department of Lands and Forests, Maple, on). Pishchepromizdat, Moscow.
Barth, J.M., Villegas-Ríos, D., Freitas, C., Moland, E., Star, B., André, C., Knutsen, H., Bradbury, I., Dierking, J., Petereit, C., Righton, D., 2019. Disentangling structural genomic and behavioural barriers in a sea of connectivity. Mol. Ecol. 28 (6), 1394–1411.
Bartley, D.M., de Graaf, G., Valbo-Jørgensen, J., 2015. Commercial inland capture fisheries. In: Craig, J.F. (Ed.), Freshwater Fisheries Ecology. John Wiley & Sons, pp. 438–448.
Beamish, R.J., McFarlane, G.A., 1983. The forgotten requirement for age validation in fisheries biology. Trans. Amer. Fish. Soc. 112 (6), 735–743.
Benessia, A., Funtowicz, S., 2015. Sustainability and techno-science: What do we want to sustain and for whom? Int. J. Sustain. Dev. 18 (4), 329–348.
Bernatchez, L., 2016. On the maintenance of genetic variation and adaptation to environmental change: considerations from population genomics in fishes. J. Fish Biol. 89 (6), 2519–2556.
Bernos, T.A., Jeffries, K.M., Mandrak, N.E., 2020. Linking genomics and fish conservation decision making: A review. Rev. Fish Biol. Fish. 30 (4), 587–604.
Bogolin, A.P., Davis, D.R., Kline, R.J., Rahman, A.F., 2021. A drone-based survey for large, basking freshwater turtle species. PLoS One 16 (10), e0257720.
Bolch, E.A., Hestir, E.L., Khanna, S., 2021. Performance and feasibility of drone-mounted imaging spectroscopy for invasive aquatic vegetation detection. Remote Sens. 13 (4), 582.
Bowman, D.M., Stokes, E., Rip, A., 2017. Embedding New Technologies Into Society: A Regulatory, Ethical and Societal Perspective. Pan Stanford Publishing Pte. Ltd., Singapore.
Bradley, D., Merrifield, M., Miller, K.M., Lomonico, S., Wilson, J.R., Gleason, M.G., 2019. Opportunities to improve fisheries management through innovative technology and advanced data systems. Fish Fish (Oxf.) 20 (3), 564–583.
Brown, N., Rappert, B., 2017. Contested futures: A sociology of prospective techno-science. Routledge, NY.

Brownscombe, J.W., Lédée, E.J., Raby, G.D., Struthers, D.P., Gutowsky, L.F., Nguyen, V.M., Young, N., Stokesbury, M.J.W., Holbrook, C.M., Brenden, T.O., Vandergroot, C.S., Murchie, K.J., Whoriskey, K., Flemming, J.M., Kessel, S.T., Krueger, C.C., Cooke, S.J., 2019. Conducting and interpreting fish telemetry studies: considerations for researchers and resource managers. Rev. Fish Biol. Fish. 29 (2), 369–400.
Cañete, F.T., Oyanedel, R., Gelcich, S., 2022. Adoption and impacts of fishing gear innovations: Insights from a small-scale fishery in Chile. Fish. Res. 248, 106200.
Caddy, J.F., 1999. Fisheries management in the twenty-first century: will new paradigms apply? Rev. Fish Biol. Fish. 9 (1), 1–43.
Caddy, J.F., Cochrane, K.L., 2001. A review of fisheries management past and present and some future perspectives for the third millennium. Ocean Coast. Manag. 44 (9–10), 653–682.
Calderwood, J., Marshall, C.T., Haflinger, K., Alfaro-Shigueto, J., Mangel, J.C., Reid, D.G., 2021. An evaluation of information sharing schemes to identify what motivates fishers to share catch information. ICES J. Mar. Sci. fsab252. http://dx.doi.org/10.1093/icesjms/fsab252.
Cantorna, D., Dafonte, C., Iglesias, A., Arcay, B., 2019. Oil spill segmentation in SAR images using convolutional neural networks. A comparative analysis with clustering and logistic regression algorithms. Appl. Soft Comput. 84, 105716.
Capo, E., Song, G., Norman, S., Königsson, H., Bartels, P., Byström, P., 2019. Droplet digital PCR assays for the quantification of brown trout (*Salmo trutta*) and Arctic char (*Salvelinus alpinus*) from environmental DNA collected in the water of mountain lakes. PLoS One 14 (12), e0226638.
Carvalho, G.R., Hauser, L., 1994. Molecular genetics and the stock concept in fisheries. Rev. Fish Biol. Fish 4, 326–350.
Channell, D.F., 2017. A History of Technoscience: Erasing the Boundaries Between Science and Technology, first ed. Routledge, London.
Childress, E.S., McIntyre, P.B., 2015. Multiple nutrient subsidy pathways from a spawning migration of iteroparous fish. Freshw. Biol. 60 (3), 490–499.
Cocherell, S.A., Cocherell, D.E., Jones, G.J., Miranda, J.B., Thompson, L.C., Cech, J.J., Klimley, A.P., 2011. Rainbow trout *Oncorhynchus mykiss* energetic responses to pulsed flows in the American River, California, assessed by electromyogram telemetry. Environ. Biol. Fish. 90 (1), 29–41.
Collatos, C., Abel, D.C., Martin, K.L., 2020. Seasonal occurrence, relative abundance, and migratory movements of juvenile sandbar sharks, Carcharhinus plumbeus, in Winyah Bay, South Carolina. Environ. Biol. Fish. 103 (7), 859–873.
Connon, R.E., Jeffries, K.M., Komoroske, L.M., Todgham, A.E., Fangue, N.A., 2018. The utility of transcriptomics in fish conservation. J. Exp. Biol. 221 (2), jeb148833.
Cooke, S.J., Allison, E.H., Beard, T.D., Arlinghaus, R., Arthington, A.H., Bartley, D.M., Cowx, I.G., Fuentevilla, C., Leonard, N.J., Lorenzen, K., Lynch, A.J., Nguyen, V.M., Youn, S., Taylor, W.W., Welcomme, R.L., 2016b. On the sustainability of inland fisheries: finding a future for the forgotten. Ambio 45, 753–764.
Cooke, S.J., Arlinghaus, R., Johnson, B.M., Cowx, I.G., 2015. Recreational fisheries in inland waters. In: Craig, J.F. (Ed.), Freshwater Fisheries Ecology. John Wiley & Sons, pp. 449–465.
Cooke, S.J., Bartley, D.M., Beard, T.D., Cowx, I.G., Goddard, C., Fuentevilla, C., Leonard, N., Lynch, A.J., Lorenzen, K., Taylor, W.W., 2016a. From ideas to action: Ten steps to responsible Inland fisheries that support livelihoods, food security, and healthy aquatic ecosystems. In: Goddard, C., Leonard, N., Taylor, W.W., Bartley, D. (Eds.), Freshwater, Fish, and the Future: Proceedings of the Global Cross-Sectoral Conference. American Fisheries Society, Bethesda, pp. 343–351.
Cooke, S.J., Brownscombe, J.W., Raby, G.D., Broell, F., Hinch, S.G., Clark, T.D., Semmens, J.M., 2016d. Remote bioenergetics measurements in wild fish: opportunities and challenges. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 202, 23–37.
Cooke, S.J., Dunlop, W.I., Macclennan, D., Power, G., 2000. Applications and characteristics of angler diary programmes in Ontario, Canada. Fish. Manag. Ecol. 7 (6), 473–487.
Cooke, S.J., Martins, E.G., Struthers, D.P., Gutowsky, L.F., Power, M., Doka, S.E., Dettmers, J.M., Crook, D.A., Lucas, M.C., Holbrook, C.M., Krueger, C.C., 2016c. A moving target—incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. Environ. Monit. Assess. 188 (4), 1–18.
Cooke, S.J., Midwood, J.D., Thiem, J.D., Klimley, P., Lucas, M.C., Thorstad, E.B., Eiler, J., Holbrook, C., Ebner, B.C., 2013. Tracking animals in freshwater with electronic tags: past, present and future. Anim. Biotelem. 1 (1), 1–19.
Cooke, S.J., Nguyen, V.M., Chapman, J.M., Reid, A.J., Landsman, S.J., Young, N., Hinch, S.G., Schott, S., Mandrak, N.E., Semeniuk, C.A., 2021a. Knowledge co-production: A pathway to effective fisheries management, conservation, and governance. Fisheries 46 (2), 89–97.
Cooke, S.J., Venturelli, P., Twardek, W.M., Lennox, R.J., Brownscombe, J.W., Skov, C., Hyder, K., Suski, C.D., Diggles, B.K., Arlinghaus, R., Danylchuk, A.J., 2021b. Technological innovations in the recreational fishing sector: implications for fisheries management and policy. Rev. Fish Biol. Fish. 31 (2), 253–288.
Correia, R.A., Ladle, R., Jarić, I., Malhado, A.C., Mittermeier, J.C., Roll, U., et al., 2021. Digital data sources and methods for conservation culturomics. Conserv. Biol. 35 (2), 398–411.
Cowx, I.G., 1989. Developments in Electric Fishing. Fishing New Books, Oxford, UK.
Craig, J.F. (Ed.), 2016. Freshwater Fisheries Ecology. John Wiley & Sons.
Crandall, C.A., Monroe, M., Dutka-Gianelli, J., Fitzgerald, B., Lorenzen, K., 2018. How to bait the hook: identifying what motivates anglers to participate in a volunteer angler data program. Fisheries 43 (11), 517–526.
Cvitanovic, C., Hobday, A.J., van Kerkhoff, L., Marshall, N.A., 2015. Overcoming barriers to knowledge exchange for adaptive resource management: The perspectives of Australian marine scientists. Mar. Policy 52, 38–44.
Davies, P., Britton, R.J., Nunn, A.D., Dodd, J.R., Crundwell, C., Velterop, R., Ó'Maoiléidigh, N., O'Neill, R., Sheehan, E.V., Stamp, T., Bolland, J.D., 2020. Novel insights into the marine phase and river fidelity of anadromous twaite shad Alosa fallax in the UK and Ireland. Aquat. Conserv. 30 (7), 1291–1298.
Day, C.C., Landguth, E.L., Bearlin, A., Holden, Z.A., Whiteley, A.R., 2018. Using simulation modeling to inform management of invasive species: A case study of eastern brook trout suppression and eradication. Biol. Conserv. 221, 10–22.
Di Minin, E., Fink, C., Hausmann, A., Kremer, J., Kulkarni, R., 2021. How to address data privacy concerns when using social media data in conservation science. Conserv. Biol. 35 (2), 437–446.
Dominguez Almela, V., Palmer, S.C., Andreou, D., Gillingham, P.K., Travis, J.M., Britton, J.R., 2021. Predicting the outcomes of management strategies for controlling invasive river fishes using individual-based models. J. Appl. Ecol. 58 (11), 2427–2440.
Dominguez Almela, V., Palmer, S.C., Gillingham, P.K., Travis, J.M., Britton, J.R., 2020. Integrating an individual-based model with approximate Bayesian computation to predict the invasion of a freshwater fish provides insights into dispersal and range expansion dynamics. Biol. Invasions 22 (4), 1461–1480.
Dubreuil, T., Baudry, T., Mauvisseau, Q., Arqué, A., Courty, C., Delaunay, C., Sweet, M., Grandjean, F., 2022. The development of early monitoring tools to detect aquatic invasive species: eDNA assay development and the case of the armored catfish *Hypostomus robinii*. Environ. DNA 4, 349–362.
Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C., et al., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81 (2), 163–182.
Egbue, O., Long, S., 2012. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. Energy Policy 48, 717–729.
Eigaard, O.R., Marchal, P., Gislason, H., Rijnsdorp, A.D., 2014. Technological development and fisheries management. Rev. Fish. Sci. Aquac. 22 (2), 156–174.

Erbe, C., Parsons, M., Duncan, A., Osterrieder, S.K., Allen, K., 2017. Aerial and underwater sound of unmanned aerial vehicles (UAV). J. Unmanned Veh. Syst. 5 (3), 92–101.

Encyclopedia of Science, Technology, and Ethics, 2019. Technoscience. www.encyclopedia.com/science/encyclopedias-almanacs-transcripts-and-maps/technoscience (accessed 20 June 2022).

Euclide, P.T., MacDougall, T., Robinson, J.M., Faust, M.D., Wilson, C.C., Chen, K., Marschall, E.A., Larson, W., Ludsin, S., 2021b. Mixed-stock analysis using rapture genotyping to evaluate stock-specific exploitation of a walleye population despite weak genetic structure. Evol. Appl. 14 (5), 1403–1420.

Euclide, P.T., Robinson, J., Faust, M., Ludsin, S.A., MacDougall, T.M., Marschall, E.A., Chen, K., Wilson, C., Bootsma, M., Stott, W., Scribner, K.T., Larson, W.A., 2021a. Using genomic data to guide walleye management in the great lakes. In: Bruner, J.C., DeBruyne, R.L. (Eds.), Yellow Perch, Walleye, and Sauger: Aspects of Ecology, Management, and Culture. In: Fish & Fisheries Series, vol. 41, Springer, Cham, pp. 115–139. http://dx.doi.org/10.1007/978-3-030-80678-1_5.

Fanelli, E., Aguzzi, J., Marini, S., del Rio, J., Nogueras, M., Canese, S., et al., 2020. Towards naples ecological research for augmented observatories (NEREA): the NEREA-Fix module, a stand-alone platform for long-term deep-sea ecosystem monitoring. Sensors 20 (10), 2911.

Fernando, A.V., Short, W.C., Nault, K.N., 2019. Comparison of angler pressure counts by manned and unmanned aircraft on an Arkansas tailwater fishery. J. Southeast. Assoc. Fish Wildl. Agencies 6, 94–99.

Fielder, D.G., Hayden, T.A., Vandergoot, C.S., Krueger, C.C., 2020. Large-scale fish movement affects metrics of management importance as indicated by quantitative stock assessment. J. Great Lakes Res. 46 (3), 633–642.

Flanagan, M., Howe, D.C., Nissenbaum, H., 2008. Embodying values in technology: Theory and practice. In: van den Hoven, J., Weckert, J. (Eds.), Information Technology and Moral Philosophy. Cambridge University Press, pp. 322–353.

Fleck, J., 1993. Innofusion: Feedback in the innovation process. In: Stowell, F.A., West, D., Howell, J.G. (Eds.), Systems Science. Springer, Boston, MA, pp. 169–174.

Franceschini, S., Mattei, F., D'Andrea, L., Di Nardi, A., Fiorentino, F., Garofalo, G., et al., 2019. Rummaging through the bin: Modelling marine litter distribution using Artificial Neural Networks. Mar. Pollut. Bull. 149, 110580.

Gehri, R.R., Larson, W.A., Gruenthal, K., Sard, N.M., Shi, Y., 2021. eDNA metabarcoding outperforms traditional fisheries sampling and reveals fine-scale heterogeneity in a temperate freshwater lake. Environ. DNA 3, 912–929.

Groves, P.A., Alcorn, B., Wiest, M.M., Maselko, J.M., Connor, W.P., 2016. Testing unmanned aircraft systems for salmon spawning surveys. Facets 1 (1), 187–204.

Gundelund, C., Arlinghaus, R., Baktoft, H., Hyder, K., Venturelli, P., Skov, C., 2020. Insights into the users of a citizen science platform for collecting recreational fisheries data. Fish. Res. 229, 105597. http://dx.doi.org/10.1016/j.fishres.2020.105597.

Gundelund, C., Venturelli, P., Hartill, B.W., Hyder, K., Olesen, H.J., Skov, C., 2021. Evaluation of a citizen science platform for collecting fisheries data from coastal sea trout anglers. Can. J. Fish. Aquat. Sci. 78 (11), 1576–1585. http://dx.doi.org/10.1139/cjfas-2020-0364.

Hansen, B.K., Bekkevold, D., Clausen, L.W., Nielsen, E.E., 2018. The sceptical optimist: challenges and perspectives for the application of environmental DNA in marine fisheries. Fish Fish (Oxf.) 19, 751–768.

Happel, A., 2019. A volunteer-populated online database provides evidence for a geographic pattern in symptoms of black spot infections. IJP-PAW 10, 156–163.

Harris, J.E., Hightower, J.E., 2017. An integrated tagging model to estimate mortality rates of Albemarle Sound-Roanoke River striped bass. Can. J. Fish. Aquat. Sci. 74, 1061–1076.

Harris, J.M., Nelson, J.A., Rieucau, G., Broussard, III, W.P., 2019. Use of drones in fishery science. Trans. Am. Fish. Soc. 148 (4), 687–697.

Harrison, I., Abell, R., Darwall, W., Thieme, M.L., Tickner, D., Timboe, I., 2018. The freshwater biodiversity crisis. Science 362 (6421), 1369.

Hayden, T.A., Holbrook, C.M., Fielder, D.G., Vandergoot, C.S., Bergstedt, R.A., Dettmers, J.M., et al., 2014. Acoustic telemetry reveals large-scale migration patterns of walleye in Lake Huron. PLoS One 9 (12), e114833.

Hayden, T.A., Vandergoot, C.S., Fielder, D.G., Cooke, S.J., Dettmers, J.M., Krueger, C.C., 2019. Telemetry reveals limited exchange of walleye between Lake Erie and Lake Huron: Movement of two populations through the Huron-Erie corridor. J. Great Lakes Res. 45 (6), 1241–1250.

He, X., Johansson, M.L., Heath, D.D., 2016. Role of genomics and transcriptomics in selection of reintroduction source populations. Conserv. Biol. 30 (5), 1010–1018.

Hilborn, R., 2007. Managing fisheries is managing people: what has been learned? Fish Fish (Oxf.) 8 (4), 285–296.

Hinderer, J.L.M., Blevins, Z., Cooke, S.J., Dunlop, E., Robinson, K.F., Stang, D.L., Stewart, T.J., Tyson, J.T., Welsh, A.B., Young, N., Muir, A.M., 2021. Insights from a novel, user-driven science transfer program for resource management. SEPR 3 (4), 337–362.

Honarmand Ebrahimi, S., Ossewaarde, M., Need, A., 2021. Smart fishery: a systematic review and research agenda for sustainable fisheries in the age of AI. Sustainability 13 (11), 6037.

Houde, A.L.S., Akbarzadeh, A., Gunther, O.P., et al., 2019. Salmonid gene expression biomarkers indicative of physiological responses to changes in salinity and temperature, but not dissolved oxygen. J. Exp. Biol. 222 (13), jeb198036.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., et al., 2015. Aquatic animal telemetry: a panoramic window into the underwater world. Science 348 (6240), 1255642.

Ives, J.T., McMeans, B.C., McCann, K.S., Fisk, A.T., Johnson, T.B., Bunnell, D.B., et al., 2019. Food-web structure and ecosystem function in the Laurentian Great Lakes—Toward a conceptual model. Freshw. Biol. 64 (1), 1–23.

Jalal, A., Salman, A., Mian, A., Shortis, M., Shafait, F., 2020. Fish detection and species classification in underwater environments using deep learning with temporal information. Ecol. Inform. 57, 101088.

Jarić, I., Correia, R.A., Brook, B.W., Buettel, J.C., Courchamp, F., Di Minin, E., Firth, J.A., Gaston, K.J., Jepson, P., Kalinkat, G., Ladle, R., Soriano-Redondo, A., Souza, A.T., Roll, U., 2020a. Iecology: harnessing large online resources to generate ecological insights. Trends Ecol. Evol. 35 (7), 630–639.

Jarić, I., Roll, U., Arlinghaus, R., Belmaker, J., Chen, Y., China, V., Douda, K., Essl, F., Jähnig, S.C., Jeschke, J.M., Kalinkat, G., Kalous, L., Ladle, R., Lennox, R.J., Rosa, R., Sbragaglia, V., Sherren, K., Šmejkal, M., Soriano-Redondo, A., Souza, A.T., Wolter, C., Correia, R.A., 2020b. Expanding conservation culturomics and iecology from terrestrial to aquatic realms. PLoS Biol. 18 (10), e3000935.

Jeffrey, J.D., Carlson, H., Wrubleski, D., Enders, E.C., Treberg, J.R., Jeffries, K.M., 2020. Applying a gene-suite approach to examine the physiological status of wild-caught walleye (*Sander vitreus*). Conserv. Physiol. 8 (1), coaa099.

Jeffries, K.M., Connon, R.E., Davis, B.E., Komoroske, L.M., Britton, M.T., Sommer, T., Todgham, A.E., Fangue, N.A., 2016. Effects of high temperatures on threatened estuarine fishes during periods of extreme drought. J. Exp. Biol. 219 (11), 1705–1716.

Jeffries, K.M., Teffer, A., Michaleski, S., Bernier, N.J., Heath, D.D., Miller, K.M., 2021. The use of non-lethal sampling for transcriptomics to assess the physiological status of wild fishes. Comp. Biochem. Physiol. B Biochem. Mol. Biol. 256, 110629.

Jenkins, L.D., 2022. Power, politics, and culture of marine conservation technology in fisheries. Conserv. Biol. 36 (3), e13855.

Jerde, C.L., 2021. Can we manage fisheries with the inherent uncertainty from eDNA? J. Fish. Biol. 98 (2), 341–353.

Jerde, C.L., Chadderton, W.L., Mahon, A.R., et al., 2013. Detection of Asian carp DNA as part of a Great Lakes basin-wide surveillance program. Can. J. Fish. Aquat. Sci. 70 (4), 522–526.

Jerde, C.L., Mahon, A.R., Chadderton, W.L., Lodge, D.M., 2011. Sight-unseen detection of rare aquatic species using environmental DNA. Conserv. Lett. 4 (2), 150–157.

Jiménez-Alvarado, D., Sarmiento-Lezcano, A., Guerra-Marrero, A., Tuya, F., Santana Del Pino, Á., Sealey, M.J., Castro, J.J., 2019. Historical photographs of captures of recreational fishers indicate overexploitation of nearshore resources at an oceanic island. J. Fish Biol. 94 (6), 857–864.
Jiorle, R.P., Ahrens, R.N., Allen, M.S., 2016. Assessing the utility of a smartphone app for recreational fishery catch data. Fisheries 41 (12), 758–766. http://dx.doi.org/10.1080/03632415.2016.1249709.
Johnson, D.G., Wetmore, J.M., 2021. Technology and Society: Building Our Sociotechnical Future, second ed. MIT Press, Boston, MA.
Johnston, F.D., Simmons, S., van Poorten, B., Venturelli, P., 2022. Comparative analyses with conventional surveys reveal the potential for an angler app to contribute to recreational fisheries monitoring. Can. J. Fish. Aquat. Sci. 79 (1), 31–46. http://dx.doi.org/10.1139/cjfas-2021-0026.
Jothiswaran, V.V., Velumani, T., Jayaraman, R., 2020. Application of artificial intelligence in fisheries and aquaculture. Biot. Res. Today 2 (6), 499–502.
Kalacska, M., Lucanus, O., Sousa, L., Vieira, T., Arroyo-Mora, J.P., 2018. Freshwater fish habitat complexity mapping using above and underwater structure-from-motion photogrammetry. Remote Sens. 10 (12), 1912.
Kalff, J., 2002. Limnology: Inland Water Ecosystems. Prentice Hall, Upper Saddle River, New Jersey.
Kochzius, M., Seidel, C., Antoniou, A., Botla, S.K., Campo, D., et al., 2010. Identifying fishes through DNA barcodes and microarrays. PLoS One 5 (9), e12620. http://dx.doi.org/10.1371/journal.pone.0012620.
Krueger, C.C., Holbrook, C.M., Binder, T.R., Vandergoot, C.S., Hayden, T.A., Hondorp, D.W., Nate, N., Paige, K., Riley, S.C., Fisk, A.T., Cooke, S.J., 2018. Acoustic telemetry observation systems: challenges encountered and overcome in the Laurentian Great Lakes. Can. J. Fish. Aquat. Sci. 75 (10), 1755–1763.
Lackey, R.T., 2005. Fisheries: history, science, and management. In: Lehr, J.H., Keeley, J. (Eds.), Water Encyclopedia: Surface and Agricultural Water. Wiley and Sons Inc., New York, pp. 121–129.
Lacoursière-Roussel, A., Côté, G., Leclerc, V., Bernatchez, L., 2016. Quantifying relative fish abundance with eDNA: a promising tool for fisheries management. J. Appl. Ecol. 53, 1148–1157.
Ladle, R.J., Correia, R.A., Do, Y., Joo, G.J., Malhado, A.C.M., Proulx, R., Roberge, J.M., Jepson, P., 2016. Conservation culturomics. Front. Ecol. Environ. 14, 269–275.
Lahoz-Monfort, J.J., Chadès, I., Davies, A., Fegraus, E., Game, E., Guillera-Arroita, G., Harcourt, R., Indraswari, K., McGowan, J., Oliver, J.L., Refisch, J., Rhodes, J., Roe, P., Rogers, A., Ward, A., Watson, D.M., Wintle, B.A., Joppa, L., 2019. A call for international leadership and coordination to realize the potential of conservation technology. Bioscience 69 (10), 823–832.
Latour, B., 1990. Technology is society made durable. Sociol. Rev. 38 (1), 103–131.
Lennox, R.J., Sbragaglia, V., Vollset, K.W., Sortland, L.K., McClenachan, L., Jarić, I., Guckian, M.L., Ferter, K., Danylchuk, A.J., Cooke, S.J., Arlinghaus, R., Twardek, W.M., 2022. Digital fisheries data in the internet age: emerging tools for research and monitoring using online data in recreational fisheries. Fish Fish 23, 926–940. http://dx.doi.org/10.1111/faf.12663.
Lennox, R.J., Westrelin, S., Souza, A.T., Šmejkal, M., Říha, M., Prchalová, M., Nathan, R., Koeck, B., Killen, S., Jarić, I., Gjelland, K., Hollins, J., Hellstrom, G., Hansen, H., Cooke, S.J., Boukal, D., Brooks, J.L., Brodin, T., Baktoft, H., Adam, T., Arlinghaus, R., 2021. A role for lakes in revealing the nature of animal movement using high dimensional telemetry systems. Mov. Ecol. 9 (1), 40.
Lloyd, S., Lepper, P., Pomeroy, S., 2017. Evaluation of UAVs as an underwater acoustics sensor deployment platform. Int. J. Remote Sens. 38 (8–10), 2808–2817.
Lorenzen, K., Cowx, I.G., Entsua-Mensah, R.E.M., Lester, N.P., Koehn, J.D., Randall, R.G., et al., 2016. Stock assessment in inland fisheries: a foundation for sustainable use and conservation. Rev. Fish. Biol. Fish. 26 (3), 405–440.
Lynch, A.J., Bartley, D.M., Beard, Jr., T.D., Cowx, I.G., Funge-Smith, S., Taylor, W.W., Cooke, S.J., 2020. Examining progress towards achieving the ten steps of the Rome Declaration on responsible Inland fisheries. Fish Fish. 21 (1), 190–203.
Lynch, A.J., Cooke, S.J., Deines, A.M., Bower, S.D., Bunnell, D.B., Cowx, I.G., et al., 2016. The social, economic, and environmental importance of inland fish and fisheries. Environ. Rev. 24 (2), 115–121.
Macreadie, P.I., McLean, D.L., Thomson, P.G., Partrige, J.C., Jones, D.O.B., Gates, A.R., Benfield, M.C., Collin, S.P., Booth, D.J., Smith, L.L., Techera, E., Skropeta, D., Horton, T., Pattiaratchi, C., Bond, T., Flowler, A.M., 2018. Eyes in the sea: unlocking the mysteries of the ocean using industrial, remotely operated vehicles (ROVs). Sci. Total Environ. 634, 1077–1091.
Madenjian, C.P., Hayden, T.A., Peat, T.B., Vandergoot, C.S., Fielder, D.G., Gorman, A.M., Pothoven, S.A., Dettmers, J.M., Cooke, S.J., Zhao, Y., Krueger, C.C., 2018. Temperature regimes, growth, and food consumption for adult walleye in Lake Huron and Lake Erie: A bioenergetics analysis. Can. J. Fish. Aquat. Sci. 75, 1573–1586.
Markowitz, E.M., Nisbet, M.C., Danylchuk, A.J., Engelbourg, S.I., 2017. What's that buzzing noise? Public opinion on the use of drones for conservation science. Bioscience 67, 382–385.
Marsden, J.E., Blanchfield, P.J., Brooks, J.L., Fernandes, T., Fisk, A.T., Futia, M.H., Hlina, B.L., Ivanova, S.V., Johnson, T.B., Klinard, N.V., Krueger, C.C., Larocque, S.M., Matley, J.K., McMeans, B., O'Connor, L.M., Raby, G.D., Cooke, S.J., 2021. Using untapped biotelemetry data to explore the winter biology of freshwater fish. Rev. Fish Biol. Fish. http://dx.doi.org/10.1007/s11160-021-09634-2.
Martin, D.R., Chizinski, C.J., Eskridge, K.M., Pope, K.L., 2014. Using posts to an online social network to assess fishing effort. Fish. Res. 157, 24–27.
Matley, J.K., Klinard, N.V., Martins, A.P.B., Aarestrup, K., Aspillaga, E., Cooke, S.J., Cowley, P.D., Heupel, M.R., Lowe, C.G., Lowerre-Barbieri, S.K., Mitamura, H., 2021. Global trends in aquatic animal tracking with acoustic telemetry. Trends Ecol. Evol. 37 (1), 79–94.
McClenachan, L., 2009. Historical declines of goliath grouper populations in South Florida, USA. Endanger. Species Res. 7 (3), 175–181.
McDonald, Z., 2022. Climate-Induced Changes in the Relative Abundance of Freshwater Game Fish Inferred from Digital Catch Log Data (M.Sc. Thesis). Ball State University.
McKelvey, K.S., Young, M.K., Knotek, E.L., et al., 2016. Sampling large geographic areas for rare species using environmental DNA (eDNA): a study of bull trout *Salvelinus confluentus* occupancy in western Montana. J. Fish Biol. 88, 1215–1222.
Mendo, T., Mendo, J., Ransijn, J.M., Gomez, I., Gil-Kodaka, P., Fernández, J., Delgado, R., Travezaño, A., Arroyo, R., Loza, K., McCann, P., 2022. Assessing discards in an illegal small-scale fishery using fisher-led reporting. Rev. Fish Biol. Fish. 1–12.
Meng, L., Hirayama, T., Oyanagi, S., 2018. Underwater-drone with panoramic camera for automatic fish recognition based on deep learning. IEEE Access 6, 17880–17886.
Merrifield, M., Gleason, M., Bellquist, L., Kauer, K., Oberhoff, D., Burt, C., et al., 2019. eCatch: Enabling collaborative fisheries management with technology. Ecol. Inform. 52, 82–93.
Michielsens, C.G.J., Cave, J.D., 2019. In-season assessment and management of salmon stocks using a Bayesian time–density model. Can. J. Fish. Aquat. Sci. 76, 1073–1085.
Midden, C.J., Kaiser, F.G., Teddy McCalley, L., 2007. Technology's four roles in understanding individuals' conservation of natural resources. J. Soc. Issues 63 (1), 155–174.
Midway, S.R., Adriance, J., Banks, P., Haukebo, S., Caffey, R., 2020. Electronic self-reporting: Angler attitudes and behaviors in the recreational red snapper fishery. N. Am. J. Fish. Manag. 40 (5), 1119–1132.
Miller, K.M., Teffer, A., Tucker, S., Li, S., Schulze, A.D., Trudel, M., Juanes, F., Tabata, A., Kaukinen, K.H., Ginther, N.G., Ming, T.J., 2014. Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evol. Appl. 7 (7), 812–855.
Monkman, G.G., Kaiser, M.J., Hyder, K., 2018a. Text and data mining of social media to map wildlife recreation activity. Biol. Conserv. 228, 89–99.
Monkman, G.G., Kaiser, M.J., Hyder, K., 2018b. The ethics of using social media in fisheries research. Rev. Fish. Sci. Aquac. 26 (2), 235–242.

Nathan, R., Monk, C.T., Arlinghaus, R., Adam, T., Alós, J., Assaf, M., Baktoft, H., Beardsworth, C.E., Bertram, M.G., Bijleveld, A.I., Brodin, T., Brooks, J.L., Campos-Candela, A., Cooke, S.J., Gjelland, K.Ø., Gupte, P.R., Harel, R., Hellström, G., Jeltsch, F., Killen, S.S., Klefoth, T., Langrock, R., Lennox, R.J., Lourie, E., Madden, J.R., Orchan, Y., Pauwels, I.S., Říha, M., Roeleke, M., Schlägel, U.E., Shohami, D., Signer, J., Toledo, S., Vilk, O., Westrelin, S., Whiteside, M.A., Jarić, I., 2022. Big-data approaches lead to an increased understanding of the ecology of animal movement. Science 375 (6582), eabg1780.

Neeson, T.M., Wiley, M.J., Adlerstein, S.A., Riolo, R.L., 2012. How river network structure and habitat availability shape the spatial dynamics of larval sea lampreys. Ecol. Modell. 226, 62–70.

Nguyen, V.M., Brooks, J.L., Young, N., Lennox, R.J., Haddaway, N., Whoriskey, F.G., Harcourt, R., Cooke, S.J., 2017. To share or not to share in the emerging era of big data: perspectives from fish telemetry researchers on data sharing. Can. J. Fish. Aquat. Sci. 74 (8), 1260–1274.

Nguyen, V.M., Young, N., Brownscombe, J.W., Cooke, S.J., 2019. Collaboration and engagement produce more actionable science: quantitatively analyzing uptake of fish tracking studies. Ecol. Appl. 29 (6), e01943.

Open Access Government, 2019. What is the obstacle to public sector tech adoption? https://www.openaccessgovernment.org/public-sector-tech/76652/ (accessed 2 June 2 2022).

Papenfuss, J.T., Phelps, N., Fulton, D., Venturelli, P.A., 2015. Smartphones reveal angler behavior: a case study of a popular mobile fishing application in Alberta, Canada. Fisheries 40 (7), 318–327. http://dx.doi.org/10.1080/03632415.2015.1049693.

Parente, S.L., Prescott, E.C., 1994. Barriers to technology adoption and development. J. Polit. Econ. 102 (2), 298–321.

Perritt, H.H., Sprague, E.O., 2017. Domesticating Drones: The Technology, Law, and Economics of Unmanned Aircraft. Routledge, New York, p. 416.

Peters, F.T., Drummer, O.H., Musshoff, F., 2007. Validation of new methods. Forensic Sci. Int. 165 (2–3), 216–224.

Peterson, L.K., Jones, M.L., Brenden, T.O., Vandergoot, C.S., Krueger, C.C., 2021. Evaluating methods for estimating mortality from acoustic telemetry data. Can. J. Fish. Aquat. Sci. 78, 1444–1454.

Pickles, J., 1997. Tool or science? GIS, technoscience, and the theoretical turn. Ann. Assoc. Am. Geogr. 87, 363–372.

Piczak, M.L., Brooks, J.L., Bard, B., Bihun, C.J., Howarth, A., Jeanson, A.L., LaRochelle, L., Bennett, J.R., Lapointe, N.W.R., Mandrak, N.E., Cooke, S.J., 2022. Revisiting the challenge: perspectives on Canada's freshwater fisheries policies three decades after the Pearse Report. FACETS 7, 912–935. http://dx.doi.org/10.1139/facets-2021-0145.

Pitcher, T.J., 2015. Assessment and modelling in freshwater fisheries. In: Craig, J.F. (Ed.), Freshwater Fisheries Ecology. John Wiley & Sons, pp. 483–499.

Postman, N., 2011. Technopoly: The Surrender of Culture to Technology, first ed. Vintage, New York.

Provost, E.J., Butcher, P.A., Coleman, M.A., Kelaher, B.P., 2020. Assessing the viability of small aerial drones to quantify recreational fishers. Fish. Manag. Ecol. 27 (6), 615–621.

Qin, H., Li, X., Liang, J., Peng, Y., Zhang, C., 2016. DeepFish: Accurate underwater live fish recognition with a deep architecture. Neurocomputing 187, 49–58.

Razavi, S., Hannah, D.M., Elshorbagy, A., Kumar, S., Marshall, L., Solomatine, D.P., Dezfuli, A., Mojtaba, S., Famiglietti, J., 2022. Coevolution of machine learning and process-based modelling to revolutionize earth and environmental sciences: A perspective. Hydrol. Process. (e14596).

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T., et al., 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94 (3), 849–873.

Reubens, J., Aarestrup, K., Meyer, C., Moore, A., Okland, F., Afonso, P., 2021. Compatibility in acoustic telemetry. Anim. Biotelem. 9 (1), 1–6.

Richardson, D., 1999. A brief history of scuba diving in the United States. SPUMS J. 29, 173–176.

Rogers, E.M., Singhal, A., Quinlan, M.M., 2014. Diffusion of innovations. In: An Integrated Approach to Communication Theory and Research. Routledge, pp. 432–448.

Roncoroni, M., Lane, S.N., 2019. A framework for using small Unmanned Aircraft Systems (sUASs) and SfM photogrammetry to detect salmonid redds. Ecol. Inform. 53, 100976.

Roussel, J.M., Paillisson, J.M., Tréguier, A., Petit, E., 2015. The downside of eDNA as a survey tool in water bodies. J. Appl. Ecol. 52, 823–826.

Russell, S.J., Norvig, P., 2009. Artificial Intelligence: A Modern Approach, third ed. Prentice Hall, Upper Saddle River, New Jersey.

Sbragaglia, V., Coco, S., Correia, R.A., Coll, M., Arlinghaus, R., 2021. Analyzing publicly available videos about recreational fishing reveals key ecological and social insights: a case study about groupers in the Mediterranean Sea. Sci. Total Environ. 765, 142672.

Sbragaglia, V., Correia, R.A., Coco, S., Arlinghaus, R., 2020. Data mining on YouTube reveals fisher group-specific harvesting patterns and social engagement in recreational anglers and spearfishers. ICES J. Mar. Sci. 77 (6), 2234–2244.

Semeniuk, C.A.D., Jeffries, K.M., Li, T., Bettles, C.M., Cooke, S.J., Dufour, B.A., Halfyard, E.A., Heath, J.W., Keeshig, K., Mandrak, N.E., Muir, A.J., 2022. Innovating transcriptomics for practitioners in freshwater fish management and conservation: best practices across diverse resource-sector users. Rev. Fish Biol. Fish. 1–19.

Sepulveda, A.J., Nelson, N.M., Jerde, C.L., Luikart, G., 2020. Are environmental DNA methods ready for aquatic invasive species management? Trends Ecol. Evol. 35 (8), 668–678. http://dx.doi.org/10.1016/j.tree.2020.03.011.

Serchuk, F.M., Smolowitz, R.J., 1990. Ensuring fisheries management dysfunction: the neglect of science and technology. Fisheries 15 (2), 4–7.

Shi, Y., Bouska, K.L., McKinney, G.J., Dokai, W., Bartels, A., McPhee, M.V., Larson, W.A., 2021. Gene flow influences the genomic architecture of local adaptation in six riverine fish species. Mol. Ecol. http://dx.doi.org/10.1111/mec.16317, in press.

Skov, C., Hyder, K., Gundelund, C., Ahvonen, A., Baudrier, J., Borch, T., et al., 2021. Expert opinion on using angler smartphone apps to inform marine fisheries management: status, prospects, and needs. ICES J. Mar. Sci. 78 (3), 967–978.

Standal, D., 2005. Nuts and bolts in fisheries management—a technological approach to sustainable fisheries? Mar. Policy 29 (3), 255–263.

Starck, W.A., 1973. New diving technology for marine scientists. Aust. Nat. Hist. 17 (181).

Stewart, K.A., 2019. Understanding the effects of biotic and abiotic factors on sources of aquatic environmental DNA. Biodivers. Conserv. 28, 983–1001. http://dx.doi.org/10.1007/s10531-019-01709-8.

Stöcker, C., Bennett, R., Nex, F., Gerke, M., Zevenbergen, J., 2017. Review of the current state of UAV regulations. Remote Sens. 9 (5), 459.

Suuronen, P., Bartley, D.M., 2014. Challenges in managing Inland Fisheries—using the ecosystem approach. Boreal Environ. Res. 19 (3), 245–255.

Thorne, R.E., Thomas, G.L., 1984. Recent applications of hydroacoustics to assessment of limnetic fish abundance and behavior. Lake Reserv. Manage. 1 (1), 305–309.

Thorstensen, M.J., Euclide, P.T., Jeffrey, J.D., Shi, Y., Treberg, J.R., Watkinson, D.A., Enders, E.C., Larson, W.A., Kobayashi, Y., Jeffries, K.M., 2021. A chromosomal inversion may facilitate adaptation despite periodic gene flow in a freshwater fish. Ecol. Evol. 12 (5), e8898.

Tobin, C.D., 2015. Lights, cameras, drones!. Litig 42, 1–3.

Toonen, H.M., Bush, S.R., 2018. The digital frontiers of fisheries governance: fish attraction devices, drones and satellites. J. Environ. Policy Plan. 22 (1), 125–137.

van den Heuvel, L., Blicharska, M., Blyth, S., Rönnbäck, P., 2020. Catch reporting in recreational fishing: Swedish anglers' attitudes and preferences, and the effect of social factors. Fish. Res. 223, 105444.

Venturelli, P.A., Hyder, K., Skov, C., 2017. Angler apps as a source of recreational fisheries data: opportunities, challenges and proposed standards. Fish Fish. 18 (3), 578–595.

Villon, S., Mouillot, D., Chaumont, M., Darling, E.S., Subsol, G., Claverie, T., Villéger, S., 2018. A deep learning method for accurate and fast identification of coral reef fishes in underwater images. Ecol. Inform. 48, 238–244.

Wang, J., Shi, T., Yu, D., Teng, D., Ge, X., Zhang, Z., et al., 2020. Ensemble machine-learning-based framework for estimating total nitrogen concentration in water using drone-borne hyperspectral imagery of emergent plants: A case study in an arid oasis, NW China. Environ. Pollut. 266, 115412.
Watanabe, J.I., Shao, Y., Miura, N., 2019. Underwater and airborne monitoring of marine ecosystems and debris. J. Appl. Remote Sens. 13 (4), 044509.
Weber, J., 2006. From science and technology to feminist technoscience. In: Handbook of Gender and Women's Studies. Routledge, pp. 397–414.
Weir, J.L., Vacura, K., Bagga, J., Berland, A., Hyder, K., Skov, C., et al., 2022. Big data from a popular app reveals that fishing creates superhighways for aquatic invaders. PNAS Nexus 1 (3), pgac075.
Wejnert, B., 2002. Integrating models of diffusion of innovations: A conceptual framework. Annu. Rev. Sociol. 28 (1), 297–326.
Welcomme, R.L., Cowx, I.G., Coates, D., Béné, C., Funge-Smith, S., Halls, A., Lorenzen, K., 2010. Inland capture fisheries. Philos. Trans. R. Soc. B: Biol. Sci. 365 (1554), 2881–2896.
Wellband, K.W., Heath, D.D., 2017. Plasticity in gene transcription explains the differential performance of two invasive fish species. Evol. Appl. 10 (6), 563–576.
Welsh, A., Jerde, C., Wilson, C., Docker, M., Locke, B., 2020. Management Support Tree for the Interpretation of Positive Laboratory Results. Great Lakes Fishery Commission Science, http://www.glfc.org/pubs/pdfs/research/eDNA%20STP/Decision%20Tree-FINAL_152019.pdf.
Wilcox, T.M., McKelvey, K.S., Young, M.K., Sepulveda, A.J., Shepard, B.B., Jane, S.F., Whiteley, A.R., Lowe, W.H., Schwartz, M.K., 2016. Understanding environmental DNA detection probabilities: A case study using a stream-dwelling char *Salvelinus fontinalis*. Biol. Conserv. 194, 209–216. http://dx.doi.org/10.1016/j.biocon.2015.12.023.
Wild, S., 2008. Sustainability reporting in fishing industry management-regulation versus voluntarism. Australas. Account. Bus. Finance J. 2 (3), 57–75.
Wilde, G.R., Pope, K., 2013. Worldwide trends in fishing interest indicated by internet search volume. Fish. Manag. Ecol. 20, 211–222.
Woodget, A.S., Austrums, R., Maddock, I.P., Habit, E., 2017. Drones and digital photogrammetry: from classifications to continuums for monitoring river habitat and hydromorphology. Wiley Interdiscip. Rev. Water 4 (4), e1222.
Yates, M.C., Fraser, D.J., Derry, A.M., 2019. Meta-analysis supports further refinement of eDNA for monitoring aquatic species-specific abundance in nature. Environ. DNA 1, 5–13. http://dx.doi.org/10.1002/edn3.7.
Young, N., Corriveau, M., Nguyen, V.M., Cooke, S.J., Hinch, S.G., 2016. How do potential knowledge users evaluate new claims about a contested resource? Problems of power and politics in knowledge exchange and mobilization. J. Environ. Manag. 184 (2), 380–388.
Young, N., Corriveau, M., Nguyen, V.M., Cooke, S.J., Hinch, S.G., 2018. Embracing disruptive new science? Biotelemetry meets co-management in Canada's fraser river. Fisheries 43 (1), 51–60.
Zhu, W., Lu, Z., Dai, Q., Lu, K., Li, Z., Zhou, Y., Zhang, Y., Sun, M., Li, Y., Li, W., 2021. Transition to timely and accurate reporting: An evaluation of monitoring programs for China's first Total Allowable Catch (TAC) pilot fishery. Mar. Policy 129, 104503.