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# Acoustic telemetry and fisheries management

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*Abstract.* This paper reviews the use of acoustic telemetry as a tool for addressing issues in fisheries management, and serves as the lead to the special Feature Issue of Ecological Applications titled *Acoustic Telemetry and Fisheries Management*. Specifically, we provide an overview of the ways in which acoustic telemetry can be used to inform issues central to the ecology, conservation, and management of exploited and/or imperiled fish species. Despite great strides in this area in recent years, there are comparatively few examples where data have been applied directly to influence fisheries management and policy. We review the literature on this issue, identify the strengths and weaknesses of work done to date, and highlight knowledge gaps and difficulties in applying empirical fish telemetry studies to fisheries policy and practice. We then highlight the key areas of management and policy addressed, as well as the challenges that needed to be overcome to do this. We conclude with a set of recommendations about how researchers can, in consultation with stock assessment scientists and managers, formulate testable scientific questions to address and design future studies to generate data that can be used in a meaningful way by fisheries management and conservation practitioners. We also urge the involvement of relevant stakeholders (managers, fishers, conservation societies, etc.) early on in the process (i.e., in the co-creation of research projects), so that all priority questions and issues can be addressed effectively.

*Key words: acoustic telemetry; applied science; conservation; fish tracking; fisheries biology; policy; resource management.*

## Introduction

The development of electronic animal tagging technologies (i.e., biologging, telemetry) over 60 yr ago (see Hockersmith and Beeman 2012) was a watershed moment for the study of aquatic animal behavior, and continued advances and miniaturization of electronic tags have allowed researchers to quantify previously unobserved processes important to population dynamics, reproductive performance, and fitness in a wide range of taxa (reviewed in Lucas and Baras 2000, Arnold and Dewar 2001, Cooke et al. 2004, Rutz and Hays 2009, Crossin et al. 2014, Hussey et al. 2015). In particular, the study of fish biology has benefited immensely over the past 20 yr with a near exponential increase in the number of published studies utilizing electronic tagging technology (Hussey et al. 2015). A key development that has enabled this is the passive acoustic array (Heupel and Webber 2012, Donaldson et al. 2014) and that acoustic tags often now can be equipped with sensors (e.g., pressure, temperature, acceleration) increasing the range of behaviors that can be studied (Cooke et al. 2004, 2016*a*).

Electronic tracking of fish is now in a golden age of sorts, with countless insights into fundamental processes related to biology (e.g., life-history variation in timing of migrations, variations in reproductive investment and spawning behavior, factors determining survival; DeCelles and Zemeckis 2013). However, it can be argued that electronic tracking has its greatest potential impact in the applied realm, as our ability to predict individual and

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population-level responses to environmental change is an essential component of conservation and management planning. Characterizing the high-resolution, spatiotemporal movements, physiological states, and environmental surroundings of individuals, and of interactions among individuals is indeed central to these efforts (Cooke et al. 2016*b*). Acoustic telemetry, especially when combined with other techniques, can reveal the mechanisms that both shape and disrupt fish populations and communities. In doing so, telemetry can serve as a tool to better understand, and potentially mitigate, the numerous conservation crises impacting fish populations around the world (Cooke 2008, Metcalfe et al. 2012, Hussey et al. 2015).

The goal of traditional fisheries management is to regulate fishing mortality on a given stock in a way that produces near-maximum sustainable yields (O'Farrell and Botsford 2006, Punt et al. 2014). To do so, there is a need to better understand a population's spatial ecology, as well as a means to track individual behavior over time to better understand difficult-to-estimate parameters such as catchability, natural mortality, and by-catch and release mortality (Donaldson et al. 2011, Benaka et al. 2014). The key spatial parameter in traditional management efforts is the stock unit, defined theoretically as all fish in an area that are part of the same reproductive process, with no immigration or emigration to or from the stock. However, often these data are unavailable and stock divisions are commonly assigned based on management convenience (Stephenson 1999, Smedbol and Stephenson 2001). There is growing awareness that this data gap can affect our ability to accurately assess stock status and interest in developing spatially explicit stock analysis models (Goethel et al. 2011, 2014). Electronic tracking is ideal for assessing the behaviors underlying stock structure, such as migratory pathways, home ranges, and core habitat utilizations, and it is being used to help fill this knowledge gap in highly migratory species such as tunas (Block et al. 2005) and sharks (Bonfil et al. 2005, Skomal et al. 2009). The use of coded transmitters, coupled with sensors that measure biotic variables (e.g., acceleration, tail-beat frequency, heart-rate, etc.) and abiotic variables (pressure/depth, salinity, temperature, etc.), can provide a wealth of information about behavior that can explain individual and population level variations in movement (see Payne et al. 2014). Additionally, there is a drive to place the stock concept within the broader context of ecosystems through an "ecosystem approach" to fisheries management (Garcia and Cochrane 2005). By an ecosystem approach, we mean to consider the impacts of anthropogenic development and degradation, interactions among different native fish species, identification of essential habitats, and the effects of introduced and invasive species. This approach allows management to extend far beyond traditional measures of harvest control, and embrace the more recent concepts of marine spatial planning and networked aquatic protected areas (Douvere 2008, Halpern et al. 2010, Foley et al. 2013).

We review the literature surrounding these issues, identify the strengths and weaknesses of work done to date, and highlight knowledge gaps and difficulties in applying data emanating from fish telemetry studies to fisheries policy. We then highlight the key areas of management and policy addressed, as well as the challenges that needed to be overcome to do this. Our specific aim was to provide case-examples where acoustic telemetry has led *directly* to management and/or conservation action (i.e., bridging the knowledge–action divide; Cook et al. 2013), as opposed to examples in which the potential *exists.* We review the science of acoustic telemetry in fisheries management, and then address the following management applications: habitat and protected areas management, invasive species monitoring and control, fisheries interactions and fisheries planning, and stock assessment. We conclude with recommendations as to how acoustic telemetry can be further integrated into fisheries management and conservation decisions.

## Why Acoustic Telemetry?

As noted above, there are many electronic tracking tools available for the study of wild fish (reviewed in Lucas and Baras 2000, Cooke et al. 2004). Here we focus on acoustic telemetry due to its relative affordability, ability to operate in both freshwater and marine environments, cross-compatible technology, versatility (Heupel and Webber 2012), and widespread use (Hussey et al. 2015). Acoustic transmitters emit a sonic pulse that can be detected and logged by hydrophones and receivers (see Stasko and Pincock 1977, Voegeli and Pincock 1996, for reviews of the conceptual basis and physics of acoustic telemetry, and Donaldson et al. 2014 for recent technical developments). Tracking can occur manually using a vessel to follow or locate a tag (Stasko and Pincock 1977), or by positioning autonomous receivers at known, fixed locations (e.g., Klimley et al. 1998). Fixed stations can be deployed in a variety of configurations (arrays, gates, curtains, etc.; see Heupel et al. 2006) and if detection zones overlap it is possible to position fish in two dimensions using hyperbolic navigation (Niezgoda et al. 2002, Espinoza et al. 2011*b*). Acoustic tags are most often surgically implanted, especially for longer term deployments (Wagner et al. 2011), but external attachment or gastric insertion (down the throat into stomach) are also common (Bridger and Booth 1999, Jepsen et al. 2014). Individual tags can be coded so that individual IDs are transmitted to facilitate tracking movement of individuals within a group. Acoustic tags can also be equipped with sensors that transmit environmental data (e.g., temperature, depth), or changes in individual behavioral or physiological state (e.g., acceleration, heart rate, etc.; see Cooke et al. [2004, 2016*a*] for reviews of sensor options). Acoustic telemetry systems are generally more affordable than high resolution satellite tags and global positioning systems and provide the high positional resolution needed to accurately assess the use of patchy habitat, such as proximity to oil rigs. However, back-end processing costs can be substantial due to accumulation of massive data sets. Acoustic tags can also be very small, weighing as little as 0.3 g, which facilitates the study of very small species and juvenile fishes (McMichael et al. 2010).

Beyond the operational benefits of acoustic telemetry lay the tremendous networking potential via well-established global and regional research organizations like the Ocean Tracking Network (OTN; Cooke et al. 2011), the Great Lakes Acoustic Telemetry Observation System, the Atlantic Cooperative Telemetry Network and Florida Acoustic Telemetry network , and the Integrated Marine Observing System, with more recent additions including the Southern California Acoustic telemetry tracking network, and the Integrated Tracking of Aquatic Animals in the Gulf of Mexico. All of these networks use acoustic telemetry as the principal means for tracking aquatic animals. The OTN has been instrumental in helping such networks grow. For example, OTN loaned telemetry equipment to iTAG to help increased the spatial coverage of monitoring. The importance of such networks lies in the connectivity of researchers from different organizations and jurisdictions using compatible technology such that a transmitter affixed to a fish in one locale can be detected by receivers deployed by a different researcher in another locale. Through informal and formal data sharing, researchers are able to extend the reach of their study beyond what could be logistically or financially possible. Receiver arrays and individual listening stations now extend along the Australian, South African, and North American coast lines, around many islands in the Caribbean, throughout the Arctic, Europe, and several other regions. They also extend inland up many major watersheds, including the St. Lawrence, Mekong, and Amazon rivers. The geographic scope of these networks enables researchers to address large-scale questions relevant to ocean and/or watershed management and governance (Heupel et al. 2015). For example, the iTAG network is bringing together researchers from multiple states to develop the acoustic telemetry infrastructure needed to address migrations and residency at the large marine ecosystem scale and integrate this data into ecosystem based models. To put the power of such integrated network collaborations into context, see the work of Jorgensen et al. (2009), which pooled the acoustic data from several independent research groups to describe the Pacific migrations of white sharks (*Carcharadon carcharius*).

With this in mind, the remainder of this article will review key issues facing contemporary fisheries management, with a focus on the past and present applications of acoustic telemetry to management objectives.

## Applications

### *Habitat management*

Fish habitat is the foundation for fish production in aquatic ecosystems (Hayes et al. 1996, Lapointe et al. 2014). It is therefore not surprising that great efforts are devoted to habitat management in freshwater, estuarine and marine environments. Habitat management can include habitat protection (i.e., managing the ways in which human activities and development interact directly and indirectly with fish habitat; See Goodchild 2004) and various forms of enhancement, creation and restoration (See Hobbs and Harris 2001). Underpinning any habitat management effort is a science-based understanding of how fish are distributed in space and time relative to physical features (Langton et al. 1996, Naiman and Latterell 2005, note that environmental conditions are also a component of "habitat"). More specifically, fishery habitat managers often devote significant effort to identifying critical (also termed essential) habitat requirements (e.g., spawning sites, rearing sites, overwintering sites; Schmitten 1999, Rosenfeld and Hatfield 2006) and developing policy instruments to ensure that such habitat units, and the connections between them, are protected (e.g., Minns 2001, Goodchild 2004).

Acoustic telemetry is increasingly recognized as a useful tool for supporting habitat management because it can provide information on how fish interact with different habitats at both the micro and macro scale. Indeed, most fish telemetry studies have an explicit objective related to characterizing habitat use or preference of exploited and imperiled species (e.g., Donaldson et al. 2014, Hussey et al. 2015). For example, at a broad scale, DeCelles and Cadrin (2010) used acoustic telemetry to characterize the seasonal distribution of winter flounder (*Pseudopleuronectes americanus*) in the southern Gulf of Maine. Similarly, Simpfendorfer et al. (2010) studied the distribution of the critically endangered juvenile smalltooth sawfish (*Pristis pectinata*) to generate short and long-term data on habitat use, to identify specific habitat types (i.e., shallow mud and sand banks, mangrove shorelines) that need protection (or enhancement) for population persistence and recovery. Some researchers have also used data from acoustic telemetry studies to identify construction windows for in-water works to mitigate consequences of development activities on fish populations (Rous et al. 2017). Cote et al. (1998) characterized how juvenile Atlantic cod (*Gadus morhua*) used nearshore nursery habitats by combining high precision (<1 m) monitoring of fish position with detailed habitat mapping. Such fine-scale studies (where fish are typically positioned in two dimensions using overlapping detection zones and hyperbolic navigation; see Niezgoda et al. 2002) are becoming more common and have the potential to dramatically advance our understanding of micro habitat use and habitat-specific behaviors. For example, fine-scale observations of spatial distribution and mortality provided insights to potential mechanisms of habitat preferences of juvenile Chinook salmon (*Oncorhyncus tshawytscha*; Semmens 2008). Data emanating from studies like these can be used to develop sophisticated habitat models that can feed into efforts to characterize productive capacity of habitats, often in the context of ecosystem management (Boisclair 2001).

Beyond identifying habitats that are used by fish, it is also possible to use data generated by acoustic telemetry to identify opportunities for habitat enhancement, creation, and restoration, and monitoring the success of those activities. However, only recently has acoustic telemetry been applied in that manner (reviewed in Lapointe et al. 2013). In one of the first examples, Espinoza et al. (2011*a*) examined the extent to which gray smooth-hound sharks were using a newly restored estuary in California. Acoustic telemetry data, combined with population monitoring, revealed the restored habitat provided a suitable seasonal environment for feeding and growth. Veilleux (2014) used fine-scale acoustic telemetry to compare fish use of two enhanced and two non-enhanced boat slips along the urban waterfront of Toronto, Canada. That work revealed a surprising lack of use of restored habitats, but monitoring was focused solely on adult fish so it was possible that enhanced habitats were being used by other life stages. Indeed, where possible, acoustic telemetry data should be combined with more traditional fisheries independent monitoring (e.g., netting, electrofishing, hydroacoustics) to assess the effectiveness of habitat restoration. In the future, improved knowledge of the spatial ecology of fish (at various spatial and temporal scales) should help to ensure that critical habitats are better protected and degraded habitats are more effectively restored. Conservation planning for imperiled species often focuses on habitat restoration efforts, so acoustic telemetry holds particular promise for helping to guide those efforts a priori (through better understanding of fish habitat needs) and in evaluating the effectiveness of restoration activities a posteriori.

### *Protected areas management*

Area protection or closure has become a popular management tool. In aquatic systems, this typically takes the form of zones closed to fishing activities to help maintain populations within the protected area and allow spillover of individuals to adjacent areas (e.g., Halpern 2003, Russ et al. 2015). Defining the amount of time individuals spend within protected areas is crucial to closure design and efficacy. Acoustic telemetry provides an ideal tool to define animal movement in focused regions such as protected areas (e.g., O'Dor et al. 2001, Heupel and Simpfendorfer 2005, Heupel et al. 2006, Moland et al. 2013, Lea et al. 2016). However, many protected areas are designated with little or no information about the movement patterns of species they are designated to protect (Halpern 2003). Current research suggests protected areas are likely to be highly effective for site-attached species with home ranges that are restricted to the closed area, but may be less effective for large, mobile species (McCook et al. 2010, Currey et al. 2014, Heupel et al. 2015, McLaren et al. 2015). Clearly, information on spatial ecology is crucial to determining the success of protected areas (Lea et al. 2016).

Determining the efficacy of protected areas for more mobile species is a challenging task. Thus, application of acoustic telemetry to questions about the use of protected areas is gaining popularity as it is one of the few tools that can resolve whether protected areas are large enough to adequately shelter mobile species from fishing and other pressures (Chapman et al. 2005, Ketchum et al. 2014, Espinoza et al. 2015*a, b*). Coral reefs are a common focus of protected area management and, as such, several telemetry studies have explored the efficacy of reef closures (Meyer et al. 2007*a*, Marshall et al. 2010, Pittman et al. 2014, Garcia et al. 2015, Matley et al. 2015, Lea et al. 2016). For example, Chateau and Wantiez (2009) used acoustic telemetry to examine the movement of four commercially exploited reef fish and concluded that the closed areas were not large enough to adequately protect fished species based on evidence of extensive movements outside the protected area. Meyer et al. (2007*b*) reported similar broad scale movement for green jobfish (*Aprion virescens*) in Hawaiian waters. However, acoustic telemetry has shown that some large predators use small areas and have high site fidelity over year-long periods, suggesting that protected area management can be effective for these species (e.g., Topping et al. 2006, Bellquist et al. 2008, Currey et al. 2014, Lédée et al. 2015, Matley et al. 2015).

As the examples above indicate, coral reefs have benefited greatly from closed area management. However, this tactic can benefit species in other habitats and ecosystems. For example, Moland et al. (2011) concluded that limited movements of European lobster within a marine reserve in Norway led to protection of up to 95% of tagged individuals based on acoustic tracking data. In one of the most detailed analyses, but in tropical coastal areas, not in a coral reef environment, Knip et al. (2012) used acoustic telemetry to examine the amount of time two species of coastal shark spent within a protected area. Despite similar sizes, the two shark species used the habitat differently and spent only 20–30% of their time within the protected area making numerous excursions into unprotected areas. These studies reveal that the size and scale of protected areas need to be species-specific and demonstrate the power of acoustic telemetry to define these metrics to improve management. Although acoustic telemetry provides discrete data for defining protected area use and efficacy, future challenges involve defining how localized studies can and should be applied to the broader population. It is also important to acknowledge that marine protected areas may not be capable of protecting the entire range of large, mobile predator species, and so protected area design must identify areas of critical habitat, for example, those most important to reproduction.

Perhaps equally important as identifying habitat use and level of residency within protected areas is why fish select those habitats and how they are important to life-history and population processes. Acoustic telemetry revealed the importance of Hawaiian and Caribbean atolls to the seasonal movements and spawning of giant trevally *Caranx ignobilis*, and Nassau grouper *Epinephelus striatus*, respectively, both of which aided marine protected area planning (Meyer et al. 2007*a*, Starr et al. 2007). These examples show the utility of acoustic telemetry in identifying basic aspects of a species life history, while also providing valuable information for their conservation and management.

Although acoustic telemetry is a powerful means for understanding fish movements within and around protected areas, delineating protected areas first requires longitudinal studies to measure seasonal patterns of home range size, habitat selection and utilization, and breeding/non-breeding behaviors, which may take several years to attain. The ability to more rapidly predict fish movements, and use these to predict important habitats, would be very valuable. Resource managers might therefore benefit from the development of predictive, mechanistic home-range models of the sort presently used in some terrestrial systems (Börger et al. 2008, Van Moorter et al. 2009). While certainly complicated and requiring some initial investment of time for a given fish species, once a mechanistic home-range model is developed it might be easily adapted to other related species and habitats (e.g., coral reef fish assemblages).

### *Invasive species monitoring and control*

Invasive species are a principal threat to aquatic biodiversity and economies that depend on stable ecosystems. Invasions have increased concurrently with globalization, prompting governments to develop programs to detect, prevent, and manage invasions by nonnative species (Simberloff et al. 2013). Unlike native fishes, understanding the movements and dynamics of invasive fishes can be more challenging because basic information about their life history and ecology are often lacking in the new environments that they have colonized (Simberloff 2003, Grubich and Odenkirk 2014). While attempts to eradicate some invasive fish populations have been successful (Genovesi 2005), such achievements are rare. Acoustic telemetry, however, has been used to predict and detect invasions, seek and destroy invaders, assess population structure, and evaluate harvest control rules (reviewed in Lennox et al. 2016). Furthermore, the management of most invasive populations typically involves long-term monitoring (Ruzycki et al. 2003), which can be achieved with acoustic telemetry.

Brute-force mechanical or chemical eradication of invasive species may be important for stemming the effects of early invaders (Smith and Tibbles 1980, Simberloff 2003), and acoustic telemetry has been instrumental to such efforts. For populations that aggregate, acoustic telemetry can facilitate direct removal by tracking tagged individuals to aggregations (i.e., Judas technique). Bajer et al. (2011) used acoustic and radio telemetry to track invasive common carp, *Cyprinus carpio*, to conspecific aggregations, which facilitated the removal of 52–94% of populations with seine nets. Acoustic telemetry has also been used to map the spawning locations of lake trout (*Salvelinus namaycush*) in Yellowstone Lake as a first step toward their eradication (Jason Romine, *personal communication*) and the recovery of devastated native populations of cutthroat trout (*Oncorhynchus clarkii*; Ruzycki et al. 2003). Due to their high spawning site fidelity, known spawning locations can be targeted year after year, thus increasing the likelihood of successful eradication (Binder et al. 2016). This is preferable to other means of eradication, like whole-lake poisoning or other control methods, which can have collateral effects on non-target species and on the environment (Bajer et al. 2011).

Acoustic telemetry has been used to directly assess the effects of invasive fishes on native populations. Karam et al. (2008) used acoustic telemetry and visual observation by SCUBA diving to show that mortality of native razorback sucker, *Xyrauchen texanus*, in Lake Mohave, USA, was higher than previously known and attributed losses to nonnative striped bass, *Morone saxatilis*. Romine et al. (2014) tracked acoustic-tagged native juvenile salmonids (*Oncorhynchus tshawytscha* and *O. mykiss*) and nonnative predators (*Morone saxatilis*, *Micropterus dolomieu*, and *M. punctulatus*) in the Sacramento River, USA, to identify when, where, and which salmonids were consumed.

Control strategies for invasive populations, including migration barriers, exclusion devices, and removal strategies, can be informed by acoustic telemetry data. Romine et al. (2015) showed that a water cannon could displace invasive bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*), but that more work is needed before water guns might be used to block their movement. Holbrook et al. (2014) used acoustic telemetry to show that a lock and dam in a tributary to Lake Huron, USA, blocked movement of invasive sea lamprey (*Petromyzon marinus*), suggesting that populations in inland lakes farther upstream were landlocked (Johnson et al. 2016). Holbrook et al. (2016, this issue) further showed that sea lamprey abundance may have been underestimated in the St. Mary's River, suggesting that traps and sterilization were less successful at population control than previously assumed. Bacheler et al. (2015) used acoustic telemetry to show that Indo-Pacific lionfish (*Pterois volitans*) on the continental shelf off North Carolina, USA remained in small areas (<400 m in diameter) for up to six months, suggesting that localized control efforts might be effective until new colonization occurs. The latter example is one of few where acoustic telemetry has been used to study an invasive species in the marine environment, likely a result of the scale of monitoring. Given the spatial scale of species introductions and invasions and the growing importance of effective control programs, network collaborations may be essential for supporting the scales of monitoring needed before eradications and restoration efforts can move forward.

### *Defining management units*

Fisheries management is based on the unit stock, typically considered as the individuals within a geographic region where the population is self-sustaining (Gulland 1983). Assignment of catch rates and allowable catches for fisheries requires an accurate understanding of the size of a given population or stock (Hilborn and Walters 2003). Fisheries planning is rooted in knowledge of where various life-stages (juvenile, sub-adult, and mature fish) of a species occur, animal abundance, and the location and timing of spawning. Important in sustainable harvesting is the need to define the distribution of the population in space and time.

Historically, the spatial distribution of commercially exploited species was described through a combination of mark–recapture data, acquired fishers' knowledge, and fisheries surveys. While these approaches have successfully quantified the post spawning movement rates of walleye in a lake-chain system (Herbst et al. 2015) and allowed a reassessment of the spatial stock structure of pollock (*Pollachius virens*) in Canadian Atlantic waters (Neilson et al. 2006), these data typically lack the resolution to describe movement patterns beyond a coarse level of detail. Telemetry data are actively challenging existing knowledge about animal movements that was based on traditional approaches (fisheries surveys, etc.). For example, mark–recapture of Greenland halibut in the Canadian Arctic suggested a sink population within a coastal Sound and led to the establishment of a management line dividing a community based winter fishery from the offshore fisheries allocation (Treble 2003). In contrast, recent telemetry tracking of this species revealed a seasonal migration of the proposed sink population within the entire Sound, resulting in different fisheries harvesting the same stock (Hussey et al. 2017, this issue). These data led to the conditional relocation of the fisheries management line with resultant benefits for the local aboriginal community. Telemetry has also revealed large-scale migration patterns of walleye (*Sander vitreus*), where fish were found to use most of the U.S. nearshore waters of Lake Huron (Hayden et al. 2014). These tracking data revealed connectivity between Saginaw Bay and Lake Huron populations, indicating a need for stock-specific spatial management.

While acoustic telemetry is limited to detecting fish that are within range of a receiver, the use of gliders, autonomous vehicles, mobile receivers attached to platforms of opportunity (for example oceanographic moorings, fish aggregating devices [FADs], and even larger animals; Holland et al. 2009, Lidgard et al. 2012, Govinden et al. 2013, Hayes et al. 2013, Haulsee et al. 2015) in conjunction with fixed arrays, provide opportunities to monitor fish at the scales required for fisheries planning. The option to incorporate strategic "wandering" receivers, whereby receivers are randomly placed within a management area for short time periods and repositioned on multiple occasions will provide spatial detection data over a much larger range than a fixed array alone. Powerful statistical models that incorporate detection uncertainty coupled with habitat and environmental data could then be used to create predictive spatial maps of occurrence outside of the fixed array.

In the context of an ecosystem management approach, telemetry can describe the distribution and movements of bycatch species of concern in addition to those of commercial interest (Huff et al. 2011). Ecosystem management requires detailed knowledge on a species' transboundary movements (Heenan et al. 2015). Fisheries boundaries are often framed around jurisdictional borders (Haliday and Pinhorn 1990) that have no relation to the population structure of exploited species and that neglect the connectivity of aquatic environments. Telemetry data could be used to inform a hierarchy of fisheries boundaries that account for fisheries impacts on target and non-target species (e.g., Heupel et al. 2015).

Incorporating genetic or genomic approaches to telemetry studies will provide managers with the sorts of data that can bolster the delineation of management boundaries and preserve genetic diversity (Christiansen et al. 2015, Stewart et al. 2016), while chemical tracers like stable isotopes and trace elements can provide a means for determining site fidelities to areas critical to different life-history stages (juvenile rearing, reproduction, etc.; Bergstad et al. 2008, Honda et al. 2012, Matich and Heithaus 2014, Papastamatiou et al. 2015). Linking traditional tag recapture data sets with telemetry will improve our understanding of species movements relative to management areas (Holbrook et al. 2014, Raabe et al. 2014), while also allowing estimation of population demographics such as survivorship and population size (Dudgeon et al. 2015).

Recognizing the dynamic nature of aquatic animal behavior and movements with respect to the effects of climate change and ocean acidification, approaches that embrace resilience are among the next step for fisheries planning. With the growth of big data available on a diverse range of species, telemetry will be key to developing flexible management approaches that account for (and predict) shifting distributions of species over time. Global and regional networks such as those listed above will be critical for strategically placing and coordinating infrastructure and tagging efforts to generate the required data to feed in to this management approach.

### *Fisheries interactions*

The unintentional fishing-induced mortality (e.g., juveniles, or other individuals outside of pre-established fish size or seasonal restrictions) of a commercially important target species can impede the sustainability of fisheries (e.g., Broadhurst et al. 2006, 2008). Furthermore, bycatch mortalities can create conservation crises in non-exploited species (e.g., Lewison et al. 2004). Many notable conservation problems have arisen from the latter, which often involve charismatic megafauna with *K*-selected life histories (e.g., seabirds, marine mammals, sea turtles, elasmobranchs, etc.) and low tolerance to fisheries capture stress (Gales et al. 1998, Dulvy et al. 2008). Reducing or managing this problem can be achieved by avoiding non-target species through spatial or temporal changes to fishing effort or by decreasing rates at which they are landed (i.e., through increased selectivity of the fishing gear). Alternatively, changes to fishing gear that minimize immediate or delayed mortality can be made. There are two ways in which acoustic telemetry has been used to inform efforts to employ these tactics: (1) identify places or times to avoid fishing in order to reduce encounter rates (James et al. 2005) and (2) provide estimates of post-release mortality (Bettoli and Osborne 1998). Explicit examples of the former are uncommon because the same information can often be gleaned from existing data sets generated by at-sea observers (Watson et al. 2009). However, there are some ways in which telemetry data could provide a unique contribution. For example, tracking both commercially fished tunas and bycatch species including silky sharks (*Carcharhinus falciformis*), oceanic triggerfish (*Canthidermis maculata*), and rainbow runner (*Elagatis bipinnulata*) at drifting FADs in the western Indian Ocean revealed distinct diel association patterns (Forget et al. 2015). Similarly, data on vertical movements of non-target species could be used to direct fisheries away from the depths/times at which aggregations of those species occur without causing those fisheries to have to relocate (i.e., relocate in the vertical/temporal dimensions rather than the horizontal dimension; Hussey et al. 2015, Bergstedt et al. 2016). The use of acoustic telemetry to provide estimates of post-release mortality can be done in such a way that identifies ways of reducing mortality, such as through altered fishing or release techniques (e.g., Bettinger et al. 2005). Post-release mortality estimates can also be incorporated into management models to better account for the total mortality caused by fishing (Raby et al. 2015*a*).

The method most commonly used to assess post-release mortality, especially in commercial fisheries, has been through confinement, where fish are held in tanks or net pens for some period after exposure to a capture-stressor. Confinement (i.e., net pen studies) has its strengths as a method for monitoring mortality, one of which is that the fate of each animal can be verified. However, it can be argued that recovery and survival in confinement may be very different from that in the natural environment (Donaldson et al. 2008). A small number of published studies exist in which the recovery and survival of post-captured marine fishes were compared in confinement (e.g., holding pens) vs. in the wild (using acoustic telemetry; Yergey et al. 2012, Raby et al. 2015*b*, this issue). Yergey et al. (2012) estimated the post-release survival rate for summer flounder released from a commercial trawl fishery, concluding that post-release survival rates decreased with decreasing at-release vitality, and that the total (on board + post-release) mortality rate (81%) was similar to a previous estimate based on net pen confinement (79%). They also concluded that most mortality occurred after release and would therefore be otherwise unseen. Raby et al. (2015*b*, this issue) used externally attached acoustic transmitters to monitor coho salmon after release from a commercial purse seine, and found that time-specific mortality was lower in acoustically tracked fish released back to the wild than in fish held simultaneously in a net pen. In such species (i.e., those where confinement stress causes problems; e.g., Pacific salmon) telemetry-tracking should be capable of yielding more accurate mortality estimates (Donaldson et al. 2011, Raby et al. 2015*b*, this issue).

Acoustic telemetry has occasionally been used to provide information about catch-and-release recreational angling that can be directly used by managers. For example, Lee and Bergersen (1996) manually tracked lake trout (*Salvelinus namaycush*) equipped with depth-sensing acoustic transmitters to determine that post-release mortality was exceedingly high (88%) in a recreational fishery in late summer when oxygen and temperature profiles of the lake were prohibitive of physiological recovery. That finding led to the suggestion that the (then current) management regime of enforcing slot limits (i.e., regulations that require release of fish outside a size range) would likely lead to high levels of unaccounted mortality, compromising the effectiveness of that management tactic. This has also been suggested for deepwater reef fish that are caught by hook and line, experience barotrauma, and then are released (Lowe et al. 2009). Because of the need to return these fish to depth, they are often vented or released with a descending device, but it can be difficult to determine survivorship.

Even with the decreasing size of acoustic transmitters and reducing costs, challenges remain to using acoustic telemetry to assess post-release mortality in the open marine environment, particularly with commercial fisheries. One means for effectively monitoring the post-release survival of acoustically tagged fishes is through the use of a large-scale grid receiver array at the point of release (Donaldson et al. 2012). For instance, Capizzano et al. (2016) assessed post-release survival in recreationally caught Atlantic cod (*Gadus morhua*) by rapidly attaching external depth-sensing transmitters to fish prior to releasing them into a grid of acoustic receivers. In some rare cases, it may even be possible to catch-and-release animals that are already acoustically tagged and at liberty in an area with an acoustic receiver array (Ferter et al. 2015). However, the approach of releasing fish into a grid array of receivers may not be suitable in areas where benthic fisheries occur (e.g., bottom trawls, otter trawls, etc.), as various gear types could disrupt of damage fixed array moorings. Alternatively manual tracking may provide an alternate approach in such situations, although this can at times limit the number of fishes that can feasibly be tracked, as well as the duration of monitoring periods (e.g., <24 h; Pepperell and Davis 1999, Sackett et al. 2008).

Ultimately, the ability to effectively assess post-release survival and inform management actions will likely require the use of additional sensors in combination with standard acoustic telemetry. For example, in some cases it may not be possible to determine whether the post-release movements of a fish are its own movements or those of a predator that ate the tagged fish and now carry it in its stomach (Yergey et al. 2012, but see Romine et al. 2014). Adding depth or acceleration sensors to acoustic transmitters makes it vastly easier to differentiate between these scenarios (Donaldson et al. 2008), while statistical approaches are also being successfully developed to address this point (Romine et al. 2014). Additional sensors add cost however, which may be why so few post-release survival assessments have used this approach. Nonetheless, this is a common practice in assessing the survival of released deepwater reef fish (Curtis et al. 2015). In addition, we should be clear that in some cases there are better or more efficient alternatives to acoustic telemetry for informing efforts to mitigate fisheries interactions. For instance, satellite telemetry can be a superior method for monitoring post-release survival when available (e.g., Stokesbury et al. 2011) because it enables monitoring of movements at a large spatial scale without the requirement of an underwater network of receivers. However, the use of satellite telemetry has heretofore been limited primarily to marine megafauna (sharks, tunas, marine mammals, etc.). Acoustic telemetry may remain a better option for some studies, especially of small species as acoustic tags are very small and can be as low as 1 g, and in studies where tag retention is important, as in long-term, longitudinal studies. Surgical implantation also allows tags to be retained indefinitely, whereas externally mounted satellite tags are often lost in weeks to months after attachment.

### *Stock assessment: mortality, timing, environmental correlates*

Stock assessment models are used to estimate stock size and biological reference points, with model output providing scientific advice to management (Cadrin and Dickey-Collas 2014, Punt et al. 2015). Life history data used in traditional stock assessment models includes (1) information on population structure to define the stock unit; (2) an estimate of reproductive potential, with spawning stock biomass (SSB) commonly used as a proxy, estimated using the population sex ratio, proportion mature-at-age, mean mass at age, and population abundance; and (3) natural mortality estimates. Other assessment inputs may include estimates of fisheries selectivity and catchability used as indices to tune the abundance estimates based on landings. Traditionally, age-based stock assessment models have assumed all SSB is equally productive, i.e., no significant demographic effects or interactions with other species. However, there has been substantial progress in the field of fisheries stock assessment, increased awareness of a need for better spatial assessments (Quinn 2003), and management strategy evaluations used to assess a range of complex ecological processes and how they may affect our ability to effectively manage fish stocks (Punt et al. 2015).

Data sources for stock assessments are typically based on landings, capture-based sampling, and conventional tag–recapture studies. However, acoustic telemetry is increasingly being used to estimate stock assessment parameters (Sippel et al. 2015). Stock structure has been studied with acoustic telemetry in many species, but especially those which are diadromous. For example, striped bass (*Morone saxatilis*) have been shown to occur seasonally in Massachusetts coastal waters as part of the coastal migratory stock originating from the Chesapeake Bay, Delaware River, and Hudson River spawning stocks (Kneebone et al. 2014). Similarly, Roanoke River striped bass exhibit spawning site fidelity, but outside of the spawning season migrate >1000 km along the eastern Atlantic coast where they are targeted by a mixed-stock fishery (Callihan et al. 2015). Acoustic telemetry can also be used to evaluate stock structure, and is changing theory about the commonality of open populations in marine fishes (Cowen and Sponaugle 2009). Atlantic cod provide a good example, where acoustic telemetry has identified spawning site fidelities and presumed natal homing (Green and Wroblewski 2000, Robichaud and Rose 2001, Svedäng et al. 2007, Zemeckis et al. 2014). Similarly, the common snook (*Centropomus undecimalis*) has also been shown to exhibit strong spawning site fidelity (Lowerre-Barbieri et al. 2014, Young et al. 2014).

Acoustic telemetry studies are also helping to inform both traditional measures of reproductive potential, such as SSB and fecundity, and emerging measures, such as spawning site selection and reproductive timing (Maunder and Deriso 2013). Sexual maturation data are needed to estimate SSB and the parameter most closely tied to fitness (Stearns 1992). Maturation is typically associated with ontogenetic habitat use shifts, which may affect our ability to estimate it (Gillanders et al. 2003). Lowerre-Barbieri et al. (2016, this issue) show that when telemetry is used in conjunction with biological sampling to assess reproductive state, location may be a better indicator of fish that are functionally mature (i.e., are part of the spawning population) than size. Similarly, an estimate of the population sex ratio is needed to calculate female spawning biomass and acoustic telemetry studies can help us understand sexual differences in movements during the reproductive period and how these movements affect our ability to generate a representative sample of sex ratios using fisheries surveys. Sex-specific behavior on the spawning grounds and individual turnover in spawning aggregations have been documented using telemetry in spotted seatrout (*Cynoscion nebulosus*; Callihan et al. 2013, Lowerre-Barbieri et al. 2013), shoemaker spinefoot (*Siganus sutor*; Bijoux et al. 2013), common snook (Lowerre-Barbieri et al. 2014, Young et al. 2014), and Gulf sturgeon (*Acipenser oxyrinchus desotoi*; Fox et al. 2000). These patterns have important implications for estimates of annual fecundity in marine species with indeterminate fecundity. Spawning fractions are used to estimate spawning frequency in these species (Hunter and Macewicz 1985) and annual fecundity is the product of spawning frequency and batch fecundity. Spawning fractions are estimated at the population scale (Hunter and Macewicz 1985, Lowerre-Barbieri et al. 2011, Uriarte et al. 2012), with the assumption of no immigration or emigration from the sampled areas (Hunter and Macewicz 1985). If spawning aggregations are constant, but there is high individual turn-over within the aggregation, traditional methods to estimate this important parameter will result in overestimated annual fecundity (Lowerre-Barbieri et al. 2013). Similarly, acoustic telemetry can be used to assess if individuals in a population move to the spawning grounds each year, i.e., spawn annually, which is a common assumption, or if there is skip spawning such as seen in striped bass (Gahagan et al. 2015) and common snook (Trotter et al. 2012). Reproductive behavior and movement patterns also affect fisheries selectivity and acoustic telemetry is helping decouple patterns seen in captured fish vs. natural behavior that impacts catchablity (Nielsen and Berg 2014, Villegas-Ríos et al. 2014), and productivity (Goethel et al. 2011, 2014). When considering the reproductive and movement patterns of fish populations relative to exploitation and protected area designation, it is also important to understand and document the extent of partial migration within a population (Secor 1999), e.g., the proportion of a population that remains resident vs. migratory). The conservation value of understanding this phenomenon in fish has been discussed (Chapman et al. 2012*a, b*, Gahagan et al. 2015), and several studies have characterized the factors that differentiate migrants from residents (of which reproduction is one factor [see references in Chapman et al. 2012*b*, Papastamatiou et al. 2013]). Acoustic telemetry has the potential to identify the relative proportion of a fish stock that remain resident vs. migrate, and provide clues as to why it might do so (e.g., Espinoza et al. 2016). When attempting to manage populations that undertake cross-jurisdictional movements, it is important to know timing of these events, and the spatial scales over which they occur.

Natural mortality estimates play a foundational role in stock assessment models. However, this parameter is especially difficult to assess in fish, given that it is typically unobservable (Quinn and Deriso 1999). Through acoustic tracking, there is a metric to identify dead individuals and this method has been used successfully in multiple species and systems (e.g., Hightower et al. 2001, Heupel and Simpfendorfer 2002, Bacheler et al. 2009, Friedl et al. 2013). It is apparent that acoustic telemetry is beginning to be a trusted tool in the stock assessment toolbox (Cooke et al. 2016*b*) and will undoubtedly become even more common as resource management agencies begin to incorporate acoustic telemetry into their routine stock assessments.

## Challenges with Operationalizing Telemetry Data to Inform Management and Conservation

Emerging from the papers published in this special issue along with our collective experience with acoustic telemetry for the study of wild fish, we identify and discuss three challenges to using acoustic telemetry data to inform management and conservation. We acknowledge that some of these challenges may be interconnected, and that none are wholly unique to acoustic telemetry but still presents a significant challenge to enhancing the use of telemetry in fisheries management. Moreover, this list is not exhaustive in that other unique, location-specific challenges can exist, often related to differences in governance structures, institutional capacities (for research and management), and stakeholder dynamics.

### *Challenges associated with the limitations of the science and technology of telemetry*

*Failure to be relevant (scale, research questions, data).*— If science is to be relevant to fisheries managers, carefully tailored hypotheses, with testable predictions that address management questions, must be formulated (Cumming et al. 2006, Reed et al. 2014). Special consideration should also be given to sample sizes, for the reality is that project budgets, animal care permissions, and/or accessibility to study sites will often limit the number of fish that are tagged. In addition, the battery life of an acoustic tag can dictate the longevity of the animal track, which may reduce its relevance at the management scale. These limitations question the relevance of results, as low statistical power and/or limited temporal and spatial coverage make extrapolation to population- or species-level processes complicated (Hebblewhite and Haydon 2010). A lack of standardization across telemetry studies also makes it difficult for managers to generalize among species and across spatiotemporal scales. However, many new analytical and statistical techniques have and are being developed for the analysis of movement data, and these hold great promise (e.g., state-space models, network analysis). Such tools, for example, combined with large tag–recapture data sets and fisheries survey data will be useful for making population level predictions from relatively small numbers of tagged animals (e.g., stochastic models).

*Failure to address biases and recognize the limitations.*— Study biases introduced because of the limitations of scientific and technological capabilities can be challenging to address, which may increase uncertainty and question the reliability of telemetry data and associated findings (Payne et al. 2010, Kessel et al. 2013). For instance, individual animals need to be captured, handled, and implanted (external or internally) with an electronic transmitter, which raises the question of tagging effects and selection bias based on capture methods (Cooke et al. 2013). Do individuals fitted with an electronic tag behave the same as those that have not been "tampered" with (Brown et al. 2011)? Also important is the fact that detection of tagged fish depends on receiver location, as well as detection range and efficiency. In circumstances of reduced range as a result of environmental or anthropogenic influence, a tagged animal may be in proximity of a receiver but not detected and variable range can occur over daily, monthly, and annual cycles (Udyawer et al. 2013). Failure to understand the detection range of receivers can compromise application and interpretation of movement and behavior of tagged animals (Kessel et al. 2013). Furthermore, array design dictates the detections of animals and the resolution of the collected data (Heupel et al. 2006). When animals are not detected, it is uncertain where the animal is and what it is doing, potentially creating biases and uncertainties in the data and findings, which may lead to delays or inertia in applying telemetry data to management frameworks. As such, the nuances of telemetry are sometimes poorly understood by managers and/or not fully disclosed by researchers, undermining the uptake of telemetry findings.

*Failure to be transparent about complexity and biases in acoustic telemetry studies.*—Alluded to above, acoustic telemetry research can be complex from its design to its data generation and data interpretation; thus, it is critical for researchers to be honest and transparent about the entire process when working with management. For example, errors can occur during the transmission of acoustic signals and false-positive records can be recorded when ambient noise or transmissions from multiple fish collide to produce either an unknown ID code or result in a known ID code of a tagged fish in the system (Simpfendorfer et al. 2010). This may introduce erroneous detections and lead to inaccurate conclusions if not recognized. Other protocols to ensure transparency and validity of results include assessment of detection efficiency and receiver performance, validation of tag retention and reliability, and using appropriate capture and attachment methods. Furthermore, some acoustic tags can be heard by certain predators (e.g., seals); in these cases the acoustic signals' interaction with its environment can cause problems and heighten the skepticism of its use (Stansbury et al. 2015). Lastly, as in any scientific endeavor, researchers using acoustic telemetry should to strive for clarity and complete transparency in their processing, analyses, and interpretation of data, such as the calculation of the fate of fish, and accuracy and precision of animal positioning algorithms.

### *Challenges associated with institutions*

*Naïve knowledge receptor community.*—Telemetry data may reveal novel insights that do not fit into traditional management frameworks and may appear incompatible with existing data. The hurdles to incorporating this novel information vary across institutions and may include bureaucracy, logistical constraints, institutional inflexibility, and/or inertia, and lack of capacity and knowledge to incorporate such data (Roux et al. 2006, Cvitanovic et al. 2015, Young et al. 2016*a*). Because acoustic telemetry is still considered an emerging technology, few fisheries managers are trained to understand and use telemetry as a tool and/or as a source of information. This problem will inevitably decrease over time. However, in the meantime, the reality of a relatively naïve knowledge–receptor community presents a challenge in using telemetry data in management and conservation, and is evidence for a greater need of meaningful knowledge exchange between telemetry researchers and managers related to the use of acoustic telemetry in fisheries management (Reed et al. 2014).

*Established institutional structures and cultures.*—When institutional structures and cultures are developed and established, individuals carry similar values and attitudes, limiting change and often leading to institutional inertia, which may present a barrier for new innovations or new knowledge (Hannan and Freeman 1984, Scheffer et al. 2003, Young et al. 2013). Homogeneous institutions and cultures with strong peer control often remain locked in inaction until problems with urgency arise, and when the collective opinion starts shifting (Scheffer et al. 2003). In the context of fisheries management, long-established management protocols and strategies (e.g., stock assessment) will often remain unchanged if there is institutional inertia and tendencies of "path dependence" (i.e., inability to change paths because of an attachment to historical ways), in spite of new, up-to-date, and contradictory evidence (e.g., Munck af Rosenschöld et al. 2014). The lack of formal policies and mechanisms in current management systems to incorporate new science, coupled with the incentive structures for research scientists (e.g., the "publish or perish" paradigm), contributes to the status quo, and presents a challenge for engaging scientists and managers.

Although these challenges are not specific to telemetry, they exist and present significant challenges, particularly when new knowledge or updated knowledge is presented. These areas of concern all point toward a need, and a growing tendency, of biologists and fisheries managers to collaborate with researchers from other disciplines (e.g., social sciences, psychology, economics, etc.) in order to provide the broader socioeconomic context that is so often needed when drafting new policies and/or laws regarding fish conservation and management.

### *Challenges associated with social constructs and the human dimension*

*Game theory: motivation of players involved.*—For scientific findings to be integrated into management, there has to be motivation to do so (Brown and Reingen 1987, Cleaver 2000). The motives of the different "players" involved in the adoption of telemetry data into management actions play a large role in how influential telemetry data can be. Here, the players can include: telemetry researchers, and whether they are motivated to seek collaborations and push for their findings to be used; managers and decision-makers, and whether they are motivated to take time and effort to learn about telemetry, incorporate new knowledge, or potentially "rock the boat"; stakeholder, user, and interest groups, and what their motivations are relative to information revealed by telemetry and how it aligns with their values and interests. Game theory has been used to illustrate cooperation or resistance among individual players, and how conflicting interests and/or motivations may play out (Acheson 1975, Alxelrod 1984, Ostrom et al. 1994, Honneland 1999). The challenge is navigating the motivations and interests of all players involved and affected by the management issue, which might be mitigated by building trust and relationships. Unfortunately, when there is lack of motivation from the players involved in the operationalization of telemetry to integrate data into management actions, a barrier to its application is built.

*Failure to invest in relationships and collaborations.*— Similar to the promotion of public involvement and participation in governance processes, the same idea and concept can be applied to the research process, with the idea that active participants feel accountable with some ownership of the outcomes (Bouwen and Tailleiu 2004, Phillipson et al. 2012). Involving managers and other interested parties in the development of the objectives, research questions, and design of telemetry studies can go a long way (Reed et al. 2014). It not only ensures that the research is relevant and applicable to management, but also legitimizes findings by empowering everyone involved and potentially influencing individual motivations from being disinterested in new knowledge to being partly responsible for the knowledge generated. Knowledge produced that is relevant to a user will be judged for its legitimacy, credibility, and/or reliability, because it will affect stakeholders (Cook et al. 2013, Young et al. 2016*a*). Thus, investing in relationships, trust, and reciprocity among participants can foster cooperation and positive collaborations, and reduce skepticism (Ostrom 1998, 2003). Fisheries management and other aquatic conservation issues are often interdisciplinary in nature and require the exchange of different perspectives and knowledge (Dick et al. 2016). Failure to address complexity and knowledge gaps by failing to collaborate and exchange knowledge is a challenge to gaining meaningful impacts from telemetry research (Reed et al. 2014). Building relationships also facilitates a network into which telemetry knowledge can enter (Phelps et al. 2012). Decision makers and managers often rely on their individual experiences and are unaware of the full breadth of existing science that are potentially relevant to inform their decision making (Cvitanovic et al. 2014). Telemetry scientists that invest in building a social network of both scientists and non-scientists are more likely to have their work discussed (i.e., word of mouth), increase their reputation and become a go-to source when expertise is required (regardless of the level of their expertise relative to peers); which ultimately may result in their research findings being sought out and used by the knowledge receptor community (Brown and Reingen 1987, Decker and Krueger 1999, Cvitanovic et al. 2015, Young et al. 2016*b*). Failure to recognize the value of relationships and their connection to the transfer of knowledge can hinder or delay the operationalization of telemetry knowledge in fisheries management and conservation.

*Fear of sharing.*—Sharing of acoustic telemetry detection data among research groups operating in connected aquatic environments can help answer complex ecological and management questions because of what effectively becomes a spatially receiver network (Cooke et al. 2011, Hussey et al. 2015, Stewart et al. 2016). However, fear and concerns of sharing telemetry data among the scientific community exist (Nelson 2009) that can range from: potential violation of property or ownership rights, sharing authorship, fear of loss of control over unpublished data, lack of recognition of effort and the time required to collect the data and make it available, or misinterpretation or exploitation of the data (Janssen et al. 2012). The technical complexities related to acoustic telemetry, such as detection efficiency, missing individuals, and array design (mentioned above) are potentially factors that can also drive reluctance of telemetry researchers to share their data. As a result, researchers may miss opportunities to contribute to answering management questions and to potentially address management needs.

## The Special Issue and Future Directions

We have assembled six case studies in this special issue to illustrate the increasing utility of acoustic telemetry in the refinement of fisheries management. Espinoza et al. (2015*a, b*) discerned the movement and connectivity patterns of sharks among multiple protected areas within a coral reef ecosystem and applied their findings via network analyses to the design of effective marine protected area planning. On a broader scale, Hussey et al. (2017, this issue) used acoustic telemetry in a deep-water polar environment in conjunction with Inuit community fisheries data to refine the management boundaries encompassing stocks of seasonally migrating Greenland halibut in the Canadian Arctic. Holbrook et al. (2016, this issue) tracked the movements of invasive sea lamprey in the Great Lakes ecosystem, which are responsible for the extirpation of many native fishes, and evaluated the performance of lamprey traps as a means for their eventual removal and ecological mitigation. Raby et al. (2015*b*) applied an experimental approach to examine the effect of fisheries bycatch on the behavior and survival of migrating coho salmon. Their results show that while net-pen holding can allow researchers to assess the mortality rates of bycatch, it is difficult to disentangle this from the stress of confinement; salmon captured and released with acoustic tags without being held in net-pens had higher survival. In a study of juvenile salmon, Clark et al. (2016, this issue) reveal natural patterns of variation in the survival of migrating sockeye salmon smolts, which is useful for informing population models at this critical life-history stage when mortality is naturally high. Finally, Lowerre-Barbieri et al. (2016, this issue) used acoustic telemetry coupled with biological sampling and aerial surveys to assess how reproductive behavior affects stock structure, specifically assessing spawning site selection, fidelity, and natal homing.

Acoustic telemetry is proving itself as a powerful means for guiding fisheries planning and management, and its integration with other disciplines and approaches will continue to inform our knowledge about the complexities of fish population dynamics, interactions, and responses to anthropogenic and natural stressors. Although this is a rapidly advancing field, challenges exist, which is unsurprising given that many acoustic telemetry studies are attempting to monitor the movements of individuals and populations across ever-increasing temporal, life history, and spatial scales (movements of anadromous fishes; ocean-basin-wide migrations, etc.). Ultimately, the sharing of acoustic detection data among research teams, and close partnerships with resource managers and stakeholders (throughout the research process), are likely to be two keys to maximizing the potential for acoustic telemetry to address management and conservation problems. Thus far, the few instances in which acoustic telemetry has been used to directly address fisheries management questions have involved case-specific acoustic arrays designed to address one or two locally important questions. However, this is poised to change with acoustic telemetry becoming an important component of the assessment-management cycle. Centralizing these efforts through a network approach, where infrastructure maintenance, data warehousing, and data sharing maximize collaborative links and cost-effectiveness, is an important step forward (Cooke et al. 2011). Examples of this can be found in international initiatives like the Ocean Tracking Network and the Great Lakes Acoustic Telemetry Observation System, which foster multi-agency collaborations and emphasize the importance of making acoustic telemetry research relevant to fisheries management.

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