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Contribution to the Themed Section: '*Plugging spatial ecology into sustainable fisheries and EBM*'

Quo Vadimus

The ocean's movescape: fisheries management in the bio-logging decade (2018–2028)

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Although movement has always played an important role in fisheries science, movement patterns are changing with changing ocean conditions. This affects availability to capture, the spatial scale of needed governance, and our food supply. Technological advances make it possible to track marine fish (and fishermen) in ways not previously possible and tracking data is expected to grow exponentially over the next ten years – the bio-logging decade. In this article, we identify fisheries management data needs that tracking data can help fill, ranging from: improved estimates of natural mortality and abundance to providing the basis for short-term fisheries closures (i.e. dynamic closures) and conservation of biodiversity hot-spots and migratory corridors. However, the sheer size of the oceans, lack of GPS capability, and aspects of marine fish life history traits (e.g., adult/offspring size ratios, high mortality rates) create challenges to obtaining this data. We address these challenges and forecast how they will be met in the next 10 years through increased use of drones and sensor networks, decreasing tag size with increased sensor capacity trends, the ICARUS initiative to increase satellite tracking capacity, and improved connectivity between marine and terrestrial movement researchers and databases.

Keywords: Keywords: bio-logging, fisheries, ICARUS, movement ecology, telemetry, tracking.

Introduction

Fisheries science has long acknowledged the importance of movement (Moulton, 1939; Harden Jones, 1968) but has not yet integrated advances in tracking technology and ecological theory regarding movement processes into fisheries management (Secor, 2015; Allen and Singh, 2016; Crossin *et al.*, 2017). The movement ecology paradigm (Nathan, 2008) defines an individual's movement as a function of internal state, motion and navigation capacity, and external factors. By focussing on individual lifetime tracks, it links movement with fitness and builds the conceptual foundation for movement patterns to be considered part of an animal's life history. However, this needs to be contextualized within temporal and biological scales to identify key processes important to conservation and fisheries management (Table 1). Short-term movements are associated with feeding and breeding events and drive real-time encounter rates between individuals

Table 1. Temporal and biological scales at which key processes and movements occur–important to conservation and fisheries management.

Temporal scale		Biological scale	
Process		Population	Individual
Evolutionary	Physiological environmental constraints	Distribution and movement attributes	Fisheries-induced evolution
Trans-generational	Reproductive success	Sources and sinks; stock structure; phenological impacts of climate change	Spawning site selection effect on fitness
Life time	Spatial distribution of the life cycle	Essential habitat needs and connectivity	Lifetime track
Annual	Migratory cycles for feeding and breeding	Spawning aggregation hot spots; migratory corridors	Mobility and mortality linkages
Diel	Feeding and breeding events	Inter- and intra-specific encounter rates	Bold versus timid personality

and species. But annual migratory patterns and the spatial distribution of the life cycle drive the larger patterns within which these occur and affect a population's vulnerability to fishing and habitat degradation. Reproductive success drives population stock structure and phenology, with selection over evolutionary time scales determining an animal's physiological environmental constraints (Rangel *et al.*, 2018), movement attributes, and thus population distributions. Because fitness occurs at the individual scale, and animals exhibit movement-related syndromes (Spiegel *et al.*, 2017), fishing mortality can select for particular movement attributes (Andersen *et al.*, 2018; Tillotson and Quinn, 2018).

Given that seafood is an essential source of protein for billions of people (https://www.worldwildlife.org/industries/sustainable-seafood) and that marine fish movements affect availability to surveys and fisheries, the spatial scale of needed governance, and our food supply (Pinsky *et al.*, 2018), the ability to understand and predict fish movements has great application to fisheries management and marine conservation (McGowan *et al.*, 2017). Many methods are used to study fish spatial ecology and movements, including: catch per unit effort with location (Thorson *et al.*, 2016), traditional dart tag/recapture studies (e.g. Hanselman *et al.*, 2015), soundscapes (Walters *et al.*, 2009), chemical signatures in otoliths and other body parts (Tzadik *et al.*, 2017), and genetics—as a "tag" (Miller *et al.*, 2015; Lowerre-Barbieri *et al.*, 2018) and to assess connectivity (Dalongeville *et al.*, 2019) and stock structure (Whitlock *et al.*, 2017). However, bio-logging—which is the focus of this article and which we use interchangeably with electronic tracking—is the only method which tracks individual movements, behaviour and physiology over time in an animal's natural environment (Hays *et al.*, 2016). The next 10 years has been called the "bio-logging decade," when it is expected that cheaper, smaller, more accurate tags with greater data collecting capacity will result in an exponential increase in movement data (Hussey *et al.*, 2015; Kays *et al.*, 2015) predicted to change our capacity to understand ecology (Wilmers *et al.*, 2015; Allan *et al.*, 2018) and result in new theories and management tools.

Tens of thousands of animals of many species have been or are being electronically tracked and increasingly studies integrate tracks with physiological parameters, genetics, habitat, and environmental data to assess movement drivers (Wilmers *et al.*, 2015). This movement data is being synthesized into global databases, such as Movebank (www.movebank.org), the Ocean Tracking Network (OTN, oceantrackingnetwork.org), and the Global Registry of Migratory Species (GROMS, http://www.groms.de/). Tracking data at this movescape scale (https://youtu.be/TG4eCWkdyQY) can greatly expand how we understand life processes. Similar to the role the microscope played in allowing us to understand life at scales smaller than humanly possible, global movement data of multiple species provides insights into processes too large to be observed unaugmented, but critical to understanding and maintaining ecosystem functionality (Hussey *et al.*, 2015; Kays *et al.*, 2015), and assessing how a species' movement ecology may affect its ability to survive and thrive in the Anthropocene (Flack *et al.*, 2016; Hardesty-Moore *et al.*, 2018; Tucker *et al.*, 2018).

In this article, we identify movement data needed to inform fisheries management, review current challenges and capacity to meet these data needs, and forecast technological advances expected within the bio-logging decade. To do so, we bring together authors who study and model fish, fish movements, and participate in stock assessments, as well as terrestrial movement ecologists and leaders in the ICARUS (International Cooperation for Animal Research Using Space) initiative and the Movebank animal tracking database (as discussed in detail below).

Fisheries management and movement—data needs

Management objectives are shifting from maximizing single species sustainable yields to understanding the role fisheries play in marine ecosystems and protecting ocean health (Halpern *et al.*, 2015; Dolan *et al.*, 2016). Because movement determines where a fish is in space and time it affects all levels of fisheries management, from traditional single species stock assessments to ecosystem-based approaches (Table 2). For example, the 2017 assessment of the Walleye Pollock Fishery in the eastern Bering Sea, the largest US fishery by volume (Thorson *et al.*, 2017) was complicated by a rapid shift in distribution from the well-sampled eastern Bering Sea into the rarely sampled northern Bering Sea (Jim Ianelli, pers. comm.). These movement-based complications are expected to increase in the future. However, research on spatial processes and their effect on management are less common in the marine realm than in the terrestrial. An indicator of this is the large number of publications on landscape ecology (Figure 1) compared with seascape ecology and ocean connectivity (Hidalgo *et al.*, 2016; Rooker *et al.*, 2018). In contrast, marine spatial planning and the use of marine-protected areas (MPAs) are rapidly increasing as a means to assess trade-offs and manage ocean use with increased industrialization. This, and improved tracking capacity, are fuelling more fish telemetry studies, concurrent with increasing research on movement ecology in general. In turn, increased fish tracking data is helping shape new

Table 2. Fishery management level and definition (adapted from Dolan *et al.*, 2016).Level of fisheries management, their definitions, conceptual framework, and key movements which affect assessment or management objectives at each level.

Management levels	Definition	Conceptual framework	Movement
Single species	Stock assessments produce biological reference points (BRPs); typically some proxy of maximum sustainable yield (MSY) for individual fish stocks. MSY-related BRPs are usually calculated with facets of biomass and fishing rate, from which decisions for suitable management are made	Yield, productivity is density-dependent driven	Vertical and horizontal movement affects stock structure and the probability of capture and thus estimates of abundance and yield
Ecosystem approach to fisheries	Inclusion of ecosystem factors into a (typically single species) stock focus to enhance our understanding of fishery dynamics and to better inform stock-focussed management decisions	Yield, recognizing additional factors affect productivity	Life track effects on productivity: spawning site selection; connectivity. Life tracks can be affected by external factors (i.e. temperature), changing internal factors (epigenetics and genetics), and changes in navigation or motion capacity
Ecosystem-based fisheries management	Recognizes the combined physical, biological, economic, and social trade-offs for managing the fisheries sector as an integrated system, specifically addresses competing objectives and cumulative impacts to optimize the yields of all fisheries in an ecosystem	Fishing one stock affects others and the ecosystem	Multi-species movements affect probability of by-catch and predation, ecological hot spots and migratory pathways, relatively easily-tracked species can be used as indicators of movement in more cryptic species they are associated with
Ecosystem-based management	A multi-sectored approach to management, accounting for interdependent components of ecosystems, and the fundamental importance of ecosystem structure and functioning in providing humans with a broad range of ecosystem services	Ocean health depends on ecosystem functionality; all ecosystem services have trade-offs	Movement is a key component of ecosystem functionality, ecosystem service flows, and spatially explicit biodiversity hotspots. Habitat alteration equates to service trade-offs.

management options (Maxwell *et al.*, 2015). An example is dynamic ocean management (DOM), defined as the use of near real-time biological, oceanographic, social and/or economic data for management occurring at shorter spatio-temporal scales—more in sync with the resources being managed (Lewison *et al.*, 2015).

Movement data will be critical for single species stock assessments in the future with ocean change. This is because only through tracking movement it will be possible to determine if changes in catch levels are due to changing movement patterns and availability to surveys and fisheries, or instead due to changes in abundance. Single-species stock assessment models are based on the concept of maximum sustainable yield and density-dependent productivity and remain the most common means of providing management advice (Cadrin and Dickey-Collas, 2015; Punt *et al.*, 2015). Yet many of the problems identified in the classic work of Beverton and Holt (1957) still remain including difficulty in estimating abundance and natural mortality (Maunder and Piner, 2015). Tracking can help improve these estimates (Hightower and Pollock, 2013; Hightower and Harris, 2017). Fish which die naturally are rarely visually observed. However, tracking movement (or lack of movement) allows us to collect data on natural mortality (Bacheler *et al.*, 2009) and discard mortality (Curtis *et al.*, 2015; Runde and Buckel, 2018). Similarly, both horizontal and vertical movements affect the catchability coefficient, which in turn affects the accuracy of standardized catch per unit effort data used to estimate relative abundance (Maunder *et al.*, 2006) or recapture rates in abundance estimates from tag-recapture studies (Pine *et al.*, 2003). Tracking data is also increasingly used to improve abundance estimates (Bird *et al.*, 2014; Dudgeon *et al.*, 2015).

With a better understanding of the wide range of factors affecting maximum sustainable yield, fisheries science has become more process oriented (Aksnes and Browman 2016) and open to integrating non-traditional data types (Link and Browman, 2017). This is reflected in the ecosystem approach to fisheries management (EAFM). Within this framework, tracking data is increasingly used to improve our understanding of the biological processes driving stock structure. Stock assessment models assume a unit stock can be defined which has sufficient mixing and similarity in vital rates to be useful for management advice (Cadrin and Secor, 2009; Hawkins *et al.*, 2016). Traditionally, stock units are large and based on geographic or political boundaries and the assumption of open populations. More recent studies, however, suggest spatial structuring occurs at much smaller scales and plays an important role in managing for maximum sustainable yield (Goethel *et al.*, 2015; Kerr *et al.*, 2017). Reproductive isolation drives stock structure through the processes of spawning site selection, fidelity, and dispersal. However, a mechanistic understanding of these processes for marine fish does not yet exist (Ciannelli *et al.*, 2014). To change this will require tracking data on individual spawning site selection and fidelity (Lowerre-Barbieri *et al.*, 2013; Zemeckis *et al.*, 2014) combined with genetic data, at the population scale, to identify neighbourhood sizes (i.e. mean single-generation dispersal distances) and spatially explicit breeding densities. The need to integrate these spatial processes into stock assessments and

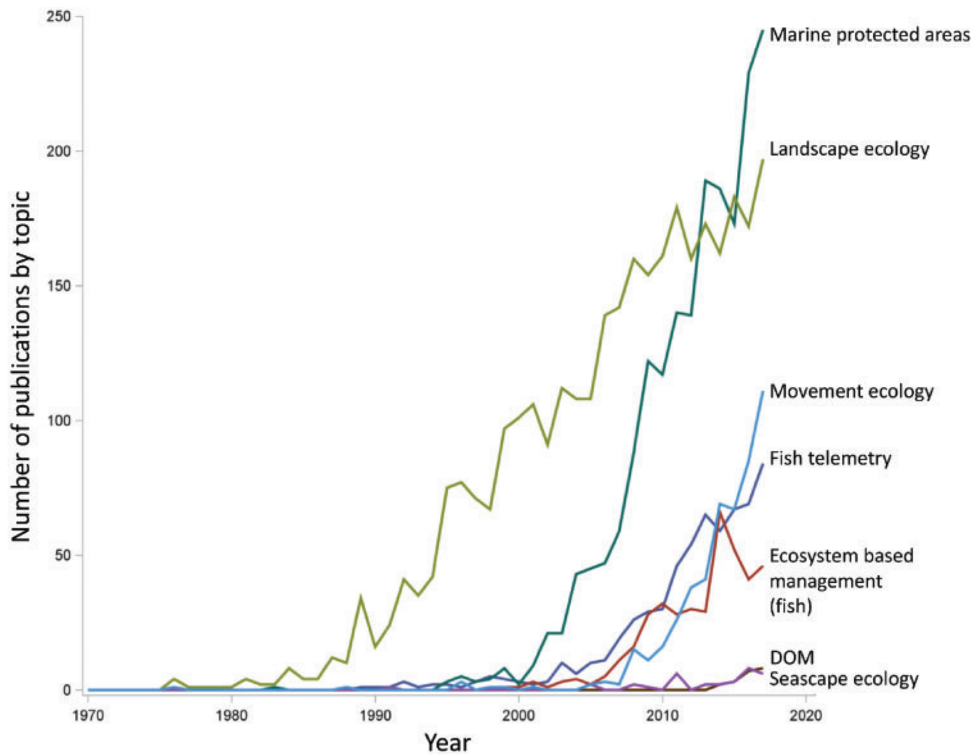

Figure 1. Annual publications trends from 1980 to 2017 on topics associated with fisheries and ocean management and movement. Data are based on Web of Science (Core collection; 8 July 2018) searches on "Topics" using the following terms: (1) "Ecosystem-based management" and "fish"; (2) "Marine-protected area"; (3) "Landscape ecology"; (4) "Acoustic telemetry" and "fish"; (5) "Movement ecology"; (6) "Fisheries Science"; (7) "Dynamic ocean management"; and (8) "Seascape Ecology."

management advise is increasingly recognized (Berger *et al.*, 2017a, b) and important to ensure there are not localized depletion or distributional shifts affecting stock productivity and resilience (Kerr *et al.*, 2010; Ciannelli *et al.*, 2013).

The ecosystem-based approach to fisheries management (EBFM) views fisheries as complex socio-ecological systems that both depend upon and affect marine ecosystems (Metcalfe *et al.*, 2012; Syed *et al.*, 2018) and that the yield of one species or stock can affect others. EBFM research and modelling often focus on food web and energy transfer connectivity. Within this framework, movement data is needed to predict predator–prey encounter rates, including those between fish and fishermen (Bertrand *et al.*, 2007; Alós *et al.*, 2012). Advances in tagging technology (Lennox *et al.*, 2017), ocean remote sensing capacity (Chauhan and Raman, 2017; Johnson *et al.*, 2017), and computing power (Allan *et al.*, 2018) make it possible to predict multi-species movements and thus where and when a fishery targeting one species might catch an endangered species as by-catch (Lewison *et al.*, 2004). With spatio-temporal data on fishing effort and species, we can predict when species overlap in space and time and use dynamic closures to prevent by-catch, often more effectively than traditional static closures (Hazen *et al.*, 2018). These real-time closures are already used in many regions, e.g. the Bering, Barents, and North Seas (Little *et al.*, 2015), and they are expected to increase in the next decade. Increased tracking data on multiple species also makes it possible to use easy-to-track animals as indicators of small, difficult to track animal abundance and distributions. For example, seabird movements can be used to estimate changes in fish abundance (Cairns, 1987). Bio-logging of seabirds has greatly increased and now often includes sensors documenting feeding (e.g. camera loggers, accelerometers, beak-opening sensors). Thus, using seabird foraging/tracking data to help inform estimates of forage fish abundance and location is expected to become an important metric in future EBFM efforts (Brisson-Curadeau *et al.*, 2017).

However, future management efforts will increasingly focus on ocean health. Ecosystem-based management (EBM) shifts from optimizing fisheries yield to understanding the impact of fisheries on biodiversity, ecosystem functioning, and ecosystem service flows (Halpern *et al.*, 2015). Species dispersal and migration are key drivers of these flows (Drakou *et al.*, 2018) and biodiversity hot spots (Jeltsch *et al.*, 2013). Annual migration data is needed to understand these processes. Using migratory birds as an example, its relevance to management is clear (McKinnon *et al.*, 2013): providing insights into essential habitats, connectivity, flyways, and stopover sites (Faaborg *et al.*, 2010, Lindström *et al.*, 2016; Clausen *et al.*, 2017). However, it is rarely available for marine fishes. Tracking data will also be needed to help identify and protect marine biodiversity hotspots. The UN's globally adopted Convention on Biological Diversity target for MPAs is 10% coverage by 2020, with current protection at approximately 2%, and more recent calls for 30% (O'Leary *et al.*, 2016). However, the effectiveness of MPA networks is limited without information on the movement patterns of species they are designated to protect (Halpern and Warner, 2003; Kenchington, 2017), necessitating data on animal's movements to determine the location and size of effective MPAs (e.g. Heupel and Simpfendorfer, 2005; Reynolds *et al.*, 2017).

Marine fish movement data—challenges and solutions

There are several key challenges to obtaining movescape scale data for marine fish, including the size of the ocean (363 million km^2), the lack of GPS capacity in the marine environment, life history patterns, and high harvest rates. The ocean covers 71% of the earth's surface, has few barriers to migration, and inhibits conventional forms of electronic transmission (e.g. radio waves). The first electronic tracking of marine vertebrates was in the 1950s (Figure 2), and there are three primary methods for electronic tracking used, with varying limitations: (1) acoustic tags which transmit an acoustic signal (typically ultrasonic) that is detected when the animal is within range of an acoustic receiver (Hussey *et al.*, 2015); (2) data storage or archival tags which archive data about the animal and its environment, but must be retrieved through programmed release and surfacing to transmit data to the ARGOS satellite (pop-up archival tags, PSAT) or by recapturing the animal (Hussey *et al.*, 2015); and (3) GPS tags which communicate with GPS satellites to establish position (Dujon *et al.*, 2014). For marine species that remain submerged, acoustic tags and PSAT tags are the only current option, as GPS signals bounce off ocean surfaces and cannot penetrate seawater.

The life cycle and lifetime movement of most bony fishes presents challenges to collecting movement data. Marine life exhibits two life history strategies in terms of adult to offspring size: a fixed-ratio strategy where offspring size is a constant fraction of adult size—similar to many terrestrial animals and associated with parental care—and a small-eggs strategy where offspring size is independent of adult size (Andersen *et al.*, 2016). Most marine bony fish fall into the latter category, with this strategy hypothesized to be driven by high and unpredictable mortality rates and/or patchiness of prey resources at relatively large spatial scales (Stearns, 1992; Winemiller and Rose, 1993). There is not a terrestrial equivalent, with the closest being some plants which produce large number of seeds, dispersed with the wind (Allen *et al.*, 2017; Lowerre-Barbieri *et al.*, 2017). Terrestrial vertebrates either lay few immobile eggs or have live birth and parental care, resulting in overlapping breeding and nursery habitats (Figure 3) and fecundity-driven population productivity. In marine bony fish offspring move away from adults into distinct larval retention and nursery habitats. This results in reproductive success being driven by a number of factors (Lowerre-Barbieri *et al.*, 2017), especially where and when fish spawn (Maunder and Deriso, 2013) due to birth site conditions driving offspring survival and consequent nursery habitat due to current regimes, salinity, and presence of egg predators (Ciannelli *et al.*, 2014).

The small size of most marine fish eggs (1 mm) and larvae presents a technological gap to tracking individuals at the lifetime scale (Hazen *et al.*, 2012; Allen *et al.*, 2017). Even at the population scale, life cycle data for marine fish such as the distribution of spawning sites or a species' nursery habitat is often unknown (Barnett *et al.*, 2015). Current state-of-the-art approaches to tracking early life dispersal include the use of underwater microscope cameras, combined with drifters released at the spawning site and adaptive plankton sampling along the drifter path to track dispersing eggs and larvae (Stock *et al.*, 2016). But progress with quantum dots (fluorescent nanoparticles) to track plankton (Ekvall *et al.*, 2013) suggests nano-tags to track fish eggs and larvae may be available within the decade. The ability to track the next stage, early juveniles, is developed for freshwater systems but not yet functional in the marine environment. Small injectable tags (216 mg) are being used to track smolts by the Juvenile Salmon Acoustic Telemetry System (Deng *et al.*, 2017) at population scales (∼28 000 fish) and at high spatial resolution (Li *et al.*, 2015). Similar capacity and sample size are expected in marine systems in the near future, given trends in increasing micro-battery capacity (Wang *et al.*, 2015).

Acoustic telemetry is the most commonly used tracking system for marine fish due to ease of deployment, relatively low cost, and capacity for tagging continuously submerged animals over a range of sizes (Hussey *et al.*, 2015). However, a limitation is that a tagged fish must come in the range of an acoustic receiver and that receivers (other than the VR4) must be retrieved to download the data. The following technological advances to acoustic telemetry are expected in the next 10 years or less (Lennox *et al.*, 2017): (1) tags will become smaller, less expensive, with longer life and greater data collection capacity; (2) there will be tag-to-tag and receiver-to-receiver communication with remote data offloading; (3) acoustic receivers will be commonly deployed on automated underwater vehicles (AUVs); and (4) there will be hybrid acoustic tags, combining archival capacity with acoustic capacity, and data offload ability when the tagged animal is in the range of a receiver. Some of these advances have already begun. Acoustic data storage tags, which unite acoustic and archival data collection have recently been developed by Vemco, although the animal must be recaptured to retrieve the archival data. Similarly, the Vemco Live system, which can transmit real-time detection data is in the testing phase. Trends in smaller tags, greater sensors, and lower cost are expected to continue. Sensors currently available include temperature, pressure, and a "predation" tag, which changes its tag ID after stomach acids digest a polymer. AUVs are increasingly carrying a wide range of sensors (Lin *et al.*, 2017; Lembke *et al.*, 2018), including acoustic receivers (Oliver *et al.*, 2013; White *et al.*, 2016). Tri-axial accelerometer tags allow translation of movements to behaviour (Wilmers *et al.*, 2015) and are increasingly used on marine fish to assess energetics and stressors impacting swimming capacity (Cooke *et al.*, 2016; Brownscombe *et al.*, 2017). However, current power limitations result in trade-offs between accelerometer data over short periods or tracking data over longer periods.

There is also the challenge of collecting movement data for marine fish at the large marine ecosystem (LME) scale, with current solutions being: (1) sharing detection data through telemetry networks; or (2) using PSAT tags. Regional acoustic networks are one way to address this and have become common in the United States: GLATOS (Great Lakes), ACT (east coast of the United States), SCATTN (southern California), FACT (east coast of Florida), and iTAG (in the Gulf of Mexico, GOM). Using iTAG as an example http://myfwc.com/research/saltwater/telemetry/itag, LME-scale tracking capacity is being built through data sharing of detections across all members' study arrays and the strategic deployment of long-term monitoring arrays (with receivers provided by OTN) throughout the GOM. Although many telemetry scientists were originally wary of sharing data, iTAG—and networks like it—are quickly changing our understanding of marine fish migratory behaviour, such as that of nurse sharks (Pratt *et al.*, 2018) and Atlantic tarpon (Griffin *et al.*, 2018). A key challenge to networks, however, is maintaining a balance between continuity in spatial coverage versus a researcher's freedom to move their receiver. To address this challenge, we have developed a receiver efficiency index to identify bio-diversity or single

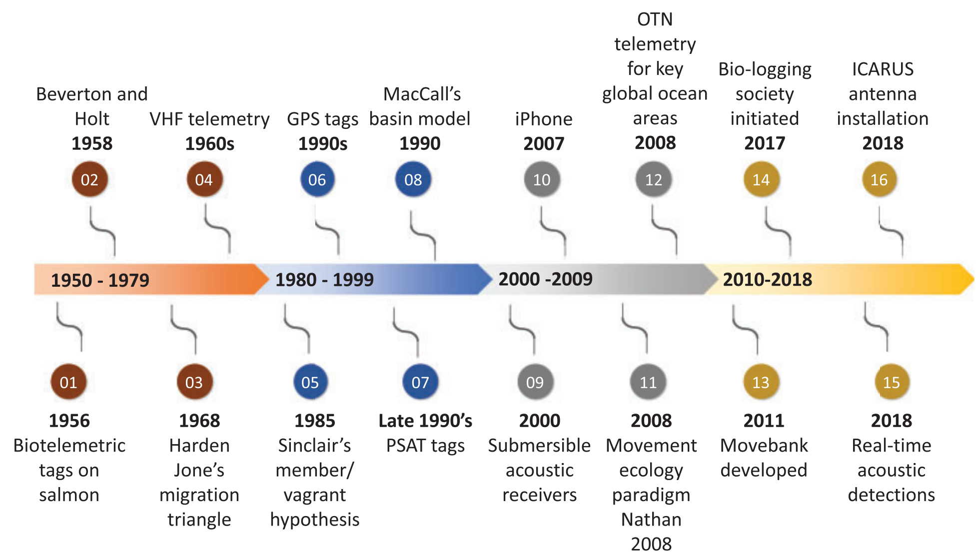

Figure 2. Key milestones in fisheries science conceptual models associated with stock structure and movement, and technological advances in tracking capacity. The date the iPhone was first released is included as a temporal reference to understanding how rapidly technology changes capacity. Full citations of class papers are in the references.

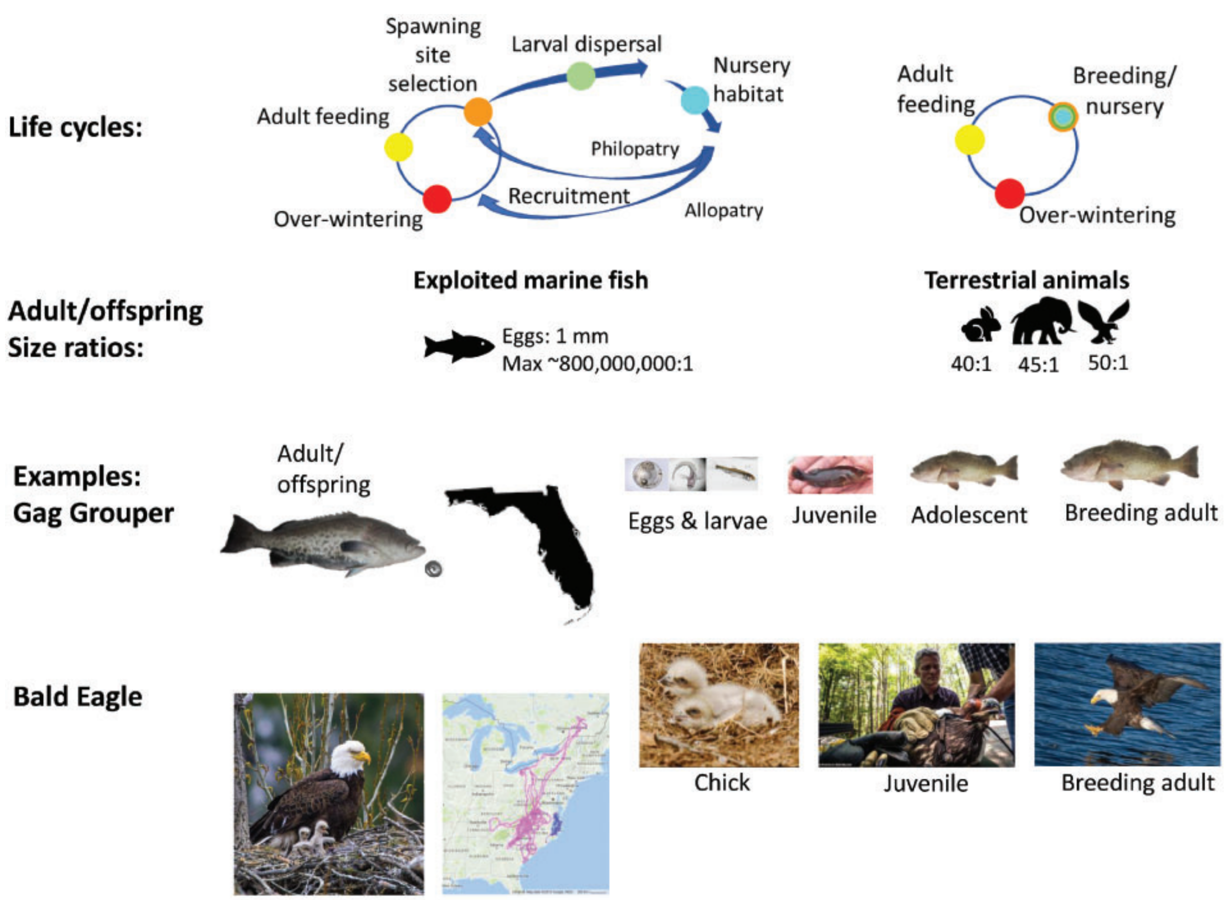

Figure 3. A comparison of typical exploited marine fish and terrestrial animal's life cycles, adult/offspring size ratios and an example of lifetime tracks in gag grouper (simulated) and bald eagle (based on tracking data). Most marine fishes have complex life cycles, and are capable of large movements in early life, and have little spatial overlap between adults and offspring. In comparison, many terrestrial animals provide parental care and do not exhibit the same range of life stages, or movement associated with those life stages. Bald eagle images provided by: Craig Goodwin (adults): https://www.craiggoodwinphoto.com/, Carolina Raptor Center (chicks), and @Untamed Science (juvenile).

species hot spots (Ellis *et al.*, 2019). In this fashion, we can use individual studies as preliminary data to identify high priority sites for monitoring when government funding becomes available.

The second solution to tracking of marine fish at LME scales is PSAT tags. Current limitations with this technology include: large tags (limiting the size range of fish which can be tagged), which are expensive and often pop-up prematurely, resulting in short-term, relatively low-spatial resolution tracks (Hammerschlag *et al.*, 2011). However, like acoustic tracking, we predict many of the challenges of satellite tracking will be resolved or at least improved within the next decade. Two of the most promising advances are: the use of acoustic signals to geolocate animals under the ocean (Fischer *et al.*, 2017; Rossby *et al.*, 2017), and the development of increased satellite tracking and tag capacity through the ICARUS initiative (Wikelski *et al.*, 2007).

The ICARUS initiative installed an antenna on the International Space Station (ISS) on 15 August 2018 which has the capacity to globally detect tags that are designed to transmit to the ICARUS receiver. These tags allow for the readout of >100 tags simultaneously within an 80×800 km scanning window in which the ISS passes within ca. 3 s. In addition, there is bi-directional communication, including a command downlink from the ISS to the tag, allowing for the re-programming of tags "on the swim" or "on the fly." Millions of tags (~4.5 g) with unique IDs can be distributed and read out globally. On-board sensor units include GPS, 3D-acceleration, magnetometer, temperature, pressure, humidity (for terrestrial applications), and others on demand.

DARPA (the Defense Advanced Research Projects Agency) will also help build tracking capability in the marine environment. It has three current initiatives associated with this: The Ocean of Things, the Persistent Aquatic Living Sensors (PALS), and the POsitioning SYstem for Deep Ocean Navigation (POSYDON) initiative. The Ocean of Things will float sensor networks that when coupled with powerful analytical tools can monitor vast regions of the ocean. Proposers will design "intelligent" floats, housing a sensor suite that can survive in the harsh marine environment and transmit information about surroundings to satellites (https://www.darpa.mil/news-events/2017-12-06). The PALS project proposes building a sensor system around behaviour of marine living resources, including sound production (https://www.darpa.mil/news-events/2017-12-06). POSYDON's goal is to develop an undersea positioning system (e.g. the equivalent of an underwater GPS) based on long-range acoustic signals propagated in known locations and detected by surface sensors with satellite connectivity, similar to the technology being used to develop new archival fish tags (Fischer *et al.*, 2017; Rossby *et al.*, 2017). This positioning system would allow AUVs and drones to obtain accurate positions without needing to surface (https://defensesystems.com/articles/2017/02/14/darpauuv.aspx? m=2). Drone/sensor systems envisioned for the future include: echo-sounders, cameras, passive recorders to detect fish sounds, as well as potential plankton ID capability.

However, for bio-logging data to inform management, the movement data from tagged individuals must represent the population we seek to manage. We see two main avenues to address this challenge: (1) releasing tagged fish in areas where individuals are evenly mixed; or (2) instituting population-wide programmes for releasing electronic tags. Electronic tracking programmes could take advantage of species whose range constricts at certain times, such as spawning aggregations, by tagging large number of fish at these sites over multiple years to account for annual variability in individual movement to the breeding site (Lowerre-Barbieri *et al.*, 2019). Alternatively, electronic tracking programmes could follow protocols developed for conventional tag-recapture programmes, where fishermen are required to ensure tracking of a certain proportion of their landings. For example, Antarctic toothfish fishing vessels are required under the Convention for the Conservation of Antarctic Marine Living Resources to tag and release one individual for every metric ton that is landed, while ensuring that tagged individuals are representative of the size distribution observed within their catch (WG-SAM, 2012). Similarly, approximately 5% of captured sablefish have been tagged and released within the stratified-random longline survey operating in the Gulf of Alaska (>300 000 tagged individuals as of 2014), conducted by the Sablefish Tagging Program (Echave *et al.*, 2013) by the Alaska Fisheries Science Center during its sablefish hook-and-line survey (Sigler 2000). Data from spatially distributed programmes such as these are likely to represent population-level processes (e.g. sablefish movement across the entire Gulf of Alaska) and therefore can be incorporated into fisheries models without biasing results due to inclusion of non-representative data (Ziegler, 2013; Hanselman *et al.*, 2015).

Conclusions

Marine fish movements are complex and driven by habitat, oceanography, and physiological constraints. Because they determine where a fish is in space and time they drive conspecific, predator–prey, observation, and fishing gear encounter rates (Figure 4). Given this complexity, it is not surprising that marine fish movements are not yet fully understood or integrated into fisheries stock assessments (Berger *et al.*, 2017a, b), nor that there are tracking capacity limitations which need to be overcome. However, the importance of investing in this effort is clear, given that movement drives ecosystem service flows and determines important areas for spatial management such as migratory corridors and biodiversity hotspots (Hays *et al.*, 2016). These data will also be needed as management entities increasingly grapple with the question of whether changing catch rates are due to changes in abundance or changes in movement affecting availability to capture (Kleisner *et al.*, 2017)—an issue expected to become increasingly important as species distributions, phenology, and movements are altered by climate change and habitat degradation (McQueen and Marshall, 2017; Pecl *et al.*, 2017).

Of course, to build capacity within fisheries and ocean management to use bio-logging data depends as much on human dimensions—ways to promote knowledge transfer and opportunities to build integrative science—as technological advances. Fisheries management remains heavily predicated on single species stock assessments (Cadrin and Dickey-Collas, 2015; Punt *et al.*, 2015) and traditional data streams (Crossin *et al.*, 2017). However, examples of terrestrial conservation informed by bio-logging (where tagging technology is more advanced) can be used to help overcome established institutional cultures and to highlight management benefits, even when they do not fit into traditional fisheries frameworks. For example, the expected benefit of tracking a wide range of marine fish throughout their migratory cycles can be demonstrated by looking at how this capacity for tracking birds affected conservation. Decreased GPS tag size and increased tag life resulted in the discovery of many small bird species' annual migratory routes. This, in turn, helped prioritize hot

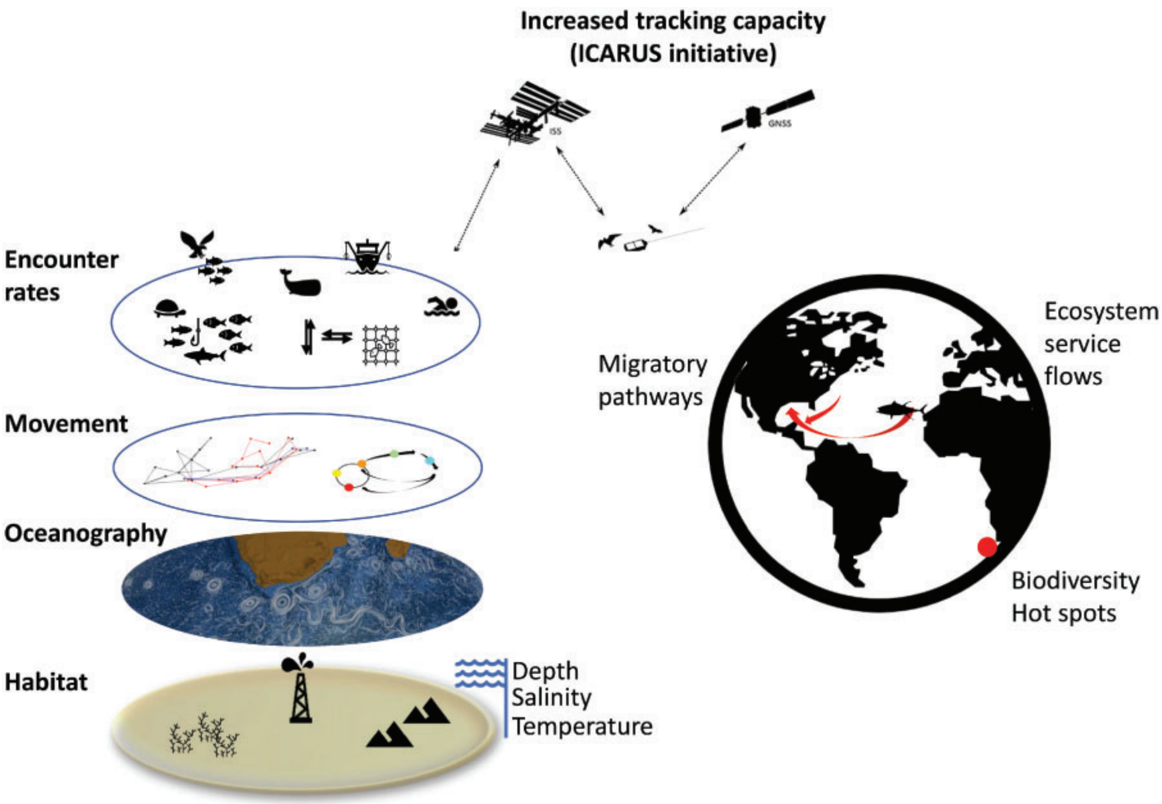

Figure 4. Movement decisions in fish are based on habitat, environmental, and oceanographic conditions and drive encounter rates. In the bio-logging decade tracking capacity will increase through a number of means, including the ICARUS initiative. This initiative builds an integrative communication system between earth and space and will improve our ability to identify biodiversity hotspots, swimways and flyways, and ecosystem service flows.

spots for conservation (Faaborg *et al.*, 2010; Bridge *et al.*, 2011; Lindström *et al.*, 2016), discover the environmental factors that create preferred flyways (Dodge *et al.*, 2014; Palm *et al.*, 2015), and demonstrate the importance of quantifying habitat connectivity to build coordinated multi-state and international management efforts (Clausen *et al.*, 2017).

For bio-logging data to inform fisheries management in the next decade, we need to develop scientific platforms that bring together academic and government fisheries scientists and promote integrative science. Bio-logging falls at the nexus between ocean observing and fisheries management and many current platforms link tracking and ocean observing systems. OTN at Dalhousie University is the global leader in marine fish acoustic tracking, conducting movement ecology research, providing a data depository for OTN members, and building global infrastructure through acoustic receiver loans and data templates. OTN works with most large-scale telemetry networks, many with a predominant academic focus, such as: IMOS ATF in Australia (Hoenner *et al.*, 2018), ATAP in South Africa (Cowley *et al.*, 2017), and developing national telemetry networks in the United States (Block *et al.*, 2016) and Europe (Abecasis *et al.*, 2018).

However, the same way telemetry scientists have argued fisheries management needs to be open to new data streams (Crossin *et al.*, 2017; Ogburn *et al.*, 2017; Young *et al.*, 2018), these efforts could be improved by increased integration of scientists from government—especially those in Federal fisheries agencies working at the assessment–management interface. These scientists have experience with the use of long-term tagging programmes (e.g. dart tags), evolving stock assessment approaches, and awareness of key fisheries management issues across species and regions.

Lastly, to meet the goals of the bio-logging decade—standardization of metadata and tracking data sets, collaborative technology development, and systematic and simultaneous global tracking of aquatic, terrestrial, and aerial species—will take building integrative efforts across ecological realms. For example, the power of global, open databases, and large-scale collaborative studies to synthesize movement over many taxa is clear (Hussey *et al.*, 2015; Hays *et al.*, 2016; Tucker *et al.*, 2018) but bringing together global databases is difficult. For example, Movebank is the global leader in terrestrial movement data and synthesis. Movebank is a free resource, using the Env-DATA System to integrate bio-logging data with global environmental data (Dodge *et al.*, 2013), and the data repository for ICARUS. Technologically, bringing together the OTN and Movebank databases is doable, but each group has evolved independently, with its own culture and there is no current funding initiative to support integrating such large global cyberinfrastructures in a sustainable and collaborative way. We expect this to change, however, as opportunities to bring together movement ecologists—regardless of taxa or realm—increase. Current efforts include: the bio-logging society (www.bio-logging.net), new journals such as Movement Ecology and Animal Biotelemetry, and the Gordon conferences on movement ecology. These, and future efforts like them, will build the foundation needed to collect global movescape-scale data that provides new insights, ecosystem indicators, and cross-scale understanding to improve our ability to sustainably manage fisheries, the ocean, and the world's ecosystems.

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