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Introduction to the Themed Section: ‘*Plugging spatial ecology into sustainable fisheries and EBM*’

Introduction

Preparing for the future: integrating spatial ecology into ecosystem-based management

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Marine resource management is shifting from optimizing single species yield to redefining sustainable fisheries within the context of managing ocean use and ecosystem health. In this introductory article to the theme set, “Plugging spatial ecology into ecosystem-based management (EBM)” we conduct an informal horizon scan with leaders in EBM research to identify three rapidly evolving areas that will be game changers in integrating spatial ecology into EBM. These are: (1) new data streams from fishers, genomics, and technological advances in remote sensing and bio-logging; (2) increased analytical power through “Big Data” and artificial intelligence; and (3) better integration of social dimensions into management. We address each of these areas by first imagining capacity in 20 years from now, and then highlighting emerging efforts to get us there, drawing on articles in this theme set, other scientific literature, and presentations/discussions from the symposium on “Linkages between spatial ecology and sustainable fisheries” held at the ICES Annual Science Conference in September 2017.

Keywords: AI, big data, bio-logging, fisheries, future data streams, movement ecology, social dimensions, socio-economic

Introduction

Marine resource management is shifting from optimizing single species yield to redefining sustainable fisheries within the context of managing ocean use and ecosystem health (Halpern *et al.*, 2015; Link and Browman, 2017), with growing recognition of the importance of spatial processes to management and conservation (Berger *et al.*, 2017; Cumming *et al.*, 2017). We use “spatial ecology” as an umbrella term to include the subfields studying these processes, including biogeography (Piatt *et al.*, 2018), seascape ecology (Hidalgo *et al.*, 2016), movement ecology (Nathan, 2008; Hays *et al.*, 2016), ocean connectivity (Hidalgo *et al.*, 2017), and spatial management to protect marine biodiversity (Jones *et al.*, 2018). Spatial ecology is complex, integrating spatial, temporal, and biological processes over multiple scales. At the most basic level, it is driven by heterogeneity in ecological context made up of multiple layers, including: (1) fairly static topography/habitat; (2) dynamic oceanographic processes, including variation and trends in temperature, salinity, fronts etc.; and (3) movement ecology of animals and fishers. Movement, or lack thereof, ultimately drives encounter rates between congeners and across species (Lowerre-Barbieri *et al.*, 2019; Rooker *et al.*, 2018; Westley *et al.*, 2018), affecting trophic dynamics and energy flows (Fenkes *et al.*, 2016) as well as fitness and reproductive resilience to external stressors (Lowerre-Barbieri *et al.*, 2017). The locations and associated environments that a given species seeks out and uses as essential habitat are driven by species-specific physiological constraints selected for over evolutionary time (Metcalfe *et al.*, 2012; Cooke *et al.*, 2014; Rangel *et al.*, 2018), and affect a species' vulnerability to the rapid changes associated with the Anthropocene (Hardesty-Moore *et al.*, 2018). To address the current mismatch in scale between ecological change and effective long-term governance of ecosystems requires an increased understanding of how multi-scale spatio-temporal processes affect the resilience of linked social-ecosystems (Cumming *et al.*, 2017; Tam *et al.*, 2017).

Current fishery management frameworks range from: (1) traditional single species stock assessments and the assumption that productivity is driven by adult abundance and density-dependent feedback loops; (2) the ecosystem approach to fisheries management (EAFM), which recognizes that complex processes affect single species productivity; (3) ecosystem-based fisheries management (EBFM), which treats fish as part of a complex integrated system and recognizes multiple trade-offs in the process of estimating optimal yield; and (4) ecosystem-based management (EBM), which focusses on ocean use management, ecosystem functionality, and ecosystem service trade-offs (Patrick and Link, 2015). However, conceptual shifts often precede operational shifts. Thus, although the concept of EBM is increasingly embraced, operationalizing it remains difficult (Link and Browman, 2017) and single-species assessments remain the most common management framework (Cadrin and Dickey-Collas, 2014). But one thing is certain, future management will increasingly focus on ecosystem health and there will be a growing need for spatial data and understanding of spatial processes.

So, what will it take to get there? We ask you to take a moment to imagine the management of marine living resources 20 years from now. We are optimists, so we ask you to imagine there has just been another EBM symposium at the ICES Annual Science Conference and a theme set is being published with many successful EBM case studies. It is 2038. What factors do you think have revolutionized fisheries and ocean management? To develop a future-looking perspective for this article, we asked ourselves and ten colleagues what would be the biggest "game changers" in EBM in the next 20 years. Colleagues were asked not to dwell on the question but simply e-mail three things that came to mind. With this exercise we identified several rapidly evolving areas critical to integrating spatial ecology into EBM (Figure 1): (1) new data streams, including data from fishers participating in data acquisition and citizen science, the genomics revolution, and improved technology, with a focus on remote sensing and bio-logging; (2) improved theoretical, computing, and modelling power with increased access to Big Data and artificial intelligence (AI); and (3) better integration of social dimensions into management, including economics, stakeholder engagement, and educating the public about the importance of marine ecosystem functionality. We address each of these areas below, first imagining the future—citing science that we feel is planting the seeds for this future—and highlighting emerging efforts that will help us get there. To do so, we draw on the articles in this themed set, other scientific literature, and presentations/discussions from the symposium on "Linkages between spatial ecology and sustainable fisheries" held at the ICES Annual Science Conference in 2017 (see Supplementary Materials for the original theme session description and list of the talks presented).

New data streams

By 2038, long-term marine monitoring stations such as at the integrated open-coastal observatory in the eastern Mediterranean within the POSEIDON system (Petihakis *et al.*, 2018) will be common and used to define the relevant spatial, temporal, and biological scales for data collection needed to assess marine ecosystems. Operational food-web indicators will be used routinely (Tam *et al.*, 2017) and genomics and other biochemical tracers (e.g. carbon and nitrogen stable isotopes and fatty acids), remote sensing, and bio-logging data will be collected to assess these indicators over space and time. The result will be real-time data on productivity in terms of: phytoplankton, which is consumed and regrown weekly, via zooplankton, forage fish, seabirds, through to apex predators which may have generation times of several decades (Hazen *et al.*, in revision). This overview would allow for assessment of energy flows at temporal and spatial scales appropriate to dynamic ocean food webs (Pethybridge *et al.*, 2018).

High-resolution spatio-temporal data on the majority of marine organisms will be available due to technological advances, improved remote sensing, and increased citizen and corporate citizen science (e.g. Dickinson *et al.*, 2012). Marine vessels will be equipped to collect continuous spatially explicit hydrological and biological data and this will be uploaded to satellite and transferred to data centres for real-time analysis. Oceanographic and biological data will also be collected from space, with remote sensing capacity to collect data at the sea surface and below. Similarly, fishery-dependent and fishery independent monitoring will be automated and conducted by fishing vessels fitted with vessel monitoring systems (VMS) that include technological observer systems with cameras, automated DNA sampling, hydrophones to record natural sounds and detect acoustic signals, and trawl-mounted CTDs to link catch data with oceanography.

A portion of non-forage fish stocks will be outfitted with bio-loggers, providing data on how fish movements change with changing oceans (e.g. temperature, acidity, and species density) and the effect this has on stock productivity and predator-prey encounter rates, including those between fish and humans (Furey *et al.*, 2018). Marine bio-logging capacity will be similar to what is becoming available in terrestrial systems (Wilmers *et al.*, 2015) and will include high-resolution geolocation capacity, small tags with multiple physiological sensors capable of exchanging information between tags, as well as with a fleet of ocean drifters, which upload the data to satellites and consequently to data centres. The resulting data stream on movement of many individuals across most species (Lowerre-Barbieri *et al.*, 2019) will be integrated with real-time oceanographic and environmental data and understood within emerging paradigms of movement ecology (Nathan, 2008) and genetic effects (Rittschof and Hughes, 2018). This will enable managers to determine when lower catches in a given area are due to changes in movement versus decreased abundance. In addition, it will improve our understanding of biodiversity hot spots and their drivers, as well as make it possible to use fish movement as an ecosystem indicator of stressors as proposed for terrestrial systems (Wikelski and Tertitski, 2016).

How to get there? Emerging technologies, genomic techniques, and citizen science (and crowd sourcing it, e.g. Zooniverse, https://www.zooniverse.org/) are laying the foundation for the future envisioned above. For example, citizen science efforts already use marine platforms of opportunity, such as ferries to survey marine mammals (Kiszka *et al.*, 2007; Aïssi *et al.*, 2015) and continuous plankton recorders mounted on commercial vessels (Lauro *et al.*, 2014). Similarly, oceanscope has already been exploring the concept of all ocean-going vessels to collect some level of data (http://scor-int.org/Publications/OceanScope_Final_report.pdf), and Global Fishing Watch uses vessel tracking

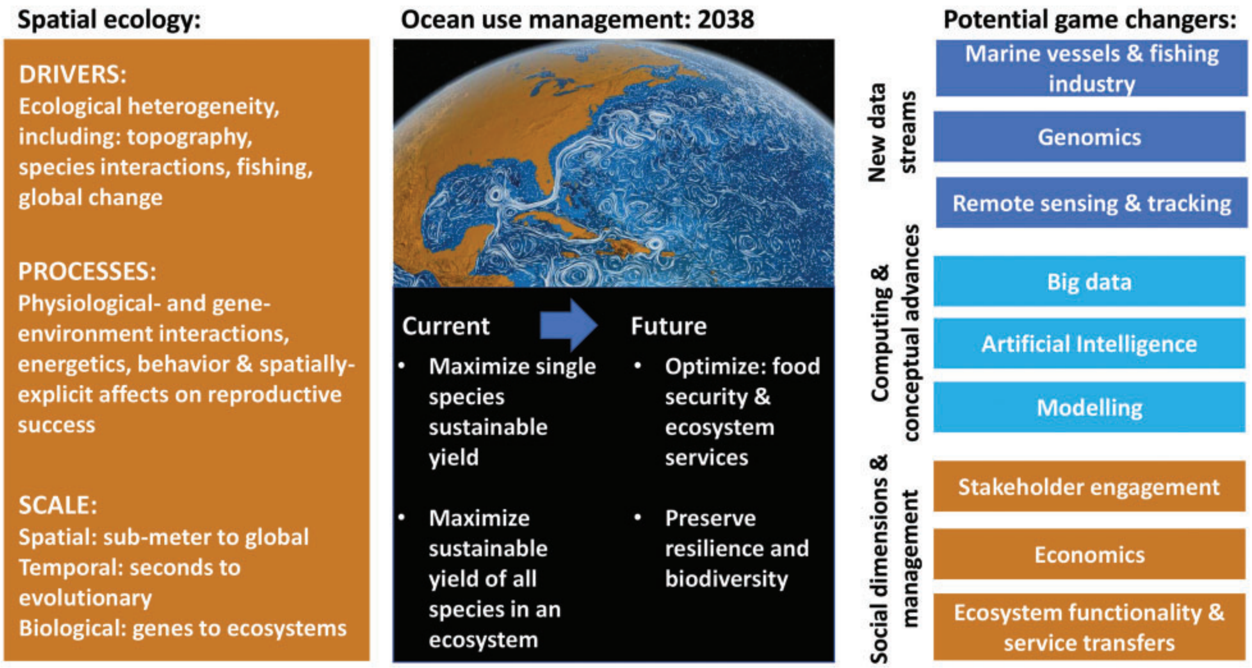

Figure 1. Drivers, processes, and scales critical to understanding spatial ecology, our projection of how this understanding will be used as future management goals evolve, and the potential game changers that will help plug new understanding of spatial ecology into EBM.

information to show the current and past distribution of fishing effort (https://globalfishingwatch.org). Remote sensing capacity below the sea's surface has been proposed using hyperspectral ocean colour sensors and ocean-optimized satellite profiling by Light Detection And Ranging (LIDAR) (Hostetler *et al.*, 2018). Many ships are currently fitted with VMS or can be tracked through automatic identification system messages (Kroodsma *et al.*, 2018) and fisheries monitoring uses technology that will be deployable in the future on fishing vessels. Examples are remote electronic monitoring cameras (Bicknell *et al.*, 2016; Plet-Hansen *et al.*, 2017), underwater stereo cameras (Underwood *et al.*, 2014; Díaz-Gil *et al.*, 2017), passive acoustic monitoring stations (Buxton *et al.*, 2018), acoustic receivers (Hussey *et al.*, 2017), genomic sensors which can remotely collect and analyze DNA from underwater (Scholin *et al.*, 2017) and drones (Raoult and Gaston 2018).

Genetic data are increasingly informing fisheries science (Waples *et al.*, 2018; Whitlock *et al.*, 2018). Single-nucleotide polymorphisms (SNPs) are being used in seascape genomics to assess management units and how they differ with changing climate and fishing pressure (Benestan *et al.*, 2016). Similarly, genomic techniques are beginning to identify how the spatial component of reproductive success affects stock structure through identification of ecotypes and metapopulations, sources and sinks, and ocean connectivity (Berg *et al.*, 2016; Johnson *et al.*, 2018). Genetic "tags" are an emerging technique in mark-recapture models to estimate abundance (Bravington *et al.*, 2016; Bernatchez *et al.*, 2017) with the advantage that these "tags" are never lost, which increases the time frame on which research can be conducted and the ability to subsequently link tagging studies with assessment of reproductive success. Metabarcoding and environmental DNA are also emerging techniques to assess spatially explicit biodiversity, spawning sites, and range shifts (Deagle *et al.*, 2018). Lastly, transcriptomic responses may now be used to assess non-lethal physiological responses to stressors and identify the spatial extent of their effect (Oomen *et al.*, 2017).

Fish movement data will be another key data stream as tags become smaller and increased in capacity including the ability to communicate with additional equipment and other tagged animals in an internet-of-things-approach to monitor marine ecosystems (Allan *et al.*, 2018). The movement ecology paradigm (Nathan, 2008) builds the foundation needed to understand movement as part of an animal's life history and is driving a deeper understanding of movement syndromes (contingents within a population exhibiting different movement behaviour, i.e. "stayers" and "goers") or migratory patterns within a population (Eiler *et al.*, 2015), their fitness consequences (Berg *et al.*, 2016; Mobley *et al.*, 2018), and how fishing may affect them and, thereby, population resilience. The trend of smaller, less expensive tags with more sensors and pathways to retrieve the data are expected to continue (Lennox *et al.*, 2017). However, two bottlenecks stand between current marine bio-logging capacity and its future potential to inform management. These are the lack of technology to track individuals over large spatial scales with high spatial resolution and the need to overcome institutional inertia associated with traditional data sharing and use (Berger *et al.*, 2017; Crossin *et al.*, 2017). Several approaches are underway to address these challenges, including: telemetry networks with digital tools to share detections of a given animal over the range of members' receiver arrays (Cooke *et al.*, 2011), using basin-wide sound sources 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 International Cooperation for Animal Research Using Space (ICARUS) initiative (Wikelski *et al.*, 2007; https://wwworn.mpg.de/ICARUS).

Four articles in this theme set highlight how tracking data can inform fisheries management. Lowerre-Barbieri *et al.*, (2019) brings together leaders of the ICARUS initiative, a fisheries ecologist and a fisheries modeller/stock assessment scientist to identify: (1) fisheries management data needs that large-scale tracking can help fill; (2) challenges to collecting movement data in marine fish; and (3) emerging solutions to meet these challenges. Alós *et al.* (2019) use spatially explicit individual-based models to assess how spatial behavioural diversity in fish and fishers affects the catch–abundance relationship. This has important management implications, with the recognition of spatial behavioural syndromes in marine fish which affect the efficacy of spatial management. Similarly, De Pontual *et al.* (2019) used archival tags to track European sea bass (*Dicentrarchus labrax*) using an innovative hidden Markov model to infer individual migration patterns from depth and temperature data. This study documented partial migration in the European sea bass, with both residential and migratory contingents. Fidelity to summer foraging grounds and winter spawning areas was observed. However, they also identified a marine-protected area (MPA) as a likely mixing zone for different stocks or sub-populations, as well as a resident population, changing current perceptions of the spatial structure of the European sea bass population. Lastly, Lowerre-Barbieri *et al.* (2019) take an integrated approach toward understanding movement dynamics and abundance of red drum (*Sciaenops ocellatus*) at a spawning aggregation site using: (1) a large dataset of genetically profiled fish (>9000), non-lethally sampled by purse seine; (2) aerial surveys; (3) acoustic telemetry; and (4) a catch mark-recapture model to estimate abundance. Although distributed over a large area during the non-reproductive period, red drum aggregate to spawn, making them vulnerable to spatial stressors and capture. Annual spawning population size is variable and capture-based abundance estimates are affected by fine-scale 3D space use.

Computing and conceptual advances

By 2038, spatially explicit ecosystem models will be fully integrated into the scientific process, with model results and predictions commonly tested in successive field-based studies. "Big Data" will be common and AI will be routinely used to extract more predictive relationships from digital data sources, combining data types currently considered unrelated. This will be much like what has been observed during the past 10 years with cell phones being used to track human mobility (Thums *et al.*, 2018) and traffic congestion (Wang *et al.*, 2012). Retrieval of data from the cloud will provide the capacity for complex models to easily and rapidly analyse high-resolution data on spatial, temporal, and biological processes over multiple scales. Fewer model assumptions will be needed, uncertainty in model results will be decreased (Fer *et al.*, 2018), resulting in improved model predictions of the level of industrialization and extraction a given system can sustain. The large increase in real-time data, and decrease in processing time, will negate the need for retrospective stock assessments, allowing for rapid assessment-based management decisions such as those proposed for dynamic ocean management (Lewison *et al.* 2015).

How to get there? To rapidly improve analytical and conceptual models in fisheries science will necessitate: learning from other fields, increased "systems" thinking and recognition of scale effects, new models and inference tools, as well as increasingly testing model predictions in follow-up studies. Big data, increasingly complex models, and AI all have the potential to provide insights into emergent properties of marine ecosystems not understandable from an individual observational stand point and thus play a critical role in building better ocean management tools (Howe *et al.*, 2008). However, if scientific effort shifts more toward analysis and fewer scientists participate in the data collection process, there is potential for scientists to become insulated from observational experience of the systems that they study. Lastly, complex datasets and models are difficult to work with and troubleshoot. Thus, new ways to build ecological models with built-in systems to identify problems, similar to systems being built for automated driving, will be needed (Wotawa *et al.*, 2018).

However, AI computer models and "learning feedback loops" have great potential (Hamet and Tremblay, 2017) and have been successfully applied to continuous flows of real-time data from predicting flu epidemics (Lazer *et al.*, 2014) to swaying elections (Gonzalez, 2017). Fisheries science does not need to redevelop the wheel to integrate these tools into EBM but rather can draw from fields such as weather forecasts and human healthcare. Weather forecasts have improved over the last decades due to more data, models that include more physical processes, and more computing power, which together cause better data assimilation to describe the current atmospheric state (Bauer *et al.*, 2015). Here, conceptual understanding and computing power have leveraged the value of data, and vice versa. Current meteorology cannot predict when and where pressure systems arise, but once they exist and can be measured, the models can predict their development and trajectory quite precisely for ∼10 days (Bauer *et al.*, 2015). Human healthcare, like EBM, is adapting to the accelerated pace of new data streams and increasingly integrating data from genetics, robotics, AI, and molecular biology to improve diagnostics and treatment (Lagrew and Jenkins, 2015). "Systems thinking" is being applied to understand the complexity of individual human bodies and their system-level responses to environmental stressors (Hamet and Tremblay, 2017). For example, multi-agent system-based modelling is being used to assess individual patient dynamics, their responses to medications, genetic predispositions, and behavioural interactions within a larger societal ecosystem through process mapping and constantly learning feedback loops (Silverman *et al.*, 2015). Similarly, fish populations are increasingly viewed as non-linear complex adaptive systems, with emergent properties from interactions at multiple scales and complex feedback loops affecting productivity (Holland 2006; Lowerre-Barbieri *et al.*, 2017). This can be seen in collective movement such as in schooling fish, with important implications for management (Secor, 2015). Similar to elephants and wolves, older individuals may act as "information repositories" (Westley *et al.*, 2018), reacting to cues and transmitting information to school mates that result in successful migrations and phenology (Rose, 1993; Huse *et al.*, 2002; Couzin *et al.*, 2005; Ward *et al.*, 2008).

Understanding species-specific spatial ecology will help build the foundation needed to improve future EBM. Contributions to this effort from articles in this theme set include that of Nikolioudakis *et al.* (2019) who developed Bayesian methods for integrative analysis of multiple spatial datasets. They applied the method to Northeast Atlantic mackerel (*Scomber scombrus*) and concluded that temperature, food availability, herring abundance, and longitude all influenced mackerel distribution and catch rates. Reglero *et al.* (2019) used modelled temperatures and experimentally observed effects on Atlantic bluefin tuna (*Thunnus thynnus*) eggs and larvae to construct a spatially explicit larval survival index. Areas for which the survival index was high overlapped with areas that other studies had identified as likely tuna spawning sites, suggesting that adding spatial processes may improve stock-recruitment projections. Similarly, reproductive timing of an individual at a given spawning site may be influenced by events that take place at other locations and times. This was studied in a model for the spawning of Pacific herring in the Puget Sound, where broad variability in spawning activity was predicted from temporal fluctuations in food availability and predators at feeding sites (Ljungström *et al.* 2019).

Of course, climate change is part of the future—causing shifts in distribution (Morley *et al.*, 2018) and increased numbers of extreme weather events—affecting the spatial ecology of many marine fishes. Hurricanes are one example of extreme weather events, expected to increase in the future, which impact fish spatial ecology. For example, hurricanes affect adult dispersal in red snapper (Patterson III *et al.*, 2001) and potential recruitment failure of yellowtail flounder in the mid-Atlantic bight (Sullivan *et al.*, 2005). In this theme set, Secor *et al.* (2019) use acoustic tracking and oceanographic modelling to demonstrate how a tropical storm caused destratification and evacuation of black seabass in the mid-Atlantic bight. If destratification events cause long-term seasonal changes, these could result in shifts in movements, food webs, and reproductive behaviours. Whether the effects of the Anthropocene increase vulnerability or alter productivity will depend on the species. In this theme set, Arechavala-Lopez *et al.* (2019) used pit tags to study distribution and population dynamics of the common octopus (*Octopus vulgaris*). Combined with a spatial mark-recapture model—an increasingly applied mechanistic model used to assess how within-population movement processes affect population dynamics (Royle *et al.*, 2018)—they found that the species could thrive in human-altered coastal environments as these had abundant shelters and food and lacked typical predators.

Social dimensions and effective management

By 2038, scientific input for management advice will routinely integrate mechanistic understanding of marine ecosystem processes with economic trade-offs (including those associated with the erosion of natural buffers) and the use of effective messaging to increase public engagement. The world population is projected to grow from 7.3 billion to 9 billion by 2038 (http://www.worldometers.info/news/) resulting in greater demand for fish as a source of human protein in developing countries (FAO, 2018a). Citizens of developed nations will have more leisure time and expendable income, potentially allowing for increased recreational fishing and purchasing power for seafood. We envision increased commercialization of the oceans, as a result of technological developments, in a wide range of areas, including: marine transportation (UNCTAD, 2017), mariculture (FAO, 2018a), mining (Sharma, 2017), drilling, and offshore energy generation from wind mill farms. There will also be increased eco-tourism (e.g. Spijkers *et al.*, 2018). However, if effective MPAs and buffer zones have been developed it may be possible to maintain the balance between ocean industrialization (extraction activity) and marine ecosystem health. However, this will necessitate taking measures while "ocean real estate" is still relatively undeveloped. For example, for each new extraction of natural resources from the ocean, there could be a marine ecosystem "tax"—commonly in the form of "purchasing" and maintaining additional MPAs— to provide a return to society for the right to harvest a publicly owned resource (e.g. economic rent or resource rent, Clark 2006). These transactions could be posted on a marine natural resource digital bulletin board to allow for stakeholder input and transparency in choices affecting planet health.

Management actions will focus on maintaining spatial resilience of socio-ecological systems, closing the gap between the scale of ecological change versus adaptive management (Cumming *et al.*, 2017). Ocean use managers will apply the lessons learned from terrestrial commercialization and the agricultural trajectory—from pastoral to agri-business—recognizing the need for proactive management measures to avoid a trajectory of "corporate" fishing, natural resource extraction, and impaired ecosystem health. Thus, management measures and incentives will be developed to maintain fishing diversity over multiple scales, including artisanal fisheries important to developing national economies and food production (FAO, 2017). Coastal community resilience will be maintained through proactive measures to adapt to sea level rise and replenish natural buffers to absorb increased catastrophic weather events. These restoration efforts will include: a reduction in manmade interfaces between land and water, increased seagrass beds, wetlands, and undeveloped barrier islands which naturally adapt to changing oceanographic and climatic conditions (Gopalakrishnan *et al.*, 2018). Fishing communities will remain, but the species that they target, and how they are fished, will adapt to changing species distributions and movement patterns (IPCC 2014, FAO 2018b; Pinsky *et al.*, 2018). Management will be local, but governance will be integrated over spatial scales from regional, to national to global. Ecosystem service transfer and the need for integrated governance for migrating species will be well recognized and efforts to protect key migratory pathways and hot spots, similar to protecting flyways and stopover sites for shorebirds, will be common.

How to get there? To manage for spatial resilience, we will need a better understanding of spatial feedback loops, scale effects, and how to measure when a system is nearing its tipping point. We know that marine ecosystems undergo regime shifts (i.e. shift to an alternate stable state) due to complex non-linear responses to long-term, slow-acting drivers/stressors (Scheffer and Carpenter 2003; Bland *et al.*, 2018). However, it is often difficult to predict these shifts—which can occur rapidly after years of sustained stress—and once a shift has occurred, it may not return to the previous state. Spatial resilience focuses on processes that operate across multiple locations and spatial scales, explicitly considering the spatial distribution of system components and their interactions, including ecological and social connectivity (Cumming *et al.*, 2017) and should be integrated within EBM. To lay the ground work for this, we outline needs of EBM that have been identified previously (Link *et al.*, 2017; Marshall *et al.*, 2018) and discuss them within the context of spatial resilience. These include: (1) better understanding of linkages across ecological, economic, and social processes resulting in effective indicators and reference points; (2) efficient multi-stakeholder frameworks to develop and inform management, drawing on multiple knowledge systems that facilitate decision making, its legitimacy, and subsequent compliance; and (3) improved communication channels to ensure knowledge transfer, public engagement, and the needed feedback loops for new ideas to resonate within the social system (Pielke, 2007; Dearing and Cox, 2018).

Spatially explicit data are rapidly increasing, as are ecosystem indicators, but we need to develop new means to synthesize these data and utilize it in management. An emerging method to achieve this is to evaluate ecosystem health through decision trees consolidating multiple ecosystem indicator trends over various time steps (Shin and Shannon, 2010; Lockerbie *et al.*, 2018). An informative example of this approach, coupled with a pressure-state-response Framework, is that used to assess the Benguela sardine fishery (Jarre *et al.*, 2018). In this example, in addition to evaluating trends in indicators over time, the model evaluated the pressure exerted by spatially disproportionate fishing on a forage fish and the effect it had on the state of dependent predators such as seabirds. The result was a "report card" of the effects of the sardine fishery on the Benguela ecosystem at differing time steps, with scores of acceptable, good, or bad. Another example is ecosystem service trade-off analysis, such as that used to develop spatial planning to maximize the benefits of increased offshore wind energy structure, commercial fishing, and whale-watching sectors in Massachusetts (White *et al.*, 2012).

Multi-scale governance mechanisms that recognize cross-scale influences with local consequences are needed (Honti *et al.*, 2017). People develop emotional ties at the local or regional scale and many ecosystem processes occur at this scale, supporting spatially explicit approaches to natural resource management (Crowder and Norse, 2008). In addition, because there are no standard rules for EBM (Long *et al.*, 2015), its effectiveness is dependent on regional ecosystem characteristics, available information, status of the resource, human perceptions and values, and trade-offs between management costs and benefits (Pitcher *et al.*, 2009). However, it is important to recognize that the regional and relatively short time frames of most ecosystem research can shift perceptions of disturbances and their frequency and that it is critical to integrate regional processes with global processes such as climate change and marine pollution, e.g. the dispersal and impact of marine plastics (Cumming *et al.*, 2017).

"Blue growth" has been suggested as a way to use EBM to develop proactive and holistic management measures—recognizing that diverse ocean uses are interconnected and better managed jointly rather than in isolation—to ensure minimally impactful ocean industrialization (Burgess *et al.*, 2018). However, successful operationalization of this is dependent on inclusive management integrating stakeholders, multiple models and decision criterion, and effective feedback loops, linking human welfare with ecosystem health (Long *et al.*, 2017). There will also need to be a shift in focus from short-term economic growth to increased valuation of long-term well-being and the role healthy ecosystems play in this. This is beginning to occur in developed nations to address coastal community resilience in the face of climate change (Brown *et al.*, 2018; Mehvar *et al.*, 2018). However, there we need to apply this approach to developing nations and also learn more from terrestrial case studies with clear industrialization/ecosystem trade-off time series. These case studies are important to better understand spatial resilience/industrialization trade-offs, as well as to highlight the challenges that will emerge if proactive measures are not taken, given the difficulty in changing established practices. The resistance met in global efforts to shift from fossil fuels to renewable energy (Liang *et al.*, 2019) being a good example of this.

Inclusive management of a given location or species is a method to integrate multiple stakeholders and is increasingly used for commercial (Jentoft, 1989; d'Armengol *et al.*, 2018) and recreational fisheries (Kearney, 2002; Arlinghaus and Cooke, 2009). Its holistic perspective supports and benefits from spatially explicit EBM (White *et al.*, 2012; Castrejón and Charles, 2013, Long *et al.*, 2017). However, inclusive management relies on all stakeholders being willing to meet and actively contribute to the process. A common deterrent to this is perceived and real power imbalances, i.e. sectors that may not be willing to participate if they feel political currents go against them. This is often manifested between recreational and commercial fishing sectors, although the perception of the impacts of these fisheries differs with country. For example, in Germany and Switzerland catch-and-release fishing is thought to cause unacceptable suffering to the fish (Browman *et al.*, 2018). In contrast, in many countries a common argument put forward is that recreational fishing has less environmental impact and results in greater economic benefits than commercial fisheries. Although valuations integrating across the sectors remain relatively rare, they can help highlight important synergistic effects of both sectors (Voyer *et al.*, 2017). In addition, as global recreational fisheries have grown, so too have the challenges they present to management. Because recreational fisheries are made up of huge numbers of fishers, with varying skill sets and access to stocks, their impact on marine ecosystems can be much harder to evaluate than commercial fisheries. In the European Union, for example, member states are obligated to collect data on recreational marine fisheries, with pilot marine recreational fishery surveys in place by 2020 (Hyder *et al.*, 2018). But to effectively track recreational fishing effort will necessitate the development of new indicators and digital tools.

Lastly, we will need to improve communication and outreach to increase knowledge transfer and build effective feedback loops tied to ecosystem functionality. A huge challenge to overcome is the lack of perceived connectivity between most people's daily lives and the health of marine ecosystems. We can learn from the feedback loops and community scale extraction under which ancient hunter-gatherer cultures evolved. In these ancient civilizations human survival depended on understanding animal movement, food webs, and healthy ecosystems. Technology has both caused a disconnect with planetary health and can help solve this problem. Examples include consumption choices aimed at increasing ecological sustainability (Niva and Jallinoja, 2018); social media outlets highlighting ecosystem issues such as marine plastics; and the integration of traditional and scientific knowledge to improve scientific products and build trust and stakeholder engagement. This can be seen in the article in this themed set by MacCall *et al.* (2019), who use traditional knowledge of the Haida Nation to develop hypotheses about herring spawning site selection and address the question of whether migratory behaviour to these spawning sites is learned from older individuals. This effort was undertaken in part based on the recent statement by Chief Gidansta (Guujaaw) of the Haida Nation that: "Once herring lost the elders they lost their way to their spawning grounds." Understanding the processes affecting migration to spawning grounds is of primary importance for Pacific herring, and other aggregating species, as many of the social, ecological, and economic services associated with these species are linked to their spatially distinct spawning grounds (Levin *et al.*, 2016).

Conclusions

Oceans cover more than half of our planet, providing habitat for a huge diversity of life, as well as affecting global climate, ecosystem processes, and services. However, monitoring the status and trends of component species and protecting diversity and ecosystems are challenging, given that they are all under water and often far from human habitation. Rapid technological advances and improved computing/modelling power are increasing our understanding of marine spatial ecology as well as the capacity for ocean industrialization during a time of ocean change. Each article in this theme set highlighted at least one spatial process with important implications for current fisheries management, including: improved estimates of abundance, stock structure, shifting distributions, and spawner-recruit dynamics. The articles taken together cover a range of spatial processes, species, and management areas—all of which are critical to understanding spatial resilience and integrating spatial ecology with EBM. To help promote forward thinking, in this time of rapid change, we have presented them within the context of future needs and fields we can learn from.

Many of the processes that we study do not have short-term feedback loops that affect the average citizen, yet the long-term consequences will. Improving knowledge transfer and the need for evidence-based management decisions entails greater engagement with stakeholders and the public. Science institutions must find a way to communicate abstract, complex ideas in ways people can recognize as affecting their quality of life and well-being. This entails using behavioural science (Cinner, 2018) to develop communication channels (Dearing and Cox, 2018) that can change value systems and more closely tie human health to the planet's health. A useful first step is reflecting on our own scientific social systems and how open they are to change. For new fields and methodologies to emerge, it is not realistic to expect first attempts to out-perform established methods. These attempts, however, show the seeds for future methods and paradigms. With this in mind, we would like to acknowledge that this theme set owes thanks to all of the participants in the symposium on "spatial ecology and sustainable fisheries" at the 2017 ICES Annual Science Conference, as well as to the scientists who submitted manuscripts to this theme set that were not accepted. We learned from all of you.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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