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New tools for the spatial management of living marine resources

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Until recently, our ability to implement and assess spatial marine management approaches has been limited by a lack of information regarding processes that bind marine ecosystems, including habitat locations, larval and adult movement, trophic interactions, and fisher behavior. However, recent advances in habitat-mapping technologies, genetics, marine microchemistry, animal tracking and numerical modeling have greatly enhanced our knowledge of these processes. Although these advances have yet to be fully integrated into management decisions, they have the potential to revolutionize spatial marine management. Nevertheless, this revolution will require advances in our ability to share and integrate data into models of marine ecosystems.

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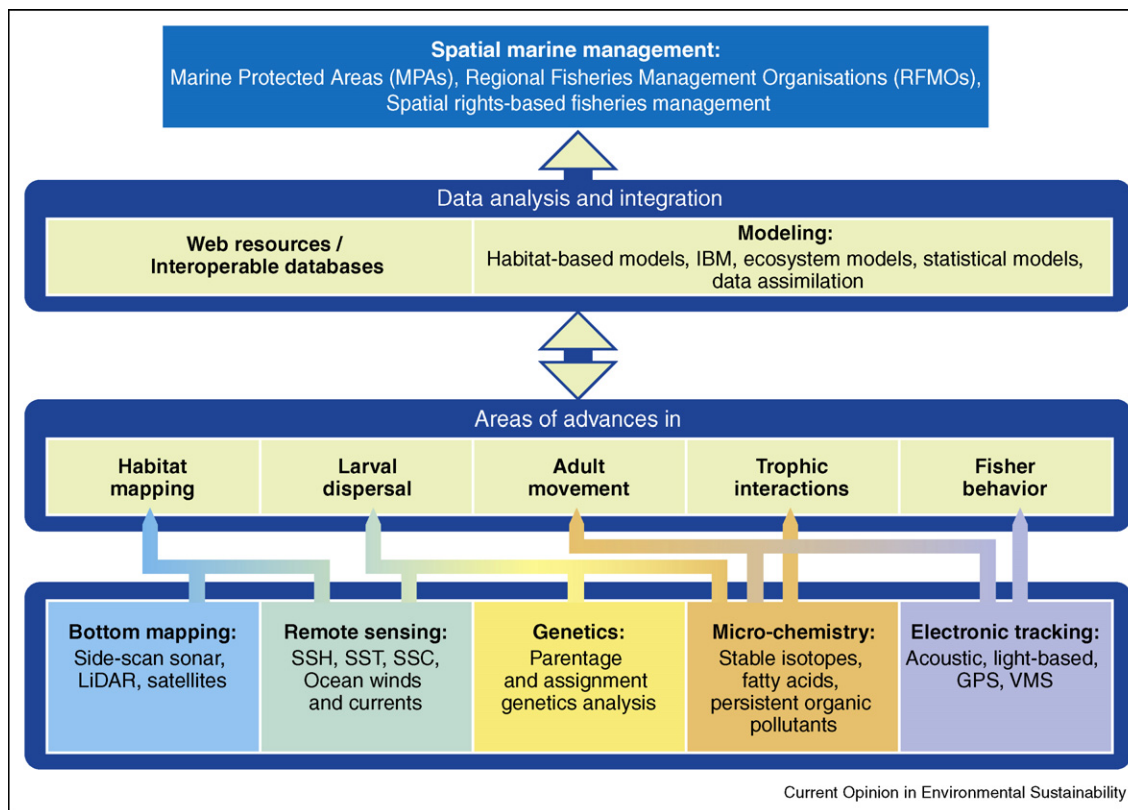
Introduction

The management of living marine resources has been moving in two different directions over the last decade. On the one hand, there has been a massive emphasis on the 'spatialization' of marine management. Although marine protected areas (MPAs) are the most visible part of this trend [1], regional fisheries management organizations (RFMOs), spatial right-based fisheries management [2*] and the impending spatio-temporal changes in marine ecosystems due to climate change (e.g. [3,4**]) have all necessitated an increasingly spatialized and regional approach to marine management. On the other hand, much of our understanding of marine systems (e.g. [5,6*]) and the ecosystem approach to fisheries (EAF; [7]) are moving toward more integrative approaches that cross boundaries of individual species, human impacts or spatial zones. In order to effectively manage both at the local scale of an individual management action and to ensure persistence and ecosystem services at global scales, one needs detailed knowledge of the processes that structure marine ecosystems [8]. These processes include the spatial extent and organization of marine habitats, larval dispersal and adult movement, trophic interactions, and fishers' reaction to management.

Understanding all of these processes at the level necessary for effective spatial management is an enormous task. Until recently, these processes have been difficult to study, and the vast majority of spatial marine management has been based on expert opinion, very simple models (e.g. [9]) and/or siting algorithms that take only resource location into account [10*]. Nevertheless, recent advances in habitat-mapping technologies, genetics, microchemistry, animal tracking and numerical modeling have greatly enhanced our ability to describe in detail marine ecosystems. With the exception of habitat data, which has quickly been incorporated into management decisions through existing habitat-based reserve-placement algorithms [10*], most of these advances have yet to significantly impact spatial marine management. However, the increasing precision and accessibility of these technologies, combined with the proliferation of rich statistical and numerical models potentially capable of incorporating these data, suggest that we are primed for a revolution in spatial marine management. Here we describe some of these recent advances in our ability to understand marine ecosystems. While our goal is not to provide an in-depth analysis of each technique, we do indicate how they are likely to contribute to future

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Figure 1



Overview of the different advances in the study of marine ecosystems that are discussed in the paper, how they contribute to the various processes that must be understood for effective spatial marine management and what are the likely efforts necessary to more fully integrate these advances into management planning and assessment.

management efforts, as well as highlight some of their weaknesses and limitations (Figure 1).

Habitat definitions

Accurate descriptions of marine habitats have long been central to spatial marine management. Despite important differences between marine and terrestrial systems in the connectivity between subpopulations and the nature of anthropogenic pressures [11], habitat-based approaches remain (justifiably so) the first step in spatial marine management. In coastal environments, a number of high-resolution habitat-mapping technologies exist that provide accurate data over wide areas, including multi-beam side-scan sonar, airborne light detection and ranging (LiDAR), and certain types of satellite remote sensing [12]. Although these technologies differ in the specifics, they all capture an acoustic or electro-magnetic signal reflecting from the bottom. The resulting reflectance, color, rugosity and/or steepness data can then be used to classify bottom types [13], which play a major role in structuring coastal ecosystems. Although these methods remain relatively expensive, their immediate value for management (e.g. [14,15]) has justified significant investment. One example: California plans to invest

USD 15 million in multi-beam side-scan sonar surveys of state waters to support development of a MPA network.

Recently, there has been a move toward the use of MPAs, in addition to existing RFMOs, for the management of offshore, pelagic ecosystems [16–18]. Offshore ecosystems are typically not connected to bottom features and are often much more dynamic in space and time than coastal ecosystems [19]. Although the division of the oceans into large provinces, based primarily on insulation, global oceanographic climatologies and satellite-based surface primary productivity, by Longhurst [20] provides an essential starting point for classifying pelagic ecosystems, remote sensing and animal tracking data have recently been used to study the fine details of pelagic ecosystems. For example, satellite data on sea-surface color (SSC) and sea-surface height (SSH) have been used, in combination with animal behavior data from tagging and rich statistical models, to determine preferred foraging habitats in relation to contemporaneous oceanographic conditions (e.g. [21]). One potentially interesting use of this information is to dynamically select management actions based on realtime environmental data [18].

Larval dispersal

In the context of spatial marine management, larval dispersal has been an area of significant focus because the majority of marine species produce many small larvae that are transported by currents for long periods [22]. Larval dispersal has been considered a black box in marine ecology due to the difficulty in tracking numerous microscopic larvae. Rough estimates of dispersal scales have been based on the length of the larval period combined with oceanic current characteristics and larval behavior data [23,24]. Additional information can be gleaned from genetic variation in the adult population [25], though this is problematic due to the mismatch in timescales between the larval period and that of genetic mutation [26•].

Significant advances in genetics, marine microchemistry and individually based modeling (IBM) have revolutionized our understanding of larval dispersal recently [27]. It is now possible to directly assess larval dispersal patterns over a single generation. One technique involves artificially chemically marking reproducing individuals at a location (e.g. with radioactive, trans-generational markers) and later testing new recruits for the chemical signal [28•]. This approach relies on integration of the marker into the bodies of individuals, usually through calcareous structures such as fish otoliths or mollusk shells. Genetic fingerprinting (i.e. using genetic markers to uniquely identify individuals) combined with parentage analysis has been used to identify the point of origin and recruitment of coral reef fish [29], with application to marine reserves [30••]. Both of these techniques currently rely on having a manageable population size, but costs and speed of analyses are both coming down, making larger studies foreseeable. Furthermore, in some systems, gradients in ambient chemical markers may be sufficient to identify the origins of individuals without the need for artificial markers [31,32].

Despite advances, direct input to spatial management will almost certainly pass through dispersal models. Increases in computing power have made simulations of large numbers of individual larvae feasible [33]. These IBM generally use oceanographic simulations, as well as larval physical and behavioral information, to simulate dispersal patterns. Notable case studies include evaluation of connectivity in the Caribbean [34] and understanding the life cycles of small pelagic species in upwelling systems [35•]. Nevertheless, validation of these models via comparisons with direct measures of larval dispersal patterns (such as those described above) and integration of improved data on larval behavior and mortality (also potentially from the techniques described above) remain major areas of future research.

Adult movement and behavior

Spatial marine management has increasingly turned toward mobile pelagic and demersal species [16,18,36]

despite the fact that mobile species are likely to move between management zones, complicating assessment efforts. Models suggest that accurate assessment of movement is essential for predicting and understanding the impacts of spatial management (e.g. [37,38]). Until recently, most data on marine animal movement came from observations of population density as a function of season and/or age group, or mark-recapture data, neither of which gives the full trajectory of an individual. For spatial management, 50% of individuals spending all their time in a zone is quite different from 100% of individuals spending 50% of their time in a zone. As such, new tools that greatly enhance our knowledge of individuals' movements are essential.

Perhaps the most exciting development in the study of marine animal movement and behavior has been the explosion in the use of electronic tags. These tags consist of time recorders combined with physical (e.g. light, temperature, and pressure) and/or biological (e.g. location, swimming/diving activity, feeding behavior, and heart rate) sensors. They provide concurrent environmental and physiological/behavioral/ecological data at the temporal and spatial scales at which animals operate. Animal location can be obtained using a variety of techniques based on either the reception of a physical signal (light-based geolocation, GPS) or the emission of a signal (acoustic, ARGOS). Internal or external acoustic transmitters emit sound signals that are collected by special receivers to determine fish location. Due to the dissipation of sound in water, they are most often used over relatively small spatial scales (<10 km) in coastal environments [39,40], though recent efforts to build large, collaborative networks of receivers may expand the spatial scales accessible with these tags [41]. External electronic recorders used for light-based geolocation of birds [42•] and marine species [5] determine longitude and latitude using the local time of sunrise and sunset, as well as the duration of the day. Due to limitations in the precision of light-based geolocation, these tags are typically used to track animals over long periods of time (several months) and are particularly appropriate for the recording of long migrations. Finally, GPS recorders are increasingly used, and allow very fine scale analysis of animal movements for those species that are regularly at the ocean surface (e.g. reptiles, birds and marine mammals) [43]. Despite the increasingly small size and the obvious conservation applications [44,45] of electronic tags, their size and cost largely limits their use to megafauna.

While these technologies provide detailed information on megafauna over relatively short time periods (months to years), chemical tracers provide important information for a large class of marine species regarding habitat use and trophic interactions throughout an individual's lifetime. A number of such chemical tracers exist, including stable isotopes [46], fatty acids [47,48] and persistent organic

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pollutants [49], listed roughly in order of increasing cost and complexity of interpretation. These tracers, in combination with environmental data, can provide crucial information regarding trophic level [50] and seasonal, ontogenic or migratory movements [50,51*,52]. Combining different tracers [53*], measuring the same tracer on different tissues with specific metabolic turnover rates [54] or integrating these tracers with more-detailed short-term tagging studies hold the potential to provide fine-grained information over a variety of temporal and spatial scales.

Fisher behavior

Although fisher behavior itself is often overlooked by biologists, it is extremely important for determining the final effects of spatial management efforts (e.g. through the reallocation of fishing effort after MPA creation [55]) and is generally central in the mind of the fishing industry itself. Over the last decade, improvements in GPS technology accessibility have made vehicle-monitoring systems (VMS) the norm in many industrial fishing fleets and RFMOs. These devices provide regular (e.g. hourly) positions of fishing vessels. It has been suggested that they play a central role in enforcing spatial and temporal management efforts [18], but assuring VMS use on all vessels remains challenging [56]. Though the use of these data for scientific purposes is complicated due to privacy concerns (e.g. knowledge of individual boat fishing practices), it has the potential to provide a wealth of information on fish habitats and predator behavior (i.e. humans as predators [57*]).

Conclusions

The new techniques described above provide invaluable information on the functioning of marine ecosystems. Even since a previous survey of new technologies for MPA implementation in 2003 [58], there have been dramatic advances, particularly in our ability to track individuals during all life phases. Nevertheless, the majority of these techniques have yet to significantly impact spatial management efforts. One reason for this is the difficulty of scaling up (e.g. to large population size) or down (e.g. to specific locations) these techniques to scales appropriate for informing management decisions. For example, existing larval and adult tracking techniques have difficulty assessing species of greatest interest for fisheries, that is, those having large populations extending over significant areas. For the majority of the techniques described here, costs, labor and time needed to perform analyses are decreasing, making larger and more exhaustive analyses potentially feasible in the near future. Furthermore, as the value of these techniques becomes evident, significant investment in them should follow and, over time, rich, reusable datasets will develop.

Another major challenge is packaging available information in a way that it can be easily integrated into

management decision-making. As management decisions will increasingly be based on data from different sources, interoperability and open-access to data will become increasingly important. Recent efforts to develop rich web resources for sharing and communicating biological data are a major step in the right direction [59]. But these web applications do not solve the problem of how to use data that will necessarily be partial (i.e. covering a subset of species' life cycles, spatial zones, trophic webs, etc.) and imperfect for quantitatively informing management decisions. More profound confrontation between data and models (e.g. tracking data and IBM models of animal behavior) is necessary part of confirming the value of models for management decisions. In addition, there has recently been a move in marine modeling toward using more complex models inspired by the success of oceanographic forecasting models [60]. This trend has the potential to open the door to rich sets of data assimilation and Bayesian inference techniques that are regularly used in oceanographic forecasting (e.g. [61]). Nevertheless, much work remains to be done to validate these integrative approaches and make them accessible to resource managers.

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