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# MARINE PROTECTED AREA DESIGN: TOWARD A GENERALIZED LIFE HISTORY APPROACH

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## SUMMARY

One of the primary challenges of designing marine protected areas (MPAs) is the application of empirical data obtained from one site to the design of other sites within or between large marine ecosystems. Central to this challenge are questions about location, size, and number of MPAs within a network. Existing scientific studies have aided site-specific MPA efforts but do not necessarily inform the process of MPA design and implementation in other areas. We propose a research agenda that will lead to a generalized empirical model to ultimately provide managers with a more substantive "tool box" from which to draw upon when identifying options for MPAs. We present an example of such an approach focused on particular life history characteristics of fishes, but which can be used for a wide variety of taxa. The approach is two-tiered and requires data about: 1) sources and sinks for larvae, and 2) movement rates-at-age for targeted umbrella species. Related ecological data can then be used to "fine-tune" MPA site and network designs.

## 1.0 INTRODUCTION

The appropriate size and number of terrestrial protected areas needed to conserve diversity received extensive attention in the late 1970s. The relative benefits of single large or several small (SLOSS) reserves within a region were hotly debated in the scientific literature (1,2). The "resolution" of the debate ended with the ultimate emphasis in protected area design resting on a species or site-specific approach (3), in which the characteristics of the species or ecosystem targeted for protection dictates reserve size and shape. The SLOSS debate, however, has yet to be resolved with respect to the design of marine protected areas (MPAs; here we define MPA as a no-take zone for the conservation of biological diversity of all taxa), due to important differences between marine and terrestrial systems (4). For example, where populations in terrestrial protected areas are largely replenished as a function of local adult fecundity, with minimal immigration and dispersal of offspring occurring within protected area boundaries, most marine populations are distinguished by some or all of the following characteristics: planktonic dispersal of larval stages, high migration rates, and spatially distinct sub-populations, making design of MPAs more difficult (5).

The tale of MPAs in temperate and boreal seas, thus far, is largely one of unfulfilled potential. Despite increasing interest in MPAs by a wide range of stakeholders for the conservation of biological diversity (6-11) as well as for fisheries management (12-17), there continues to be a disconnect between the desire to designate sites and the ability to demonstrate the utility of MPAs to those opposed to such conservation

measures. In particular, there is a paucity of data to inform the designation process regarding alternatives for size, shape, number, and location of MPAs within a region.

There are at least three potential explanations for this problem. First, in many instances, the disconnect is likely due to the "crisis driven" mentality that often requires designation of a site for reasons of political expediency without taking the time to incorporate existing science (18). Of the approximately 1300 MPAs designated worldwide, the vast majority of these have been designated for socio-political reasons rather than scientific ones (19). Second, in many circumstances it is equally likely that the necessary information about the ecology of the organisms targeted for protection is not yet. Especially for areas away from the coast, the costs for ship time and the sampling systems (e.g., multibeam sonar, research submersibles) required to collect data at appropriate spatial and temporal scales can be extremely costly. And third is the reluctance of both scientists and managers to base decisions on ecological information collected elsewhere.

So the question to be answered is how can the scientific community proceed from the current set of circumstances towards the desired goal of reducing uncertainty in advice to decision-makers regarding designation of networks of MPAs? Asked another way, how can we target research efforts to make the whole greater than the sum of the parts? Clearly there will never be enough financial resources and time to study everything everywhere. Models are needed to provide predictive capabilities regarding size, shape, number, and location of MPAs. Such models must be able to take empirical data from specific studies and generalize the results for use in other locations. The result of such efforts will be to create a "tool-box" of models for use by conservation professionals.

We suggest that such models be based on the life history strategies of the major taxa of interest. Assuming that organisms with particular life histories (and morphologies) exhibit behaviors within a defined envelope, it should be possible to develop generalized conceptual models such that life histories define the size, shape, number and location of MPAs. In this paper we discuss the utility of a two-tiered approach that requires information about: 1) sources and sinks for larvae, and 2) movement rates-at-age for species targeted for conservation. The resulting generalized models can then be modified and clarified over time as data from future empirical studies are available. Here we use fishes in the Gulf of Maine (Northwest Atlantic) as an example of the application of these concepts.

## **2.0 EARLY LIFE HISTORY CONSIDERATIONS FOR DESIGNING NETWORKS OF MPAS**

MPAs are by their very nature "leaky" systems when populations of organisms are considered. Vagile species immigrate and emigrate through the borders of MPAs and propagules are exported unless current patterns (and the behavior of larvae or pelagic juveniles) allow entrainment. Sources of recruitment need to be considered in order to avoid local extinctions. Since the ultimate goal of MPAs is to conserve diversity, a network design requires a level of self-sustaining properties such that sources and sinks of a wide range of taxa are considered.

Knowledge of circulation patterns, as well as larval period for a wide range of taxa

within a region, is a fundamental requirement for siting a network. Circulation data can come from a variety of sources. For example, current drifters were used to identify patterns of sources and sinks for fish larvae to Caribbean reefs (20). Many regions of North America have historic or ongoing circulation modeling work focused on recruitment of particular species of economic importance (e.g., 21)

Data on larval period can be summarized from existing publications for a variety of taxa. Larval periods can be quantified and used in conjunction with circulation models to develop distributional "envelopes" around larval source areas (Figure 1). Preliminary results of modeling 30-day larval trajectories to and from Stellwagen Bank National Marine Sanctuary in the Gulf of Maine has shown that recruitment to the site generally comes from mid-coast Maine and propagules from the site move into Cape Cod Bay and towards Great South Channel (22). Here the location of an individual MPA can be identified using knowledge of fish spawning aggregations and predicted areas of juvenile fish settlement. The distance between individual MPAs in the network is determined by the larval period of targeted taxa combined with knowledge of oceanographic conditions.

Using circulation models and knowledge of larval period for multiple taxa, it is possible to model alternative site locations and sizes to optimize recruitment potential within a network. Model results could be used to develop sets of predictions based on the types of faunal information used to parameterize the model. Empirical tests of predictions could then be used to refine and expand the network. Such knowledge is critical for planning networks (number and location of MPAs) at regional scales.

### **3.0 SIZE AND CONFIGURATION OF MPAS BASED ON LIFE HISTORY PATTERNS OF JUVENILES AND ADULTS**

Information on the movement rates of each species after settlement is critical for determining the appropriate size of individual MPAs. In developing a model for the designation of MPA size and configuration, movement-at-age for the taxa targeted for protection must be determined, as well as how that movement occurs relative to features in the marine environment.

Movement at age is highly variable among fishes. For example, modeling studies demonstrated the importance of MPA size relative to the movement of adult fish for species with relatively high movement rates such as Atlantic cod (*Gadus morhua*), pollock (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*) (23-25). Fish survivorship in these studies is highly dependent on reserve size relative to fish movement rates. Other studies (26,17) showed survivorship of juvenile fish to be dependent on fish movement rate, reserve size, and seafloor habitat quality.

Fish tagging with both passive and acoustic tags can provide vital data on the movement rates of individual fish. For example, studies have assessed movement of cod over time scales varying from days to years using visual tags, primarily in coastal waters. Using passive tags, Pihl and Ulmestrand (27) showed that over a 3-year period off the coast of western Sweden the mean total distance traveled by cod ranging from 30-50 cm did not exceed 37.4 km and mean distance traveled day<sup>-1</sup> did not exceed 537 m. Acoustic tags were used by Clark and Green (28) to track cod in Broad Cove in Conception Bay, Newfoundland. Fish tracked for up to 21 days traveled a

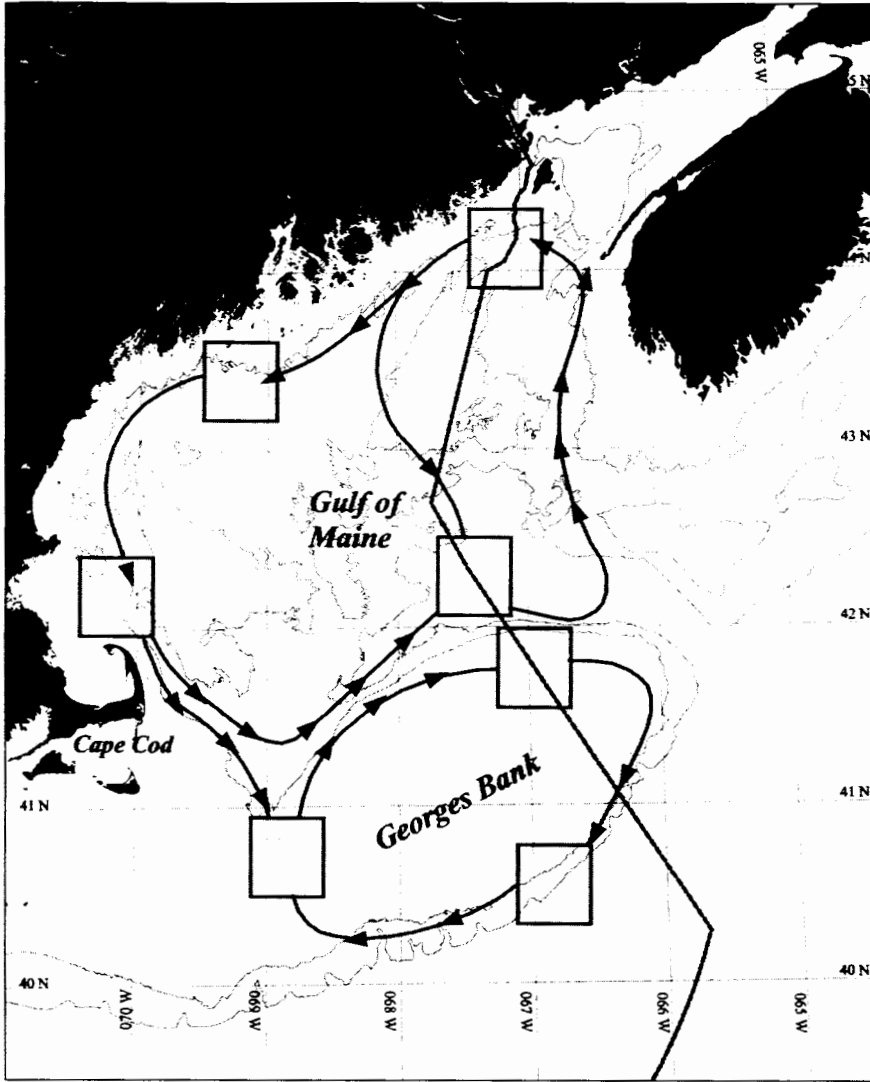


Figure 1. Hypothetical network of MPAs in the Gulf of Maine and Georges Bank. Individual MPAs (boxes) are positioned relative to current trajectories (48) so that larvae dispersed from MPAs have some probability of settling in the next site "downstream". Note the interconnectedness of all sites within the network. The size of individual sites can be determined by movement rates of taxa of interest. The distance between MPAs can be identified using information on fish larval period and dominant current patterns.

maximum of 8 km from the cove and movement varied significantly seasonally and over the course of a day.

As information on the movement rates (e.g., daily, monthly, seasonal, annual) for individual fish of a range of species is collected, these data can be used to scale the size of individual MPAs (Figure 1). An MPA can be sized to capture some percentage of the range of a single species or taxa (e.g., umbrella species), or multiple species. Planners can use such models for regions where no direct empirical studies have been conducted.

Knowledge of oceanographic conditions and bathymetry can be used for the configuration of an individual MPA (Figure 2). In this example, MPAs can be oriented parallel to the dominant current regime under high energy conditions (Box A) thereby capturing the greatest part of the range of an organism that is subjected to strong currents. MPAs can also be oriented perpendicular to isobaths (Box B) where movement of targeted taxa is known to occur over a range of depths or with the tides.

#### **4.0 FINE TUNING MPA DESIGNS WITH THE BEST AVAILABLE DATA**

Once a general framework for a network of MPAs has been identified, the location, size and configuration of individual MPAs in the network can be fine-tuned using available data on the taxa targeted for protection. For example, associations of fishes with seafloor habitat are critical relative to the size and configuration of a MPA. A species that associates strongly with one microhabitat feature of the seafloor might behave differently over different areas. Field and laboratory studies indicate that individual juvenile Atlantic cod (*Gadus morhua*) exhibit strong site fidelity in high relief habitats such as boulder or rock reefs, while juveniles have been observed to school in the water column over low relief habitats such as sand and gravel (29-31). Other studies demonstrated that many fish species exhibit statistically significant but facultative associations at various life history stages with specific microtopographic structures (=microhabitats) in low topography environments on the northwest Atlantic continental shelf (32-37).

While species assemblage patterns at the regional scale can be defined by temperature and depth contours in the northwest Atlantic (38,39), fish movement at smaller scales, relative to particular habitat types, remains highly uncertain for outer continental shelf species. However, it is for precisely these smaller scales that movement data are required for the design and implementation of MPAs for fish conservation and management.

Individual MPAs can be sited within assemblage boundaries and/or transition areas between seafloor habitat types (Figure 3). This approach has been discussed in the context of using fish as umbrella species and maximizing diversity of seafloor invertebrates by maximizing sediment (i.e., grain size) diversity (11).

Fish movement rates alone will offer insight into MPA size, but the direction of that movement relative to seafloor habitat may take a range of forms (Figure 4), all of which bear directly on the configuration of an MPA. For example, if fish movement occurs linearly along a feature (Figure 4 a-d), a narrow MPA oriented parallel to the major axis of movement may capture a larger number of individuals within its borders.

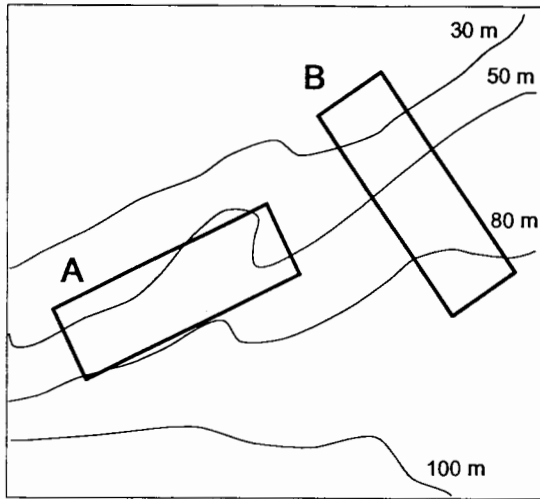


Figure 2. Alternative configurations of MPAs based on organismal responses to seafloor bathymetry. An individual MPA can be configured parallel to isobaths (Box A) to protect those taxa that move along isobaths (e.g., based on alongshore currents), or perpendicular to isobaths (Box B) to protect taxa that move across a range of depths (e.g., based on tidal period).

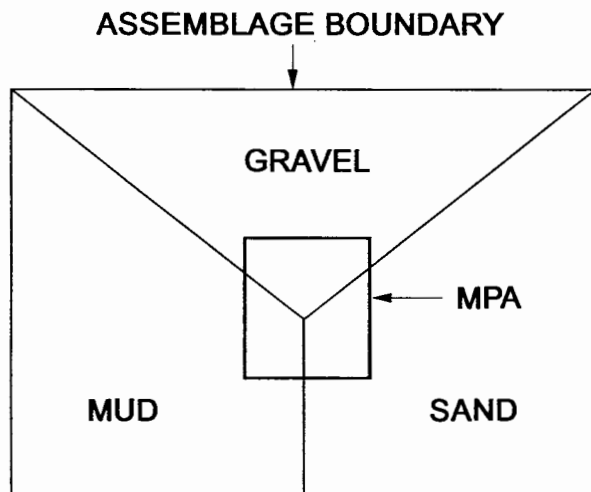


Figure 3. Individual MPAs can be sited within fish assemblage boundaries and in areas of transition zones between seafloor habitat types to maximize seafloor habitat diversity (which will enhance diversity of infaunal and epifaunal species).

This is the case with juvenile cod on the northeast peak of Georges Bank (northwest Atlantic), where the orientation of the gravel substrate (generally west to east), the dominant clock-wise current gyre, and the association of juvenile cod with gravel substrate combine to move fish generally west to east. Alternatively, fish might exhibit central-place foraging, such as around a boulder reef, ranging near around particular features (Figure 4 e & f). Cunner (*Tautogolabrus adspersus*) move away from reefs in flow refuge areas to forage. As tidal currents change, they move to other flow sheltered areas. At night, all individuals return to shelter within the reef (40).

## 5.0 THE APPLICATION OF DATA BETWEEN SITES

The application of ecological information produced at one site to the design and implementation of an MPA at another site has proven to be problematic. Scientists and managers alike are forced to grapple with a range of fundamental questions on this issue. For example, does information on fish movement in the coastal zone adequately inform the process of MPA design in areas well offshore where movement rates of the same species are unknown? How does a particular species' association with seafloor habitat change throughout its range? Are oceanographic conditions at one site sufficiently similar at other sites to make comparisons valuable? Often the answers to these questions come only from a consideration of the information in its ecological context.

A second hurdle for the use of ecological information for the design of MPAs systems from the type of studies that produced the information. A great deal of information on the behavior of fish comes from laboratory experiments that are conducted at very small scales. For example, a series of experiments conducted in the U.S. and Canada in small aquaria indicate that the survivorship of early benthic phase juvenile Atlantic cod (*Gadus morhua*) is mediated by the complexity of the habitat to which they settle (41-44). The size of the aquaria in which these experiments were conducted represent less than 1% of the probable range of cod in the wild. These experiments, however, provide critical information on the ecological processes operating on an organism.

Computer and mathematical models are another source of data on the design of MPAs (23,45,46,26,17,47). Such models are, by definition, abstractions of reality. Even the most robust model involves a host of simplifying assumptions about the behavior of the organism targeted for protection and/or the environmental conditions of the habitat in which the targeted organism lives. The presence of uncertainty in aquatic systems need not preclude the use of models for MPA design. Rather it requires an adjustment in expectations of the modeler. Simple, yet powerful, models of a given system, or sub-system, can provide important information to scientists and managers alike with respect to future trajectories of a system's development given an range in MPA size and configuration (26).

Ultimately, the applicability of information collected at one site to the design of an MPA at another site is dependent upon a case by case analysis of the study's ecological significance. Ecological data derived from multiple sources and scales are rarely mutually exclusive, rather they are often complementary and explanatory depending upon the scale of analysis. Such data allow us to refine our understanding of

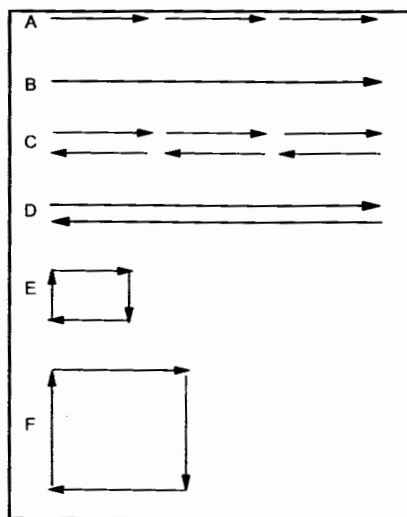


Figure 4. Fish movement relative to seafloor habitat can be used to fine-tune the configuration on individual MPAs. Movement might occur linearly along features (A-D), or around particular features (E and F).

how organisms interact among each other and with the physical environment. Using the general life history model we presented as a foundation for MPA design, ecological information from a range of scales, regions and data sources can be used to design an MPA network (11).

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