Knowledge through partnerships: integrating marine protected area monitoring and ocean observing systems

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Escalating concern over the state of coastal marine ecosystems highlights the need for a better understanding of how such systems are structured by physical, biological, and chemical processes, and how human activities interact with these processes. Marine protected area (MPA) networks are being established around the world, in an effort to protect marine populations, communities, and ecosystems. Concurrently, ocean observing systems (OOSs) are being developed and implemented to identify and describe changes in the coastal oceans. Because marine ecosystems are strongly influenced by oceanographic processes, proper interpretation of ecological data to assess MPA performance requires information generated by coastal OOSs. At the same time, OOSs designed with the goal of identifying ecosystem responses to climate change require information from long-term ecological monitoring studies of MPAs. Collaborative integration between ecological and oceanographic monitoring programs is central to elucidating both the role of MPAs for conservation and the influence of climate change on marine ecosystems.

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Recently, marine policy concerning resource sustainability and resilience in coastal ecosystems has emphasized the importance of understanding ecosystem function and predicting change in the face of continued extraction (Leslie and McLeod 2007; Levin and Lubchenco 2008) and climate change (Scavia *et al*. 2002; Cochrane *et al*. 2009; Doney *et al*. 2009; Rabalais *et al*. 2009). Improved understanding of coastal ecosystems will help us formulate management policies that more effectively mitigate human impacts on coastal regions. Networks of marine protected areas (MPAs) have been established as tools for achieving conservation objectives and monitoring the "natural" (eg unfished) state and trajectory of coastal marine ecosystems and habitats (McLeod *et al*. 2009). At the same time, ocean observing systems (OOSs), designed to monitor the state of coastal oceans and facilitate predictions of how coastal environments will respond to anthropogenic alterations and a changing global climate, are rapidly expanding. Independently, OOS and MPA initiatives can inform ecosystem-based management of coastal marine ecosystems. However, integration of OOS and MPA monitoring programs will broaden the purpose and value of each. Several examples of potential MPA monitoring and OOS partnerships already exist worldwide. In Australia, an existing network of MPAs is monitored by the Great Barrier Reef Marine Park Authority (www.gbrmpa.gov.au). The Joint Australian Facility for Ocean Observing Systems (http://cawcr.gov.au/bmrc/ocean/JAFOOS/) has been established to integrate its ocean monitoring networks. Canada has also created an MPA network (www.dfo-mpo.gc.ca/oceans/marineareas-zonesmarines/mpa-zpm/index-eng.htm) and the Atlantic Zone Monitoring Program, which combines monitoring of biological, chemical, and physical variables (www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html). On a more local scale, individual MPA monitoring efforts have been linked to long-term oceanographic monitoring time series (Mosetti *et al*. 2005). Here, we draw examples from the developing MPA network and OOS along the coast of California, to illustrate the synergistic value of this integration.

In a nutshell:

- Ocean conditions and marine ecosystems are being transformed as a result of climate change
- In order to protect these ecosystems and the services they provide, we need to understand and predict how these changes interact with human uses of marine resources
- This will require a novel integration of ecological and oceanographic monitoring programs across a wide range of spatial and temporal scales
- Marine protected area (MPA) monitoring can reveal how coastal ecosystems are responding to the changing ocean conditions documented by ocean observing programs
- In turn, ecological monitoring requires oceanographic information to properly evaluate the effectiveness of MPAs

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Evaluation of MPA performance and ecosystem responses to changing ocean conditions

"Marine protected area" is an umbrella term that encompasses a range of spatially explicit management regulations that restrict human activities for the purpose of conserving or restoring marine ecosystems. The most restrictive form of MPA, the "no-take marine reserve", typically allows human access, but permanently prohibits extraction of any component of the marine ecosystem. Other forms include areas with restrictions on fishing, public access, and tourist activity (NRC 2001; Ward *et al.* 2001; Sobel and Dahlgren 2004).

MPAs are established to achieve specific objectives, most often to (1) protect and restore populations of fished species; (2) protect the natural structure of ecological communities; and (3) protect functions and resilience of entire ecosystems (Sobel and Dahlgren 2004). In addition, MPAs can provide "natural baselines", against which human-impacted ecosystems outside MPAs can be compared and evaluated. To achieve these objectives, MPAs must be designed and assessed using information about both the structure and function of ecosystems targeted for protection and the oceanographic processes affecting them. In particular, historical and contemporary patterns of variation in ocean conditions provided by OOSs are essential for understanding seasonal, interannual, and overall ecosystem variability, and provide historical context for interpreting observed ecosystem dynamics. Because coastal ecosystems are valuable to society economically and culturally, as well as for research, education, and recreational activities, objectives of MPAs and their associated monitoring programs must also include socioeconomic factors that are sensitive to changes in ocean conditions (Sanchirico *et al.* 2002; Pomeroy *et al.* 2005).

Frequently, legislation establishing MPAs includes a requirement for monitoring and evaluation, to determine if stated objectives of the MPA are being achieved. The expectation is that MPAs will be managed adaptively (eg making changes in design or regulations, or eliminating an MPA altogether) in accordance with ongoing monitoring and evaluation of the state of the ecosystem. Although references exist for designing ecological monitoring programs to evaluate MPAs (Pomeroy *et al.* 2005), few, if any, include any mention of simultaneously monitoring and forecasting oceanographic processes that affect MPA performance indicators, such as abundance and size structure of target populations or indices of stability and resilience of protected ecosystems. Because regional-scale oceanographic processes influence larval transport, as well as movement, growth, and survival of marine organisms, these processes can determine temporal and spatial patterns of ecological responses across MPA networks (Barth *et al.* 2007; Woodson and McManus 2007; Botsford *et al.* 2009; Gaines *et al.* 2010; Hamilton *et al.* 2010). In conjunction with local-scale oceanographic processes, these regional-scale processes also play a major role in shaping patterns of ecological responses within individual MPAs and their "reference" sites (ie sites outside the MPA that are monitored and used for comparison with the MPA). In addition, large-scale, long-term processes – such as the El Niño Southern Oscillation (ENSO), decadal shifts, and regime shifts related to climate change – can directly influence the transport, growth, mortality, and recruitment of larvae, and the productivity and availability of their prey (Holbrook *et al.* 1997; Mantua *et al.* 1997; Hollowed *et al.* 2001; Edwards and Richardson 2004).

Because oceanographic processes can determine the rate and distribution of ecological processes across a range of scales, oceanographic monitoring is a necessary part of interpreting the evaluation of MPAs. MPA evaluations can therefore benefit greatly from incorporating existing regional OOS programs into monitoring designs. Indeed, OOSs are mainly intended to provide information that will help society mitigate the impacts of, or otherwise adapt to, changing coastal ecosystems (eg Global Ocean Observing System, www.ioc-goos.org); one important component of this effort is providing data for MPA monitoring and evaluation, as evidenced by recently funded Integrated Ocean Observing Systems (IOOSs) proposals. In turn, monitoring of MPA networks can provide ecological data necessary for OOSs to identify ecosystem responses to changing ocean conditions. Integration of OOS and MPA monitoring will therefore help regional OOS programs achieve their primary objectives.

Two key considerations for successfully designing an integrated OOS and MPA monitoring scheme are: (1) what ecological and oceanographic variables need to be monitored in order to assess ecosystem change and MPA effectiveness?, and (2) at what spatial and temporal scales do these variables need to be resolved and analyzed? We address each of these considerations in the following sections.

What variables need to be monitored to assess ecosystem change and MPA effectiveness?

Determination of important ecological and oceanographic variables is a requisite for assessing MPA performance. MPA objectives should first be partitioned into specific performance indicators and demographic variables (Figure 1). Next, oceanographic processes that exert an influence or governing effect on these performance indicators and demographic variables should be identified. In order to interpret variability of performance indicators through time, or between MPAs and reference sites, it is necessary to understand to what extent differences are explained by fluctuations in oceanographic processes. Concurrently, MPA monitoring of population, community, and ecosystem trends can be used to evaluate the implications of changes in ocean conditions documented by OOSs. In the examples presented below (drawn primarily from rocky-reef ecosystems in the California Current, a Pacific Ocean current that runs along the west coast of North America), three fundamental MPA objectives are used to illustrate the series

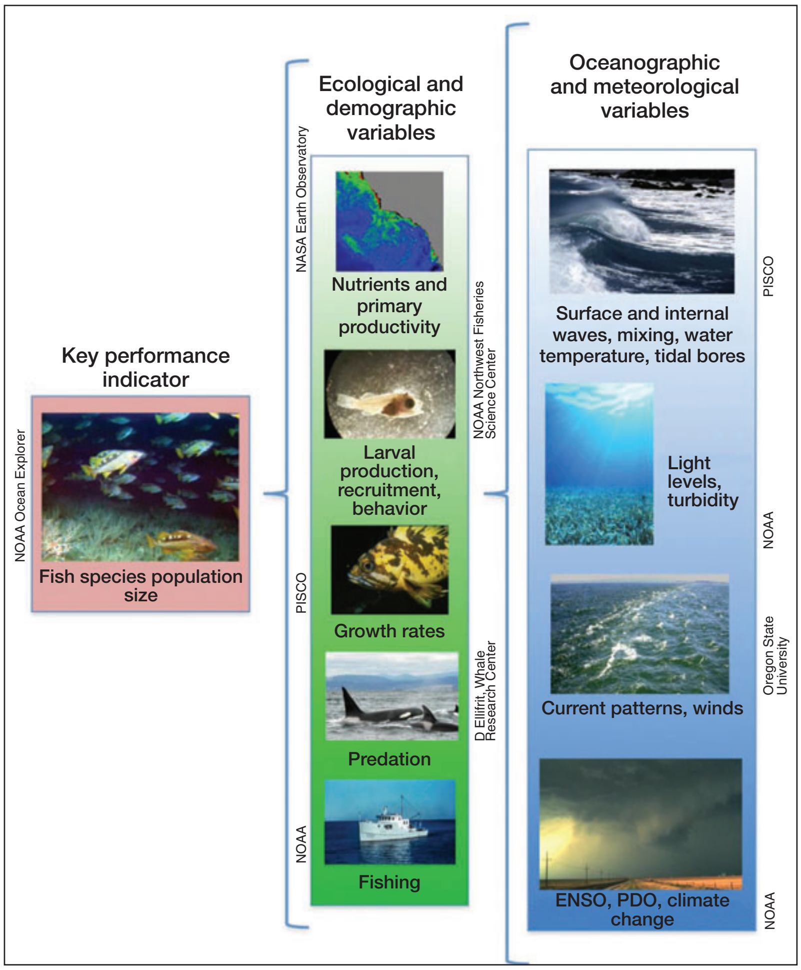

Figure 1. *Representation of linkages between management questions, ecological variables, and oceanographic processes.*

of connections between causal and response variables that must be identified and quantified in order to evaluate MPA performance.

Example 1: increase the number of large individuals and/or the overall size of a fished population

Two predictions to be tested by a monitoring program are that larger individuals and greater densities of a species targeted by fishing will occur within an MPA (Figure 2a–d). Important demographic variables underpinning these performance indicators include juvenile recruitment, individual growth, and size-specific mortality rates. These ecological variables are, in turn, governed by a series of explanatory variables, such as predation, habitat, larval production, and behavior (Figure 2e and f). Oceanographic processes that cause spatial and temporal variations in explanatory variables may include internal waves, swell, upwelling, and large-scale oscillations and regime shifts (eg ENSO, climate change; Figure 2g). Associated measurable variables, such as water temperature, light levels, nutrients, and current velocities, that characterize oceanographic processes of interest can then be identified (eg Broitman *et al.* 2005; Mace and Morgan 2006; Siegel *et al.* 2008). Including these metrics in the MPA monitoring scheme will minimize the potential for misinterpreting both the effects of the MPA on the local marine ecosystem and whether or not the MPA's objective is being met.

Example 2: preserve relative abundances and functional roles of species within a community

To assess whether the establishment of an MPA results in a species assemblage where the proportion of fished species increases, one would perform a multivariate evaluation of species composition and relative abundance. These variables are directly affected by differential rates of recruitment, mortality, and emigration (Figure 3). These are, in turn, determined by species-specific explanatory variables, such as larval production, behavior, refuge availability, and predation. In addition, interactions between species – including competition, mutualism, and disease – alter their relative abundance. These ecological variables can be greatly influenced by environmental, physiological, and behavioral processes. For example, rates of emigration across MPA boundaries for different species may vary as a result of species-specific responses to environmental conditions, such as resource availability, turbidity, currents, and temperature. Swell exposure can also affect depth distributions and movement patterns of fish species that inhabit nearshore areas and exhibit varying preferences for, or tolerance of, greater swell exposure (Freidlander *et al.* 2003). More generally, the relative importance of predation, competition, and other environmental stresses in determining structure of a community can vary across gradients of physiological stresses such as temperature and swell exposure (Menge and Sutherland 1987; Sanford 1999). Given these factors, key measurable oceanographic quantities related to this management objective include water temperature, swell, turbidity, current patterns, and upwelling (Figure 3g).

Example 3: preserve or protect functional processes of an ecosystem

To achieve this objective, MPAs must preserve habitat, primary production sources (eg kelp forests, seagrass beds), and energy transfer pathways within trophic webs (Figure 4a–d). In order to determine if these goals are being met, abundance and production of macroalgae, planktivores, detritivores, and higher-level consumers responsible for incorporating primary and secondary production into local trophic webs should be monitored. Both primary production and biogenic habitat are controlled via "top-down" and "bottom-up" processes. For example, in top-down trophic interactions, higher level predators such as lobsters, reef fishes, and sea otters control the abundance and behavior of herbivores like sea urchins, which are capable of deforesting entire reefs of kelp forests (Estes *et al*. 1998; Steneck *et al*. 2002; Graham 2004). Furthermore, commercial or recreational harvesting, of either kelp or kelp-associated species, can alter rates of growth, mortality, and recruitment within kelp forests. Alternatively, variations in delivery of nutrients and light affect photosynthesis, leading to bottom-up effects on growth and mortality rates (Zimmerman and Kremer 1984; Broitman and Kinlan 2006; Burkepile and Hay 2006; Bracken and Stachowicz 2007). Turbidity and resultant light attenuation can impair foraging ability of planktivores and affect kelp forest productivity, while sedimentation can smother algae (as well as corals and filter-feeding invertebrates). Swell exposure and geological substrate not only determine the level of physical stress in the environment, but also strongly influence many of the ecological variables mentioned above. In addition, current velocities and water column stratification affect rates of plankton delivery and retention, as well as detrital production. According to this analysis, primary oceanographic metrics requisite for determining whether the MPA is achieving the given objective are temperature, current velocities, turbidity, nutrients, and swell.

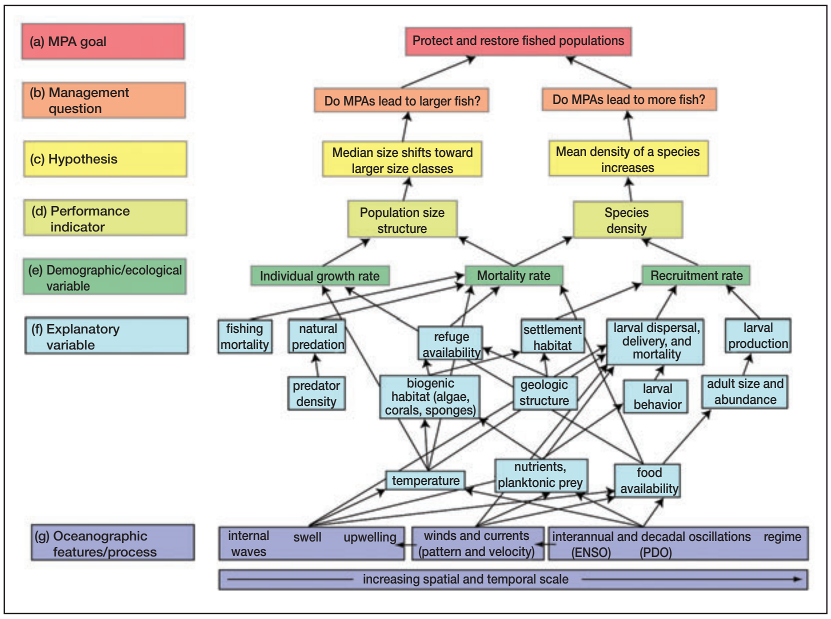

Figure 2. Relationships between population-level management goals, ecological variables, and oceanographic processes. Arrows indicate direct influences on higher level factors, variables, and demographic rates. This figure is intended as an example and may vary depending on region.

■ Key oceanographic variables

The three examples of MPA objectives presented above are among the most common goals motivating the implementation of MPA networks. Considering these objectives together (Figures 2–4), the key measurable physical, biological, and chemical oceanographic variables related to MPA evaluation are: (1) water temperature, (2) salinity, (3) current velocity, (4) primary production (including phytoplankton biomass), (5) secondary production (including zooplankton diversity and biomass), (6) nutrients, (7) light level or turbidity, (8) water column density structure, and (9) bottom/habitat characteristics.

Each of these explanatory variables is ranked in the top 20 variables for IOOSs and recommended as routine measurements for OOSs (Ocean.US 2002). In addition, these variables have been identified as critical baseline measurements for informing ecosystem-based management methods (Cury and Christensen 2005). These oceanographic and ecosystem indicator variables are directly linked to important marine policy and management questions (Figures 2–4) and should therefore be incorporated into MPA monitoring efforts. It is not always clear, however, at what spatial and temporal scales these variables should be monitored (Comin *et al*. 2004); in the following sections, we discuss

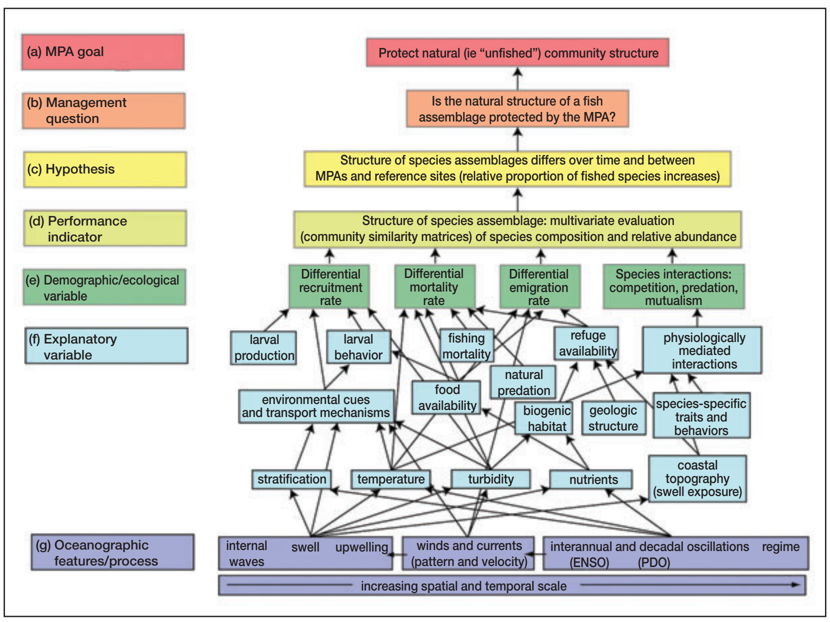

Figure 3. Relationships between community-level management goals, ecological variables, and oceanographic processes. Arrows indicate direct influences on higher level factors, variables, and demographic rates. This figure is intended as an example and may vary depending on region.

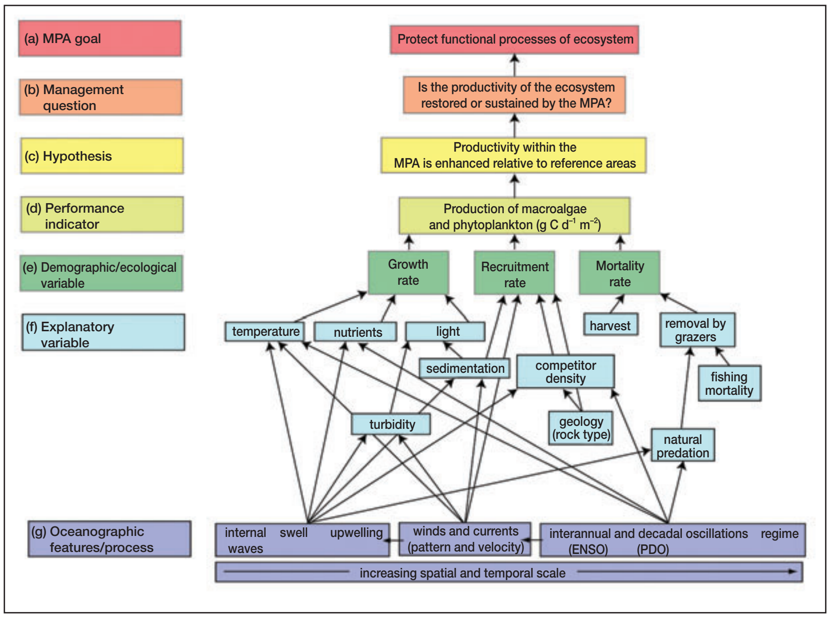

Figure 4. *Relationships between ecosystem-level management goals, ecological variables, and oceanographic processes. Arrows indicate direct influences on higher level factors, variables, and demographic rates. This figure is intended as an example and may vary depending on region.*

strategies for determining how, when, and where these metrics should be assessed for effective MPA evaluation.

■ Temporal and spatial considerations for partnered OOS–MPA monitoring programs

Understanding temporal and spatial scales of important biological processes within the context of oceanographic conditions, and the phenomena influencing these processes, is the key to MPA evaluation (Figure 5). Oceanographic variables such as temperature, salinity, and current velocity are relatively easy to monitor at high sampling rates over long periods of time with the use of moored instrumentation. Given that it is impossible to measure these variables across all temporal and spatial scales, monitoring design should focus on both the scales that affect performance indicators of interest and the scales of acting oceanographic processes. OOS programs are particularly important in characterizing these larger scale processes. For example, the Central and Northern California Ocean Observing System (CeNCOOS) is an established regional IOOS program along the central and northern coast of California. One of the stated goals of CeNCOOS is to provide information for monitoring and evaluation of MPAs. Recently, through the Marine Life Protection Act initiative (www.dfg.ca.gov/mlpa/), a regional network of MPAs was established along the coast of California. Here, we draw upon the Central Coast MPA and CeNCOOS network to provide examples of how to construct an ecological–oceanographic monitoring system that will enhance assessments of MPA effectiveness.

Coastal systems display variability in physical parameters across a range of spatial and temporal scales, from minutes to centuries and from centimeters to ocean basins (Figure 5). This physical variability can strongly affect populations of algae, invertebrates, and fishes in coastal marine systems across a range of scales (Holbrook *et al.* 1997; Hollowed *et al.* 2001; Edwards 2004). Such populations within newly established MPAs are likely to respond both to cessation of fishing activities and to larger scale oceanographic forcing, both of which should be monitored across a similar range of scales to isolate cause, effect, and responsible processes. Larger scale processes can be monitored by appropriate oceanographic indices (eg Pacific Decadal Oscillation Index, Multivariate ENSO Index; Mantua *et al.* 1997) and remotely sensed data (eg sea surface temperature, chlorophyll concentration, currents). There are many examples of the application of these indices and variables coupled with oceanographic models (eg regional ocean models) to resolve large-scale processes that contribute to ecological responses at local scales (eg larval recruitment, primary production; see Broitman and Kinlan 2006; Mitarai *et al.* 2008; Siegel *et al.* 2008). Regional-scale variation can be monitored via OOS regional data and long-term mooring sites as well. OOS programs are particularly useful for producing regional-scale oceanographic data relevant to MPA efficacy assessment because OOS and MPA objectives both require measurements of key metrics of the system (eg current velocity fields, temperature, winds). Such data are often available online or through national or regional organizations (eg US IOOS). However, local ecosystems and environmental conditions may exhibit different responses to the same large-scale processes (Bennett *et al.* 2004; Field *et al.* 2006; Peterson *et al.* 2006). Thus, in order to assess the responses of a local environment to global- and regional-scale forcing, and to determine to what extent MPAs and reference sites reflect these processes, it is critical to monitor oceanographic variables at sites both within and outside MPAs.

Across intermediate spatial and temporal scales, advective processes influenced by wind, freshwater input, or interactions between flow and bathymetry are important. For example, topographic differences may cause two vastly different flow regimes and, consequently, different ecosystem responses within and surrounding each MPA (Figure 6). Local-scale variability in temperature and primary production can lead to inaccurate interpretations of important performance indicators (eg growth and size structure) compared across sites. However, such misinterpretations can be avoided through appropriate consideration of interannual variability in oceanographic conditions (eg oceanographic data anomalies), along with

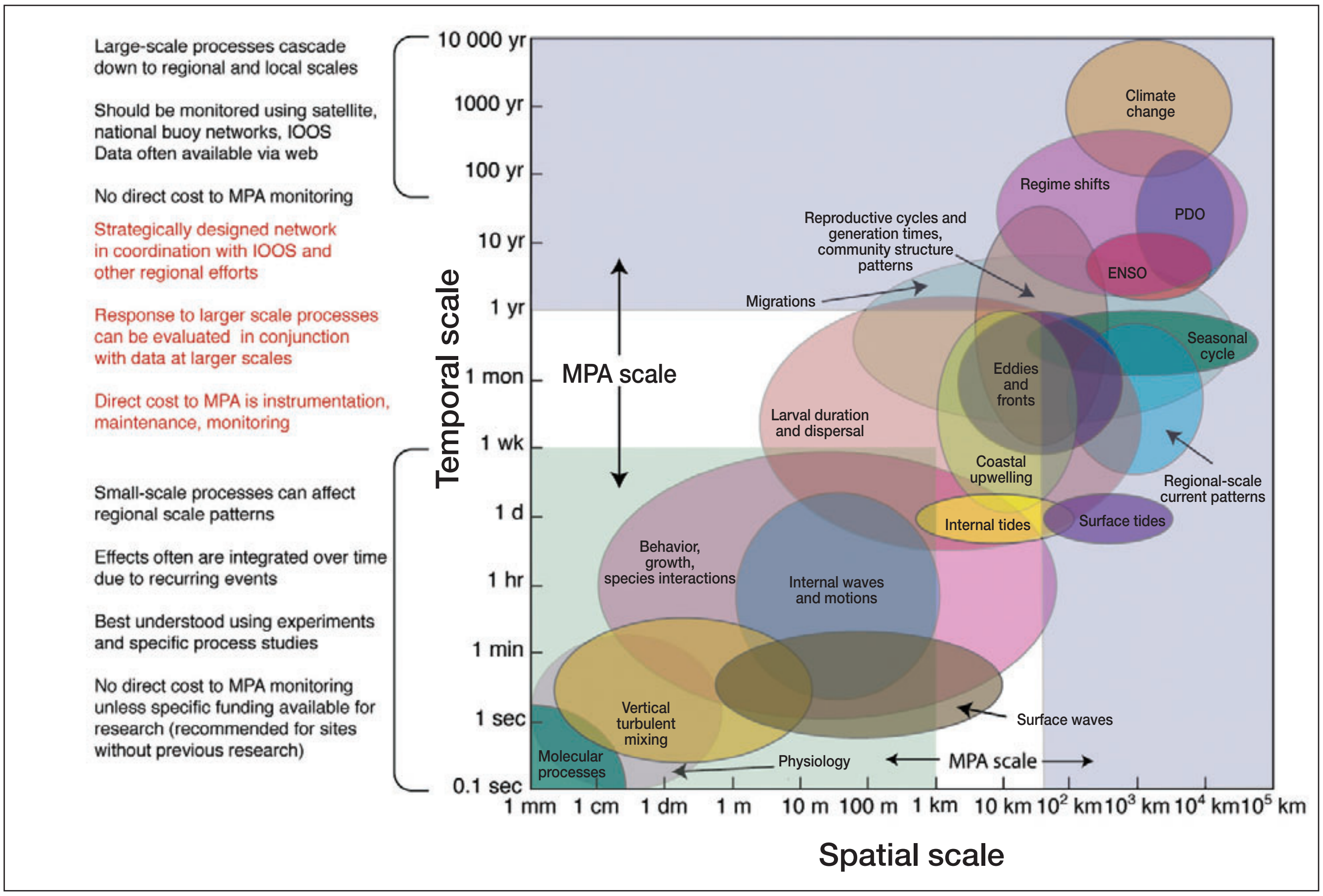

Figure 5. *Spatial and temporal scales of oceanographic processes and variables affecting key performance indicators monitored to evaluate MPA effectiveness (redrawn from Dickey 1990). MPA spatial scale is representative of a single MPA (~1 km) up to a network of MPAs and associated reference sites (hundreds of kilometers).*

regional data from OOS programs (eg upwelling, currents) and knowledge of local-scale conditions (eg temperature). For example, analysis of covariance models can be used to determine MPA effects by comparing MPA treatment levels while taking into account environmental variation both from small-scale processes observed locally and the effects of large-scale processes predicted from oceanographic models. At the same time, by examining the relative contributions of MPAs and oceanographic processes in explaining spatial and temporal patterns of ecological responses, such analyses can show how coastal ecosystems are responding to observed variations in ocean processes. Similarly, population dynamic models that explicitly incorporate biological responses to oceanographic processes (eg temperature-dependent growth) and fishing mortality could potentially characterize the interactions among these variables and indicate whether the observed responses in a variable (eg population size or structure) are consistent in magnitude with the observed differences in oceanographic conditions and fishing pressure. If not, this might suggest that other factors are contributing to the observed patterns as well (eg changing effects of species interactions). Numerous examples of such models exist for populations (Tolimieri and Levin 2005; Hare *et al.* 2010) and ecosystems (Watters *et al.* 2003; Cury *et al.* 2008), often developed to understand and predict interactions between oceanographic drivers and fisheries. Process studies that help establish connections between large-scale forcing and local-scale responses will be instrumental in interpreting these statistical relationships.

Ephemeral events like submesoscale (lateral scale of 1 km in the upper ocean) eddies can disrupt general circulation patterns and lead to additional local-scale (tens of kilometers, approximately) spatial variability. These features can also lead to dramatic differences in observations separated by only a few kilometers (Zimmerman and Kremer 1984; Pineda 1991; Shanks 1995; Mace and Morgan 2006; Cheriton *et al.* 2007; Cowen and Sponaugle 2009; Morgan *et al.* 2009). Ocean variability at these spatial and temporal scales is particularly important because these scales are comparable to the size and spacing of many MPA networks, but they must be considered within the context of larger scale variability (Botsford *et al.* 2001; Kaplan and Botsford 2005; Botsford *et al.* 2009; Gaines *et al.* 2010; Hamilton *et al.* 2010). Fortunately, this also points to the potential for MPA monitoring to interpret patterns and processes observed at intermediate and local scales within the larger context of oceanographic monitoring systems. An example of this

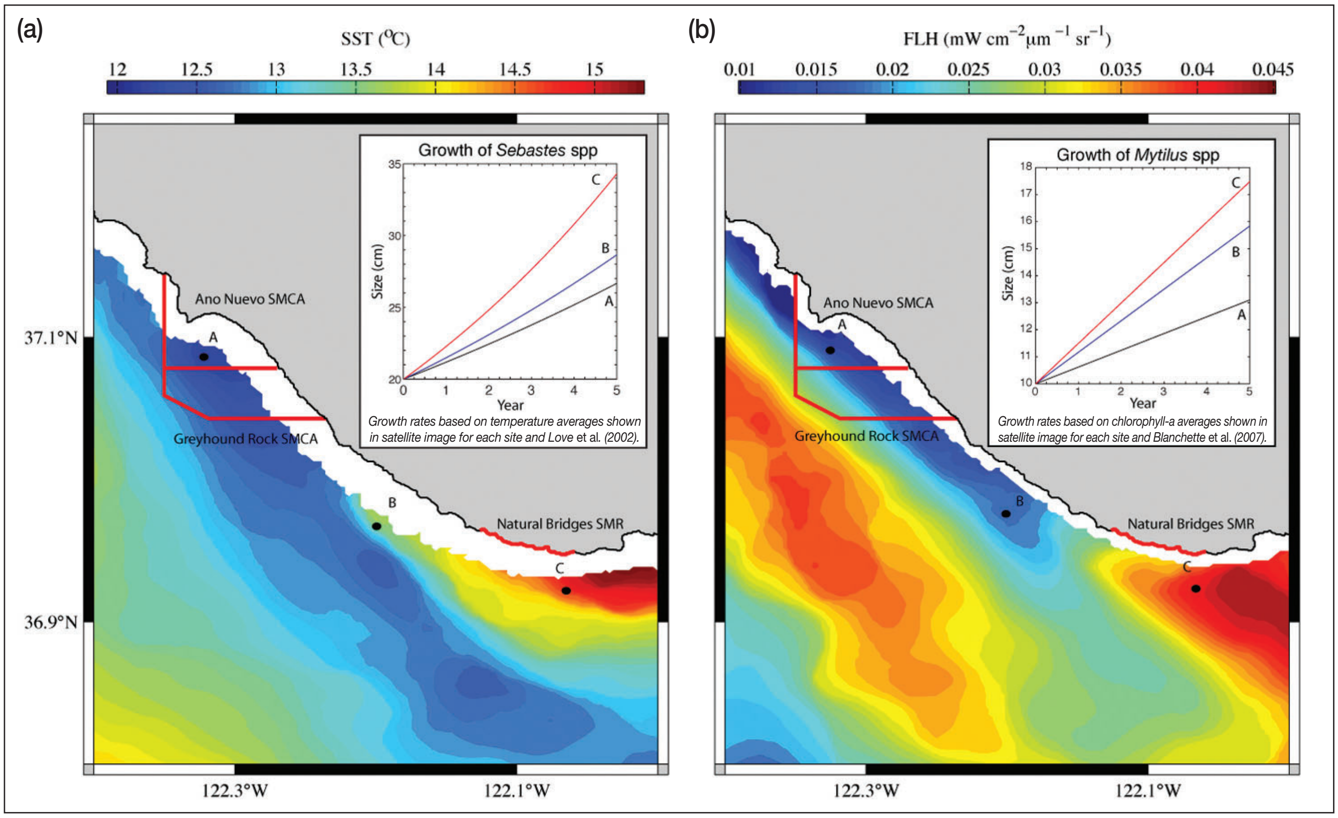

Figure 6. *Examples of how spatial variation in oceanographic conditions (sea surface temperature and chlorophyll concentration) at the scale of MPAs and reference sites along the central California coastline affect monitored response variables (rockfish and mussel growth). Monitoring sites are indicated by A (an MPA with boundaries indicated by the red lines), B (a reference site for both A and C), and C (an intertidal MPA identified by a red line along the shoreline). (a) Illustration of spatial variation in sea surface temperature (SST) and predicted differential growth of adult* Sebastes *spp (20 cm beginning length). (b) Illustration of spatial variation in chlorophyll concentration (FLH is a proxy for chlorophyll fluorescence and concentration) and predicted differential growth of* Mytilus *spp (10 mm beginning length) for 5-year initial* MPA *period. This temperature difference (~3.77 ± 0.29˚C) was consistent over a 3-year sampling period (Woodson* et al. *[2009] and unpublished data). Data used to generate growth performance models were obtained from Love* et al. *(2002); Blanchette* et al. *(2007); Woodson* et al. *(2007).*

would be hydrodynamic models that incorporate region-wide observations of large-scale forcing processes (eg wind, temperature) generated by satellites and moored OOS platforms. Such models can describe regional processes (eg advection, circulation patterns) that can explain local-scale variation in ecological variables (eg growth and recruitment of larvae).

Through establishment of integrated OOS–MPA monitoring programs, with a particular consideration of spatial variability, the effects of temporal variability over the life of an MPA monitoring program can be identified. In particular, the response of the coastal ocean to climate change and anthropogenic impacts may be revealed at multiple scales through careful collaboration between OOS and MPA partners. OOS programs are well suited to describe temporal variability of oceanographic and primary ecosystem processes.

The development of a process-based framework will be critical for effective OOS and MPA partnerships. Because oceanographic forcing at larger scales can cause unexpected variability at local scales, individual process studies should be conducted, to help us understand these effects and to integrate larger, regional-scale observations with local monitoring. In addition, process studies can provide critical information for monitoring programs about what variables to monitor, and when and how to monitor them. Ideally, such studies would characterize all responses of the MPA and nearby regions to a variety of oceanographic processes.

■ Integrating biological sampling with oceanography

A major challenge in evaluating MPA effectiveness involves integrating biological monitoring data with oceanographic measurements. It can be difficult and expensive to achieve temporal resolution of ecological variables (eg adult population size, biomass, recruitment) that is comparable to that of oceanographic measurements. However, with careful consideration of how key physical and biological processes are linked both spatially and temporally, an effective ecological sampling plan can be constructed that integrates effectively with oceanographic monitoring. For example, estimates of density and relative abundance of fish populations can differ greatly resulting from variability in the physical environment (Friedlander *et al.* 2003). During large swell events, many fish species tend to seek refuge by moving to sheltered habitats or deeper waters (consequently altering the likelihood of detection when leaving the sampling area). Monitoring programs can avoid this potential source of bias by timing surveys with knowledge of past and future swell states across a network of MPAs generated by coastal swell models. Similarly, timing of surveys to estimate spatial and interannual patterns of larval recruitment can be guided by variables (eg temperature, salinity, current) that correspond to oceanographic processes (eg the strengthening and relaxation of upwelling) that can influence timing of larval delivery.

■ Conclusions

Development of MPA monitoring programs that take into account oceanographic variability is a critical step in our ability to assess whether a given MPA is meeting design objectives (eg protection of fished species, communities, and ecosystems). To this end, it is imperative that MPA monitoring designs incorporate measurements of oceanographic variables at appropriate temporal and spatial scales. MPA monitoring efforts should be partnered with existing OOS networks to resolve oceanographic processes that affect ecosystem structure. Observations from regional OOSs can help resolve large-scale processes, while monitoring efforts specific to an MPA should aim to capture the frequency and duration of smaller scale oceanographic variability. Although monitoring alone will not provide a mechanistic understanding of the coupling between the ecosystem and the physical environment, by designing an oceanographic monitoring network that incorporates observations of coastal conditions both within and outside an MPA we can reduce or minimize the potential for misinterpretation of MPA effectiveness and increase our understanding of how coastal ecosystems respond to changing ocean conditions. Collaborative or complementary monitoring of coastal ecosystems by OOS and mandated MPA programs will benefit both partners. For MPA assessment, the data collected will lead to a more comprehensive understanding of physical–biological coupling (Botsford *et al.* 2009) and will enable quantification of (and perhaps discrimination between) the effects of spatial management implementation and natural environmental variability. Observational support for MPA assessment will provide an opportunity to address "ecosystem health" and "living resources" goals, such as those established by the US IOOS.

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