Navigating Uncertain Seas: Adaptive Monitoring and Management of Marine Protected Areas
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AUTHORS & AFFILIATIONS
Caterina D'Agrosa¹, Leah R. Gerber¹, Enric Sala², Jeffrey Wielgus¹, and Ford Ballantyne IV²,³

¹ School of Life Sciences, Arizona State University, Tempe, AZ 85287, USA
² Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, California 92093-0202, USA
³ Present address: Dept. of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544-1003 USA

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GRAPHIC DESIGN
Jorge Tirado / muelle66@gmail.com

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**Why this handbook?**

Marine protected areas (MPAs) often have the goal of protecting biodiversity and/or helping to manage fisheries at an ecosystem level. The potential benefits of MPAs include conservation of species, protection of habitats, fisheries enhancement via recovery of overexploited stocks and export of biomass to adjacent areas, reduction of management or environmental uncertainty, as well as a place to conduct research. In spite of the potential benefits of MPAs, we still do not know how and when MPAs will fulfill conservation and fishery goals. First, there are no general formulae to decide how many and what kind of MPAs have to be created to achieve specific goals. Second, most existing MPAs do not have explicit goals and expectations, and temporal changes in the species populations are generally not monitored. Therefore there are no universal tools for decision makers to prioritize the creation of MPAs, and for managers to evaluate their efficacy. Hence, management and policy in relation to conservation of marine resources are generally inconsistent and based on political issues rather than on the realities of the resources they are supposed to manage and conserve. We believe that policy decisions have to be made on the basis of both rigorous scientific data and socioeconomic issues. Although most of our examples are biological, we have included a few economic examples as well. We created this handbook to provide practitioners with a simple, straightforward guide to assessing how well a MPA is doing.

**OBJECTIVES**

Overall, our goal is to illustrate how to develop predictive
capabilities and general guidelines for the development of management and monitoring strategies when there are multiple conflicting goals and uncertainty in data. Our specific goals are to:

1. **Provide information to guide decision-makers for integrating biological and economic information for MPA design and monitoring.** This is illustrated by applying ecological models, formal decision-making methods, and treatments of uncertainty to designing and managing MPAs.

2. **Formulate a general structure for monitoring and decision-making for MPAs.** We provide a framework for determining how and when MPAs should be monitored to evaluate their efficacy using baseline data and models.

**GENERAL APPROACH**

The data and the models illustrated in this handbook have the potential to influence management and policy actions (Fig. 1). The models allow us to make predictions about biological and socioeconomic changes, which, when coupled with the appropriate amount of monitoring data, can help us determine if a MPA is effectively achieving its goals. By using a framework based in decision-theory that uses data and insight from the models and monitoring, we can directly guide management actions. This approach also provides an explicit link between monitoring and management, thus facilitating changes in management plans as new information becomes available.

Many of the tools employed in this handbook rely on biological data that are most typically available. Some of the data are regularly collected in monitoring activities or basic scientific research (e.g., surveys for species abundance and distribution). Others use data that are readily obtained from the literature or estimated from congeneric species (e.g., life history parameters). In each case, we describe the data needed, the parameters for the models, and in the case of field work, how to collect the necessary data.

**DECISION THEORY**

The formal mathematical study of the process of decision making, where a choice (or decision) is made from a finite set of possible alternatives. Decision theory is applied to real-world problems in many disciplines including economics, risk analysis, business management, behavioral ecology and conservation biology.
MPAs are one tool for managing human activities at the ecosystem level and include different types of protection, depending on management goals. Generally, multiple-use MPAs can protect specific habitats and populations while allowing selective fisheries. Marine reserves, in contrast, are a type of MPA that are fully protected against all extractive and destructive activities but still allow other human uses such as ecotourism.

EXAMPLE OBJECTIVES AND CRITERIA FOR MULTI-USE MPAS/MARINE RESERVES:

- **Conservation**: maximizing population abundance, minimizing rate of population decline, minimizing the probability that population goes extinct, maximizing species/habitat diversity in reserves.
  - **Criteria**: biogeographic representation, habitat heterogeneity, endemism.

- **Sustainable fisheries**: increasing long and short-term fishery yield.
  - **Criteria**: presence of exploitable species, vulnerable life stages, connectivity between reserves, links among habitats.

- **Economic viability**: increasing potential of protection, enhancing or maintaining economic value.
  - **Criteria**: ecosystem services, number of fishers dependent on area, value for tourism.

- **Social security**: ensuring that potential protection can benefit community social structure and security.
  - **Criteria**: ease of access, food security (maintenance of subsistence fishing, local fishing markets).

- **Scientific research**: promoting scientific research.
  - **Criteria**: Amount of previous scientific work undertaken, regularity of survey or monitoring work done, presence of current research projects, educational value.

  - **Practicality**: ensuring that reserves are feasible and practical.
  - **Criteria**: Social/political acceptability, accessibility for education, tourism, compatibility with existing users, ease of management, enforceability.

OBSERVED EFFECTS OF MARINE RESERVES:

- **Protection of habitats**, which in turn can sustain richer and more varied plant and animal communities.

- **Increased size**, reproductive output and biomass of both target animals and plants inside well-enforced reserves.
  - When protected, animals grow larger, survive longer and thus can produce more young

- **Export of biomass** to adjacent areas (local spillover).
  - Increases with time.
  - Can occur at the adult/juvenile stage or at the larval stage.

- **Fisheries enhancement**.
  - Overexploited stocks have been protected long enough for the population to recover.

- **Management** or environmental uncertainty is reduced.

- **Ample opportunity** to research reserves themselves, but also the species, communities and ecosystems within them.

- **Ecotourism** in reserves is supplementing income previously gained from fishing.
LESSONS FROM LORETO BAY

LORETO BAY NATIONAL PARK (LBNP) AND THE LEOPARD GROUPER

The Gulf of California, Mexico, is an ideal study system for exploring the intersection between monitoring and management of MPAs. It is a biologically rich and diverse area, supporting approximately 35 marine mammal and 800 fish species, and is one of the areas with the highest fish endemism worldwide. For this reason, it has long been subjected to intense fishing pressure. As a consequence, populations of many marine species have been depleted, including sharks, large groupers, and sea turtles. The case studies and examples used throughout this handbook focus on research conducted at LBNP, and many focus on the leopard grouper (see references 14, 17, 23, 31, 35, 36).

LBNP was established in 1996 to protect the bay from industrial trawling and seining, which were affecting the artisanal fisheries in the Loreto region (Fig. 2). It covers an area of 2066 km², of which 88% is marine and 12% constitutes land masses varying in area from a 151-km² island (Carmen) to islets of a few square meters. Currently, commercial and recreational hook-and-line and net fishing are permitted within most of the park boundaries. There are two small no-take marine reserves that encompass only 0.07% of the LBNP. The park also supports other recreational activities such as SCUBA diving, whale watching, and kayaking. The town of Loreto (population 12,000) is the largest hub of commercial and recreational fishing in the park, and is also a popular site for SCUBA diving. Approximately 70% of the local population is employed in the tourism sector.

The leopard grouper (Mycteroperca rosacea) is one of the most important fishery resources in the southern Gulf of California. Due to the overexploitation of some of its populations, the leopard grouper has been classified as a vulnerable species. The leopard grouper attains maturity at a length of approximately 35 cm, which is also the approximate size at which it begins to be targeted by fishers. During the spawning season fish congregate in the same spawning areas, which are easily targeted by fishers. Little is known about the biology and population dynamics of the leopard grouper. Recent studies suggest that the populations of leopard groupers are declining.
Much of MPA theory has focused on generating the optimal design of a MPA or MPA network so that they spatially capture the species or habitat under protection. A MPA is then created, which is often thought of as a success in and of itself. As we will discuss below, there are several ways to monitor such that one can assess whether the MPA is working properly. In this section, we extend the use of data obtained from monitoring (and other sources, such as pre-reserve baseline data) and focus on methods that assess whether the MPA is working: that is, is the MPA meeting its ecological goals?

**FOR WHICH TYPES OF SPECIES ARE MPAS MOST EFFECTIVE?**

Many marine species change habitats during different stages of their lives. For example, some adult fishes move to new habitats to spawn, or larvae settle from the water column to a new juvenile habitat, or large whales occupy different habitats for breeding, feeding and the corridors in between those endpoints. Often MPAs do not include the entire life cycle of a species or population (Fig. 3).

One can then develop a model (Fig. 4 and Appendix A) that incorporates the movement from one life stage to another for a given species within and across two different sites (e.g., MPA and non-MPA). Simple population analyses can suggest which species will benefit most from a MPA. If, for example, mortality of adults by fishing is reduced by 20% inside the MPA, then, as seen in this example, wrasses would benefit the most from this approach and groupers the least (Fig. 5).
Adaptive monitoring and management of Marine Protected Areas

Figure 4. This diagram (modified from Gerber et al. 2005) illustrates a general model that explicitly includes the movement of individuals from one habitat to another at different life stages, and is helpful in understanding how much the life history and dispersal can affect how well the MPA will work to protect a given species. For example, if a species occupies one habitat when it is a juvenile and another when it is an adult (ontogenetic habitat shift), and a MPA is established to protect the juvenile habitat, the MPA will have a stronger impact on that life stage than any other.

Figure 5. Change in population growth rates for species with varying life histories, illustrating which species would benefit most from the establishment of a MPA (modified from Gerber and Heppell 2004).
LESSONS FROM LORETO BAY

HOW DO DISPERSAL RATE AND LIFE HISTORY INTERACT TO DETERMINE MPA EFFICACY?

Using this type of model, one can use different values of dispersal rates to model the outcome of the population for a given species. Examples include modeling a dispersal rate of 0 (i.e., no dispersal) into the MPA; total mixing between MPA and non-MPA (rates of equal value); or high dispersal into (or out of) the MPA. It is also very informative to model these varying dispersal rates for species that have different dispersal timing— for example, a species that disperses as larvae compared to a species that disperses by adult movement. Understanding the outputs is often easier if they are compared to a control. A 10% reduction in adult mortality both in a MPA and outside was modeled, assuming no dispersal between sites. This is essentially equal to equal survivorship without dispersal in both patches.

Population growth rates that result from each of these different dispersal scenarios can then be compared to understand how different dispersal rates determine the efficacy a MPA will have on a given species (Fig. 6). The goal of the MPA is to increase the rate of population growth of a given species or species group.

This approach can also be used to understand how the timing of dispersal affects the effect that a MPA will have in protecting a certain species. For example, one can compare the effects of different dispersal mechanisms (e.g., at recruitment, of adults, of juveniles, of a habitat shift in breeding adults, and of dispersal at all ages) for several different species at two different dispersal rates (high and low) to get an understanding of how the MPA would perform.

**Population growth rate ($r$)**

Theoretically, when population growth rate = 1, the population is stable, when it is greater than 1, the population is growing, and when it is less than 1, the population is declining.

Figure 6. In this example (modified from Gerber et al. 2005), a 20% reduction in adult mortality due to MPAs was modeled for different rates of migration and for four species with differing life histories (dispersal for gray whales and turtles was modeled as adult spillover; for urchins and groupers, dispersal was modeled as recruitment; Gerber et al. 2005). The largest change in population growth rates occurred when no dispersal between sites occurred. Sea urchins and groupers responded the most to the establishment of a MPA, while whales and sea turtles exhibited a smaller increase in their population growth rates. We would thus expect most MPAs to have a general positive effect on the growth rate of species that have small home ranges and low dispersal.
WHY, WHAT, AND HOW DO WE NEED TO MONITOR?

There has been relatively little effort to design consistent monitoring strategies for MPAs. Monitoring is critical to assessing how well a MPA is working, and whether it is meeting the goals for which it was designed. Monitoring programs for MPAs may be intended to (1) detect change in the abundance and growth rate of species and communities of concern, and (2) to evaluate how well a reserve fulfills the goal of enhancing a local fishery. Ideally, the results of such a monitoring program should directly inform future management decisions. Below, we present some general monitoring guidelines that address different goals, or scales, of monitoring.

IDENTIFYING NATURAL VARIABILITY TO GUIDE MONITORING

To effectively manage a MPA to meet conservation goals, we need to understand how communities change over time, especially when one of the goals is to increase and protect biodiversity. However, just like the amount of rainfall and sunshine can influence how much and what type of vegetation grows on land, natural fluctuations in variables such as sea-surface temperature (Fig. 7), phytoplankton growth, and fresh water inputs may influence how biodiversity is distributed in the oceans. Changes in ecological communities may be related to processes occurring at regional scales and have little to do with local MPA management actions. That is, if the trends in biodiversity distribution and abundance detected through monitoring efforts in any given year are not understood in the context of the surrounding environment, then one might erroneously conclude the wrong thing about the status of the community, or population. To understand how communities respond to changes in natural variability, we often require specific methods that can handle several different variables.
Managers need to incorporate this variability into management and monitoring plans. The ability to make accurate predictions about changes in the structure and composition of biological communities will help managers make better decisions about resource use.

MEASURING EFFECTIVENESS

Demographic data have long been used to inform and guide marine conservation in several different ways. Life history data have been used to show that long-lived species with low reproductive rates, including marine mammals, seabirds, sea turtles, and sharks, appear particularly sensitive to incidental mortality in fisheries. When applied to MPA effectiveness, life history data have shown us that fisheries catch rate is more important than population growth in determining the effectiveness of a MPA in terms of both increasing the population within the MPA boundaries and increasing the export of fish outside the reserve. However, a reduction in catch rates outside the MPA will lead to higher population density in the protected area. Demographic data can also be used to predict when MPAs are most likely to be effective for a given life-history type, and this information can be used as an early step for MPA planning. An extensive review of the use of population models in marine protected areas can be found in Gerber et al. (2003).

Reserves often are created to reduce fishing pressure on a species or species group. Often, these species are of commercial importance. To increase the survival and abundance of a given species we need to understand and be able to predict the population dynamics of the species. Often we lack all of the data on the population parameters of marine species (survival, growth rates, natural mortality rates, fecundity, habitat uses, etc.) because many of them have complex life histories. This lack of data essentially restricts the effectiveness and management strategies within a MPA, and managers are often faced with having to develop management and monitoring strategies without the essential information about the population they are mandated to preserve.

One approach to having limited demographic data is to use simple demographic models, such as a matrix population model to conduct a population viability analysis (PVA). Results from a PVA can then inform fisheries managers and conservation decisions.

USING ABUNDANCE DATA: BEYOND-BACI FOR CHANGE IN SINGLE TAXA

No-take reserves (where all fishing is prohibited) result in a general increase of fish biomass, mainly the biomass of predatory fishes, over time. Although full recovery of fish biomass may involve decades because of the long life spans of the largest predatory fishes, significant increases

**Demographic (life history) data:**

Information that tells us about a population’s survival, ability to produce offspring, and mortality (both natural and human-induced). These data tell us about the organism’s lifetime pattern of growth; whether they are long lived, or if they reproduce at an early age, or if they produce a lot of young, etc. This information helps us understand how quickly a population will grow, and under what conditions, which is particularly important when trying to protect biodiversity.

**PVA:**

A quantitative method to predict the likely future status of a population (or collection of populations).
Because fish dynamics are affected by changes in the environment, managers must incorporate information about the effects of environmental variability into their decisions. Events like the El Niño/La Niña Southern Oscillation (ENSO) can be incorporated into these PVA models by using the multivariate ENSO index (MEI). In the model outcomes, one can calculate an average value for the time period between sampling events, then test whether there is a difference between the long-term survival of the population during El Niño vs. La Niña. A control model, assuming no ENSO or other environmental effects, can be incorporated for greater understanding.

Understanding the possible effects of larval dispersal between populations across sites can help managers understand how connected the sites are. Connectivity among sites will influence both long- and short-term population growth and thus management decisions. One can model different scenarios of the effects of larval connectivity of reef fish. For example, scenarios, given a certain fertility rate (see Appendix C for help calculating this), could include: 1) a population is a large net exporter of larvae; 2) a population is a small net exporter of larvae; 3) a population retains all of its larvae and imports a small portion of larvae from elsewhere; and 4) a population retains all of its larvae and imports a large portion of larvae from elsewhere.

Grouper populations have recovered relatively quickly with the establishment of no-take reserves, so such a no-take area could be implemented as a temporary conservation measure. However, the leopard grouper is a slow growing species, and recovery of the population may be slow even under a strict no-take regime. Continued monitoring of abundance would be necessary to determine when the population recovers to a level that would allow sustainable fishing, taking into account the environmental variability of the Gulf of California. Even after the leopard grouper population recovers, continued monitoring could detect possible changes in abundance arising from unexpected changes in the environment and/or fishing pressure. One of the most relevant results here was that the Carmen Island population is decreasing (Fig. 8). One major reason may be overfishing. These findings can be then linked to the approach in the “incorporating economic and demographic information to create a no-take reserve” section below, to then explore the size of a no-take reserve that would maximize revenues from economic activities at Carmen (commercial fishing and scuba diving) while allowing the leopard grouper population to recover (continued).
How does environmental variability coupled with larval dispersal affect long-term population survival?

Figure 8. This bar graph (modified from Wielgus et al. 2007) illustrates an example output and uses for a PVA model, showing minimum population growth rates over time for the variable, long-term growth rate of four populations of leopard grouper (Mycteroperca rosacea) at Loreto Bay National Park (LBNP). For each population, the bars correspond to increasing numbers of juveniles per adult fish at two different times, 1998 (light blue) and 2004 (dark blue). The thick solid line represents a long-term growth rate of 1, and is the lower limit for a population to be considered viable. The long-term population growth rate of leopard grouper at Carmen Island (shown in red) is below the threshold of one, thus is considered to be a declining population. This result was the same for models regardless of whether they considered the Carmen Island population as a source or sink of larvae. For this population, adult survival was low during La Niña periods and zero during El Niño periods, and growth of juveniles into adults was relatively low for both periods. Therefore, a precautionary approach to the management of the leopard grouper population at Carmen would be to close the island to fishing.

in biomass may be detected only a few years after protection.

If a reserve is closed off to fishing and its management is effective and meaningful, one would expect an increase in fish biomass inside a reserve relative to adjacent unprotected sites. If there were no significant increase in fish biomass in the reserve relative to unprotected sites nearby, we could conclude either that the management plan is not effective from a biological standpoint (e.g., the reserve is too small, enforcement is poor, or the habitat is too degraded), or that it requires more time to produce detectable changes in fish biomass.

Testing for the effects of a reserve on fish biomass

In an ideal world, to test for the effects of a reserve on fish populations, fish biomass must first be quantified (see Appendix D), both inside and outside the reserve, several times before and after protection. We suggest using a Beyond-BACI (Before-After-Control-Impact) design. The logic of such a design is that we would expect the creation of a reserve to cause a temporal change in the biomass of fish inside the MPA in contrast to unprotected populations in control locations outside the MPA.

Beyond-BACI Survey design

- Impact can be defined as the time (e.g., season, year) when a significant change in management or “protection,” occurred (e.g., the creation of the reserve).
- Before would thus be defined as data sampled at sites before the creation of the reserve.
- After would be data sampling at the same sites after the reserve was created.
- Control sites are located outside the reserve boundaries, where no changes in management have occurred. For consistency, they must be sampled both before and after the impact.

The expectation is that to identify the real impact of a given management action, the difference in biomass from before to after the creation of the reserve, between
the control and impact locations, is larger than the difference in biomass between the control sites (Fig. 9).

In selecting the BACI sites, we suggest selecting sites that are all similar in terms of the habitat that the species is likely (or known) to use. Additionally, if the goal is to examine different zoning strategies within the reserve, some of the “before” and “after” sites must be included in each of the zones to be tested. For example, examining the effects on biomass of a zone that allows a certain type of fishing, but restricts others.

**Figure 9.** This figure shows mean biomass for five locations, three control sites that are outside an MPA and two sites inside an MPA. The red arrow shows the time of the impact, in this case, the time the MPA was established. Data on fish biomass were collected before and after the impact for both locations, thus allowing for a straightforward assessment of the impact of the MPA on biomass.

Although LBNP was established in 1996, the management plan was not put into effect until late 2000. To assess whether the management plan was effective from the perspective of reef fish, 14 monitoring sites were selected inside the Park (Fig. 2), and seven outside the park, all of which harbored similar rocky bottoms, topography, and species pool (Sala et al. in prep.). The effects of the LBNP on total fish biomass were tested using the BACI approach.

As can be seen in figure 10, total fish biomass has not changed relative to the unmanaged areas outside the park, from before to after the management plan was in place, indicating that the management plan had no effect on total fish biomass, that the park is not fulfilling its conservation objectives, or that the management plan was not truly implemented in 2000. In any case, the BACI analysis shows that there has been no significant effect of reserves on fish populations in the park, which indicates the need for reevaluation of management.

**Figure 10.** The figure above illustrates the change in average total fish biomass per year from 1998 to 2004 for three different study areas within the Gulf. The orange line indicates the average total fish biomass for all sites within LBNP. The aqua and green lines are for the control sites located outside LBNP on the islands of Las Animas and Espiritu Santo, near La Paz, Baja California Sur. Red arrow indicates the implementation of the LBNP management plan.
MULTIVARIATE ANALYSIS FOR COMMUNITY-WIDE CHANGE

Why focus on communities instead of on individual species?

Species do no live in a vacuum. With the advent of adaptive ecosystem-based management, an effort is being made to shift the focus of managers from single species to multispecies assemblages, communities and even whole ecosystems. A broader focus helps detect ecosystem-wide patterns of change that a single species focus cannot. The ecosystem perspective also sheds light on the interactions focal species have with other components of the ecosystem. The most sensitive species, both commercially and ecologically, are often top predators, so changes in lower levels of the food chain may affect these target species. In turn, changes in the abundance of these top predators can cause change from the top of the food web down. Therefore, a thorough understanding of the processes that influence the entire community is necessary for sound management.

At what scales do we need to monitor?

The patterns that we observe in ecological communities are highly dependent on the temporal and spatial scales at which our observations are made, making it very difficult to interpret and consolidate results made at disparate scales. To effectively manage a MPA, especially when one of the goals is to increase and protect biodiversity and ecosystem function, we need to understand community dynamics over time, but also need to be able to compare and contrast these patterns to surrounding areas, previous studies, etc. We also need to incorporate this variability into management and monitoring plans so that managers are able to detect changes in the communities that are a result of management decisions. The goal of the approach is to determine a characteristic spatial and taxonomic scale for aggregating fish biomass data such that the community description generalizes the individual dynamics yet retains meaningful ecological information (Fig. 11).

Figure 11 a and b. Species abundances in a given place vary with several different variables simultaneously. In the top panel, we show how the amount of substrate that is covered with algae (green) increases as herbivores that would feed on the algae (blue) are reduced by fishing activities. We can further examine this joint variation over time (aqua circles, bottom example), seeing how the three variables interact. However, there is also variability caused by how the data are grouped and communities’ locations.
To determine how the spatial and functional scale at which we make our observations influence what we see, and how what we see changes over time, it is wise to consider different gradients, or categories, of spatial and functional aggregation. Examples of different spatial categories include: 1) sites separated by hundreds of meters to kilometers; 2) sites grouped on islands, which are separated by kilometers to tens of kilometers; and 3) islands within larger regions, separated by hundreds of kilometers. Examples of functional gradients can include biomass of the species that account for more than 90 percent of total community biomass, and the biomass of major trophic groups (e.g., piscivores, carnivores, herbivores and planktivores).

Additionally, the way we group species to describe the community itself and the spatial scale of this grouping will affect our conclusions. To understand how the definition of a community affects monitoring results, community data can be aggregated in different ways to assess how likely the results are to change (Fig. 12).

Figure 12. This figure shows an example of the relationship between the abundance of algae and herbivores at two different monitoring sites on one island (red rectangles) as well as across two different islands (green rectangles). The patterns we can detect change depending on the scale we look; thus it is imperative that the appropriate scale is chosen and that monitoring efforts are consistent so that the patterns are comparable across study sites.
In light of the underlying uncertainty of marine systems, adaptive management has been proposed as an approach to manage MPAs. In essence, managers make decisions based on the best ecological and social information that is currently available, with the implicit understanding that these decisions may be modified as new information is generated. Managers make a decision and then, through monitoring that is designed to detect the appropriate trends, observe the changes of the system during an experimental period of time. After this period management may be modified to include the information acquired during the experimental period and to account for changes in the system (Fig. 13).

A FRAMEWORK FOR GUIDING ADAPTIVE MPA MANAGEMENT

Conservation decisions are often the result of a laborious course of negotiation that rarely yields repeatable results. These ad hoc strategies are employed to arrive at a decision for a specific situation, but cannot be generalized to apply to other situations. An alternative approach entails the use of decision theory to formalize the decision-making process associated with MPA creation and management. In particular, a general protocol to link monitoring data to management decisions would be extremely helpful to guide marine conservation efforts.

MPAs have been designed to protect both vulnerable species and ecological communities. If the goal of a MPA is to recover overexploited populations of vulnerable species, the creation of a no-take marine reserve appears to be an appropriate action. Subsequently the target populations need to be monitored to determine whether the no-take area is sufficiently large to allow for significant recovery within the MPA. Because the abundance of species may fluctuate over time independent of protection status (see Identifying natural variability to guide monitoring), a reliable long-term indicator of change is the growth rate of a population. Here we present a decision framework that uses monitoring data on growth rate of a population to determine whether to create a marine reserve and to evaluate its efficacy.

Figure 13. Schematic illustrating the relationships between adaptive management and monitoring (modified from Gerber et al. 2005).
Once there is buy-in and sign-off for creating a reserve, the three general stages to decisions in the process of reserve establishment and management are:

1) Identifying the number of years of monitoring needed before a decision on creating a MPA is made (T),

2) Using estimates of annual rate of population growth of a particular species to determine how many years of monitoring data are needed to evaluate the success of the reserve (M), and

3) Determining the need for a change in the management plan (e.g., reserve size and location).

In figure 14 we show how this framework can be used for stage 1, using pre-reserve baseline data (for detailed explanation of how to estimate M, T and growth rate, see Appendix F). If population growth rate is negative or the number of years in the time series is lower than T, a reserve is established. If growth rate is positive, we assume that the MPA regulations are adequate and no reserve is necessary. This approach is precautionary because T and M are defined based on a predetermined level of risk tolerance (see Appendix F). If in subsequent years the population growth rate continues to be or becomes negative, a reserve should be established. After the creation of the reserve, monitoring continues until, after at least M years, population growth becomes positive. At this point we can conclude that the reserve is fulfilling the goal of recovering the population of the target species. Our recommendation is to maintain the reserve and not reopen it to fishing, because it has been shown that a reopened reserve not only results in rapid elimination of fish biomass within its boundaries, but also in a reduction of the likelihood of recovery after subsequent protection.

**Suggested Software for running these models**

- Matrix population models: MatLab (http://www.mathworks.com/);
- Pop Tools (http://www.cise.csir.au/poptools/)
- Economic models: MatLab (http://www.mathworks.com/);
- LIMDEP (http://www.limdep.com)
- Databases: Excel, D-base, MYSQL (http://www.mysql.com/)

**Select data sources**

- MEI index: http://www.cdc.noaa.gov/people/klaus.wolter/MEI/
RE-EVALUATING ZONATION BASED ON DEMOGRAPHIC AND ECONOMIC INFORMATION

There is a lot of uncertainty in our knowledge of how exactly marine systems work, often leading to assumptions about how a system will react to different protection measures. Because of this uncertainty, managers are often asked to manage reserves “adaptively”, making decisions as the best ecological and social information becomes available. After a management decision is made, we observe how the system behaves for an experimental amount of time, after which we adjust our management rules to incorporate new information.

LESSONS FROM LORETO BAY

HOW MANY YEARS OF DATA DO YOU NEED TO MAKE A DECISION ABOUT ESTABLISHING A RESERVE SO THAT THE RESERVE IS LIKELY TO MEET ITS MANAGEMENT OBJECTIVES?

After estimating population growth rates and their variance (a measure of variability in the estimates) for each site in question, these parameters can be used to estimate a threshold (CV) which serves as a way to identify the number of years of data needed (T) before a management decision could be made. The CV provides an indication of how much variability there is in annual estimates of population growth rate for each site, and, hence, how reliable monitoring data are in determining effects of reserves. The reason this CV value functions as a threshold is that a value with high CV shows us that there is a lot of variability in the population growth rate estimates, and thus we may not capture the “true” picture of the population in a given time. By setting the threshold at a low value (for example, 0.3) then we are trying to determine when we see estimates that are stable in time. By identifying the number of years of data necessary to detect changes in population structures, the cost of monitoring and management may be reduced. For example, if a population is confidently determined to be increasing, the traditional use of resources by local communities could be allowed to resume.

Figure 15. Possible threshold levels (CV) for population growth rates used to identify number of years of data (T) necessary for each monitoring site to decide whether to create an MPA. The red line reflects a CV of 0.3. Overall, assuming a threshold of 0.3 is chosen to represent an adequate amount of certainty in population growth rate estimates, population growth rate only 5 years of data are necessary to make the decision of whether to create a marine reserve at each site except Danzante Island, located within LBNP.
Adaptive monitoring and management of Marine Protected Areas

**ESTIMATING THE EFFECTS OF NO-TAKE RESERVES AND THEIR ECONOMIC IMPACTS.**

The best available biological and economic information were used to examine the impact of establishing marine reserves of different sizes on the growth rate of the leopard grouper population at Carmen Island, Gulf of California, Mexico, and on the economic benefits that the resource provides to commercial fishing and recreational diving (J. Wielgus, unpublished data). The planning horizon of their strategy was 10 years, an adequate period for studying the effectiveness of no-take reserves in the recovery of grouper populations. The idea is to run the models multiple times simulating the changes in survival according to different assumptions about reserve size and placement, and including environmental variability. The results from these models are then incorporated into matrix models, which yield different values of population growth rates. For example, the models can be run to include different habitats or just one, to protect spawning aggregations or other important areas, or to include different configurations that would affect harvest and survival differently. This case study examined the effects of completely eliminating grouper fishing, but allowing SCUBA diving, in all of the shallow spawning habitats coupled with closing off different proportions of the adjacent deep areas.

**Table 1. Average expected population growth rate of leopard grouper (over 10 years) for reserve sizes encompassing the entire shallow areas coupled with different proportions of the deep area at Carmen Island. Two levels of juvenile recruitment (100% and 60%) are shown, assuming that all adults remain inside the reserve at all times (J. Wielgus, unpublished data). The minimum fraction of the deep area that should be closed to fishing to achieve a sustainable population (in addition to closing the shallow area) was 50% for the “best-case” scenario, which assumed maximum recruitment and no spillover.**

<table>
<thead>
<tr>
<th>% Reserve Size</th>
<th>100% Recruitment</th>
<th>60% Recruitment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.953</td>
<td>0.901</td>
</tr>
<tr>
<td>10</td>
<td>0.962</td>
<td>0.908</td>
</tr>
<tr>
<td>20</td>
<td>0.971</td>
<td>0.917</td>
</tr>
<tr>
<td>30</td>
<td>0.82</td>
<td>0.926</td>
</tr>
<tr>
<td>40</td>
<td>0.994</td>
<td>0.936</td>
</tr>
<tr>
<td>50</td>
<td>1.007</td>
<td>0.948</td>
</tr>
<tr>
<td>60</td>
<td>1.022</td>
<td>0.961</td>
</tr>
<tr>
<td>70</td>
<td>1.038</td>
<td>0.977</td>
</tr>
<tr>
<td>80</td>
<td>1.056</td>
<td>0.994</td>
</tr>
<tr>
<td>90</td>
<td>1.076</td>
<td>1.014</td>
</tr>
<tr>
<td>100</td>
<td>1.098</td>
<td>1.036</td>
</tr>
</tbody>
</table>

**Figure 16. Tradeoff between average economic benefits per m² and reserves encompassing different proportions of the deep area (in addition to the entire shallow area) at Carmen Island, in Loreto Bay Marine Park, for a 10-year planning horizon.**

Yellow bars are average of income from harvests of leopard grouper; dark blue bars are mean economic benefits to SCUBA divers. The economic benefits for fishers decreased with the size of a no-take reserve, while the benefits for divers increased. Maximum total benefits took place at maximum reserve size for the scenario of maximum juvenile recruitment and no adult spillover. The results in this graph suggest that fishing should be closed in the entire shallow areas where adult fish aggregate to spawn and in at least 50% of the adjacent deep areas. This new proposed no-take reserve would enhance the value of the fish population for recreational SCUBA divers, whose increased willingness to pay (to see large fishes instead of small-sized reef species) potentially could compensate fishers for at least part of their losses. This potential adaptive management scheme provides a way to account for the needs of stakeholders and can be a cost-effective way to sustain the exploited fish populations (J. Wielgus, unpublished data).
CONCLUSION

This handbook was developed to improve conservation in the Gulf of California by providing decision-making tools to assist the managers of MPAs to conduct adaptive management based on models and field data on biological and socioeconomic considerations. We applied ecological models, formal decision-making methods, and treatments of uncertainty for designing and managing MPAs in the Gulf of California, and applied our models to the LBNP. Our proposed adaptive management scheme provides an approach to account for the needs of stakeholders and can be a cost-effective way to sustain exploited fish populations. The proportion of the Gulf of California that is truly protected from fishing is extremely low (less than 1%), and current regulations of the LBNP appear to be too weak to allow for the recovery of fish populations. Our results suggest that, if we are to use the marine resources of the Gulf of California in a sustainable way, more reserves must be created, and the current management plans of existing MPAs be re-evaluated.

GUIDING PRINCIPLES, A SUMMARY

<table>
<thead>
<tr>
<th>PRINCIPLE</th>
<th>CHAPTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPA design should explicitly incorporate the movement of individuals from one habitat to another (or inside/outside protected area) at different life stages. Managers should incorporate natural variability into management and monitoring plans.</td>
<td>Identifying Indicators of Ecological Change</td>
</tr>
<tr>
<td>Demographic data should be used to predict when MPAs are most likely to be effective for a given life-history type, and this information can be used as an early step for MPA planning.</td>
<td>Monitoring</td>
</tr>
<tr>
<td>When comparing sites for reserve efficacy, managers should select sites that are similar in terms of the habitat that the species is likely (or known) to use.</td>
<td>Monitoring</td>
</tr>
<tr>
<td>To detect changes in biodiversity that are a result of management decisions, managers should incorporate spatial and temporal variability in community composition at appropriate scales across sampling or MPA sites into management and monitoring plans.</td>
<td>Monitoring</td>
</tr>
<tr>
<td>There are three main stages to decision-making in the process of reserve establishment and monitoring once there is buy-in and sign-off on reserve creation, including 1) Identifying the number of years of monitoring needed before a decision on creating a MPA is made, 2) Using estimates of annual rate of population growth of a particular species to determine how many years of monitoring data are needed to evaluate the success of the reserve (M), and 3) Determining the need for a change in the management plan (e.g., reserve size and location).</td>
<td>Management</td>
</tr>
<tr>
<td>To determine the number of years of monitoring data needed to evaluate reserve success while reducing monitoring costs, estimates of the annual rate of population growth for a given species may be used.</td>
<td>Management</td>
</tr>
<tr>
<td>Managers should incorporate new information as it becomes available into their management decisions, thus manage adaptively.</td>
<td>Management</td>
</tr>
</tbody>
</table>
**APPENDIX A**

**EXAMINING DISPERAL AND DEMOGRAPHY**

**How to employ this approach**

To understand if a given species would benefit from the establishment of a MPA, the following steps should be taken for each species:

1. Collect or estimate population parameters
2. Build a matrix
3. Estimate population growth rate ($\lambda$)
4. Change model parameters according to relevant dispersal mechanism
5. Estimate new population growth rate
6. Keep iterating until all of the dispersal scenarios have been simulated
7. Plot relationship and analyze results

**Data needs**

General life history parameters required for this type of analyses include:

- Age categories
- Fecundity (eggs or offspring per year)
- Age at maturity
- Age 0 survival rate
- Adult and juvenile survival
- Habitats of juveniles and adults (even if rough)
- Type (timing) of dispersal

**Model Parameters**

To run the model, one needs to have these parameters for both patches (i.e., for inside and outside the MPA):

- Dispersal between stages and patches (can be known or estimated)
- Probability of annual survival for each age class (probability of surviving from one stage to the next each year)
- Mean annual fertility rates
- Length of juvenile stage (depends on age at maturity)

**Model outputs**

- A number, or eigenvalue, called lambda ($\lambda$), which is the population growth rate. Theoretically, when $\lambda = 1$, the population is stable, when $\lambda > 1$, the population is growing, and when $\lambda < 1$, the population is declining.

**Model advantages**

- Can estimate parameters when data unknown
- Does not need to be spatially explicit data on a fine-scale- knowing inside and outside of MPA is enough.

**Model caveats**

- None of the scenarios encompass the full biological complexity of any the species considered.
- Species by species approach (but this can be circumvented by selecting representative species).
- Lacks incorporation of density-dependent population growth.

**APPENDIX B**

**UNDERSTANDING EFFECTS OF ENVIRONMENTAL VARIABILITY ON MONITORING**

**How to employ this approach**

To understand:

1. Collect abundance data.
2. Convert to biomass.
3. Assign each species to a larger group; we suggest 4 trophic groups.
4. Conduct principal components analysis (PCA).
5. Plot PC scores vs. multivariate El Niño Index (MEI) according to appropriate time lags.
6. Conduct non-parametric analysis.

**Data needs**

Data for this type of analysis include:

- Abundance estimates for most conspicuous species (see Quantification of fish biomass section in Appendix D) over a period of several years.
- Biomass estimates for most conspicuous species (see Quantification of fish biomass section in Appendix D) over a period of several years.
- Trophic group for each species (herbivore, carnivore, piscivore, planktivore) following Ballantyne et al. (in prep.).
- Data for the environmental condition of concern; in the case of El Niño, we suggest the multivariate ENSO index (MEI), to characterize environmental conditions because it reflects large scale changes in oceanography and climate and has been linked ecological processes in a variety of systems.

**Analyses**

1. Group data according to spatial resolution and varying species assemblages.
2. Conduct PCA
3. Relate the scores of the first two principal components can then be related to environmental variable with, for example, a one-way ANOVA.
4. Examine the relationship between the PC scores and environmental variable across multiple time lags.
5. For each time lag, plotted average PC scores as a function of environmental variable and starting with the most negative MEI value, counted the number of observations of lesser magnitude in PC for greater values of MEI. This same counting process is performed for each subsequently greater value of MEI and the results are then summed to arrive at one number for each combination of time lag and PC score.

**Model advantages**

- Length to biomass estimates can be made from similar species using Fishbase (www.fishbase.org) and literature.
- Many environmental data readily available online.

**Model caveats**

- PCA assumes that variables are related to each other in a linear fashion.

**APPENDIX C**

**ESTIMATING POPULATION PARAMETERS**

**How to employ this approach**

To understand:

1. Collect abundance data
2. Estimate parameters
3. Process environmental data
4. Construct matrices
5. Compare to observed abundances in the field to ground-truth model estimates

**Model Parameters**

- Abundance of different life stages (e.g., larvae, juveniles, sub-adults, adults). For an example, see
“Quantification of fish biomass” in the “Is your reserve effective?” section.
- Probability of surviving from one stage to the next (survival)
- Probability of surviving one stage and remaining there (e.g., juvenile stage lasts more than one year)
- Number of juveniles produced by each adult (fertility)
- Number of individuals that remain in each habitat between sampling periods
- Number of individuals that move between habitats between sampling periods

In the absence of detailed biological information to estimate the model parameters, one can use several methods to estimate the parameters from abundance data. Used abundance data for life stage at different timeframes (e.g., field seasons, or years, or sampling times) coupled with parameters that are from similar species to estimate the remaining parameters for the model.

Assuming a variable environment, the growth rate of the population can be represented by the stochastic (or random) growth rate. One can then estimate expected fish densities at a given site at a given time by taking the initial fish density obtained from field surveys and multiply it by a matrix containing the probabilities of whether it is an El Niño or La Niña.

Model advantages
- Can estimate parameters when data are scarce.
- Can incorporate movement between habitats at different life stages at a site.
- Does not need to be spatially explicit data on a fine-scale knowing inside and outside of reserve is enough.
- Can use or estimate parameters that are from similar species if these data are not available for the species of concern.
- For pelagic and wide-ranging species, this approach can be useful if one can estimate abundance at different life stages over several years.
- Allows for comparison of model estimates to each other to obtain an understanding of what may be driving population parameters.

Model caveats
- As is, the model is primarily applicable to sedentary species requiring small protected areas.
- Model assumes density independent population growth.
- Does not account for possible movement (dispersal) between sites.
- Assumes average environmental effects over the long-term, so should not be used for short-term population forecasts.

Data analysis:
- Test reserve effects on fish biomass at different levels of species aggregations.
  - For example, total fish biomass, biomass of commercial fishes, and biomass of one species.
  - Generally, the species or species groups should be chosen if they are important to the reserve in some way (culturally, economically, biologically).
- If the goal is to assess the effect of the reserve vs. outside the reserve, one must assume that the threat to the species (e.g., fishing pressure) is homogeneous inside the park.
  - Ideally, use spatially explicit data on the distribution of fishing effort and catches throughout the reserve, in all zones, to circumvent this assumption.
- To test for two different types of impact (change in mean biomass after protection, and change in temporal variance), we recommend using asymmetrical analysis of variance (ANOVA).
  - Protection can be considered a “press disturbance,” since its effects are continuous and can cause a sustained increase in mean fish biomass.
  - Protection may dampen temporal variance in fish abundance relative to unprotected areas.
  - Both effects can be detected as significant interactions.
- Increased biomass after protection would cause an increased interaction between the difference from impacted to control locations before, compared with after, protection (B × 1).
  - If there is no general interaction among control locations from before to after protection (that is, B × C is not significant when tested against the Residual), B × 1 can be tested by the F-ratio of the Mean Squares for B × 1 and the Residual.
  - An effect on temporal variance can be detected as...
Appendix E

Identifying Spatial and Functional Gradients for Monitoring

How to employ this approach
1. Collect abundance data
2. Convert to biomass
3. Assign each species to a trophic and spatial group
4. Conduct principal components analysis (PCA)
5. Calculate Euclidean distances and cosines between points within and across PCA ordinations (in PCA space)
6. Run rank test and sign test

Data needs
Data for this type of analysis include:
- Abundance estimates for most conspicuous species (see Quantification of fish biomass section in Appendix D) over a period of years
- Biomass estimates for most conspicuous species (see Quantification of fish biomass section in Appendix D) over a period of years
- Trophic group for each species (herbivore, carnivore, etc.)

Model Parameters
To assess whether there is a characteristic spatial and trophic scale for reef fish communities, the following parameters are necessary:
- Varying spatial gradients (e.g., sites separated by 10s, 100s or 1000s of km) in the study area
- Functional gradient (e.g., biomass of 30 species that comprise more than 90% total biomass, biomass of a smaller number of trophic groups)

Analyses
- Group data into a few different spatial categories
- Group data into a few different functional gradients.
- Plot temporal changes in community structure in principal components data space
- To assess the utility of each community description, compare community dynamics within and between community replicates (e.g., sites, islands, regions).
- To characterize differences in the trajectory of each community replicate, calculate the Euclidean distance (change in x and y coordinates in the PCA graphs) between each point for each individual community at each time step (i.e., distance between Xt+1 and Xt, where X is one community at times t and t+1).
- To compare across sites (or islands or regions), compare the Euclidean distances between sites (each point at each time step); that is, calculate the distance between X and Y at a given time t, where X and Y are different communities.
- To statistically determine if there are differences in the changes of each community in space and according to taxonomic grouping, conduct rank tests.

Approach advantages
- Abundance data are often relatively easy to collect
- PCA is a widely used analytical tool
- Non-parametric tests allow for smaller sample sizes and non-normal data and are more conservative than parametric tests
- Allows for exploration of different spatial and functional aggregations

Model Caveats
- PCA assumes that variables are related to each other in a linear fashion

Appendix F

Using Monitoring Data for Management Decisions

How to employ this approach
1. Estimate population growth rate for each year and site
2. Estimate mean and variance for each population growth rate
3. Estimate Coefficient of Variation for each site/year combination
4. Plot relationship and analyze the results

Data needs
- Abundance of different life stages (e.g., larvae, juveniles, sub-adults, adults). For an example, see “Quantification of fish biomass” in the “Is your reserve effective?” section.
- Probability of surviving from one stage to the next (survival)
- Probability of surviving one stage and remaining there (e.g., juvenile stage lasts more than one year)
- Number of juveniles produced by each adult (fertility)
- Number of individuals that remain in each habitat between sampling periods
- Number of individuals that move between habitats between sampling periods

Estimating population parameters
1. Population growth rate for each year and site can be estimated using the inverse estimation method (Wielgus et al. Conservation Biology 21 (2), 447-454.; also see “How limited demographic data can guide manage-
ment decisions” section below).

2. Characterize population growth patterns
   a. Subsample from surveys that are contiguous through time (e.g., year 1, year 2, year 3... year n) to create progressively impoverished data sets (e.g., n, n-1, n-2, n-3, n-4). Use these data sets to estimate the variance for growth rate values for each survey duration using the perturbations.
   b. For any given survey duration, n (out of N total years), select all possible permutations of continuous sets of survey data of n years. If, for example, there were 7 years of data then there were 6 samples of two consecutive years, 5 samples of three consecutive years, etc (i.e., the number of permutations, p=n-1!)

3. Incorporate variability in growth rates
   a. Estimate the variance for growth rate values for each survey duration using the perturbations. Using the example of a 7-year data set, the 7-year subset includes only one permutation, generate a variance estimate by jackknifing the seven estimates of population growth rate. The jackknife estimation technique allows for variance estimation and bias correction (Haddon 2001). Jackknife replicates may be calculated from a data set of n values for n (non-contiguous) subsets of (n-1) data points.
   b. Estimate population growth rates and generate 50% and 95% confidence intervals from the standard errors for 7 subsets of 6 data points.

Model Parameters
- Annual population growth rates for each year and site

Model Advantages
- Considers the inherent variability in the population growth rate, even if a mean is highly accurate.
- Allows managers and policy makers to select appropriate CV based on acceptable levels of risk that are considered tolerable based on risk associated with various management outcomes.

APPENDIX G
EXAMINING ECONOMIC CONSEQUENCES

How to employ this approach
1. Obtain parameters from field data or literature
2. Estimate survivorship for fish outside the proposed reserve
3. Use matrix models to change the values of demographic schedules to model the effects of different closure scenarios.
4. Estimate the different stochastic population growth rates
5. If closing the easiest (and appropriate) area does not yield an increasing population growth rate (≥1), then add more area (e.g., different habitat, spawning zones, etc.)
6. Examine alternate economic scenarios

Model parameters
Demographic parameters for the species in question per age class and if necessary or applicable, per habitat, include:
- Survival
- Recruitment
- Growth rates
- Mortality (natural and anthropogenic)
- Estimates of the percent of the population harvested or killed annually

Economic data include:
- Data on reported fish catches (or other measure of anthropogenic impact)
- average weight of harvested fish
- mean price charged by fishers
- average catch per trip (or other measure of effort).
- Costs to fishers; e.g., gasoline for a fishing trip, cost of fishing per kg of fish, net revenue per kg
- Average annual inflation
- Data for alternative to fishing, e.g., diving; average marginal price of an adult individual species for divers, number of adults seen per dive, number of dives per year.

Analysis
Simulating of the establishment of a no-take reserve
To assess what the different effects of establishing different no-take reserves (sizes, locations) on population growth rates:
- Model the probability of surviving a given year. By changing the values of the demographic schedules (e.g., mortality by fishing in a given year, or survival in reserve in a given year) the impact of closing different areas to fishing (or other human activity) is readily seen.
- Environmental variability can also be included in the simulations by randomly selecting the projection matrix for a given environmental variable according to the probability of occurrence of each given event (e.g., the probability of an El Niño event).
- Seed the matrix, use the earliest values of population density available, then project the population to T = 100,000
- Estimate the expected long-term population growth rate
- Estimate changes in the survival probability of adults from a reduction in fishing mortality under different scenarios.

Protection of spawning aggregations
- Simulate the effects of establishing a no-take reserve only in areas that are easy (and appropriate biologically) and enforceable, for example, the shallow area adjacent to land.
- If the scenarios modeled using the simplest approach do not provide a large term population growth rate ≥ 1, then additional areas must be closed. Parameters should be recalculated simulating different closure scenarios.

Estimation of economic benefits
To examine the trade-offs in the benefits to, for example, fishers and divers accruing from different reserve sizes:
- Estimate the present value of annual economic benefits (per m2) from a given fish species to fishers and divers during the planning horizon and calculate annual fishing income (I) for each set as

$$I_t = F_t \cdot H_t \cdot p_t \cdot W$$

where Ft is adult fish harvested per m2 of the open area in period t, pt is the net revenue per kg of fish during the period, and W is the mean weight of harvested adults.
- Estimate the Compensating Surplus (CS) of divers:

$$CS_t = MP[(Ac - At)]$$

where MP is the marginal price of the fished species, Ac is the current average number of adult fish observed dur-
Adaptive monitoring and management of Marine Protected Areas

ing a day of diving, and \( \text{At} \) is the expected number of adult fish given the establishment of a no-take reserve of a certain size.

- Calculate the annual net economic value per m\(^2\), in terms of the fish sighted during dives:

\[
V_i = \left( \frac{MP \cdot D_i}{Q} \right) \cdot Y
\]

where \( Q \) is the average area observed by a diver during a dive and \( Y \) is the number of dives in the shallow area during a year.

**Sensitivity analysis**

To account for the uncertainty of these estimates, the impacts of a no-take reserve in different areas can be simulated by considering different proportions of the original estimates, for example, 80% and 60% of the original estimates. To account for the possibility of spillover, simulate the potential emigration of adult fish from the no-take reserve to adjacent areas. For each habitat scenario, the same spillover rate for each no-take reserve size can be assumed. Select spillover rates that are consistent with your species or a similar one. The impact on the economic benefits of no-take reserves of 10% and 20% annual increases in the harvest costs per kg of fish should also be incorporated to account for changes in fishing effort.

**Model outputs**

For each run of the model:

- A value of survivorship, which are then used to obtain values of \( \lambda \).
- A number, or eigenvalue, called lambda (\( \lambda \)), which is the long term, or stochastic population growth rate. Theoretically, when \( \lambda = 1 \), the population is stable over a long timeframe, when \( \lambda > 1 \), the population is growing and when \( \lambda < 1 \), the population is declining.

**Advantages**

- Works with limited data about a given species
- Data often available through field work, literature or congeneric species

**Caveats**

- Need to understand or be able to estimate population dynamics

---

**References**

**Why this handbook?**


**Marine Protected Areas and Marine Reserves**


**Loreto Bay National Park (LBNP) and the Leopard Grouper**


**Identifying indicators of ecological change: metrics of success**

16. Leslie, H., M. Ruckelshaus, I. R. Ball, S. Andelman and H.
Navigating Uncertain Seas:

Monitoring


Management


Appendices

Navigating Uncertain Seas: Adaptive Monitoring and Management of Marine Protected Areas