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Marine Reserves

A GUIDE TO SCIENCE, DESIGN, AND USE

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Research Priorities and Techniques

JOSHUA SLADEK NOWLIS AND
ALAN FRIEDLANDER

The ocean is a complex place with a wide diversity of life forms, habitats, and ecosystems. Far from a static environment, oceans change both cyclically and unpredictably. Tides ebb and flow and seasons change, both having profound effects on ocean life. Longer cycles affect oceans and the life they contain as well; an example is the El Niño Southern Oscillation (Bakun 1993). These cycles are only one reason why oceans are so complex and difficult to predict.

Deep ocean environments are more remote and less visited (by people) than the dark side of the moon (Earle 1995). With the burgeoning popularity of scuba diving in the 1950s, people began to explore coastal waters. Yet scuba only allows intensive study of shallow waters, with physiological limitations making such studies difficult at depths greater than 20 meters (65 feet). More recently, submersible technology has increased the depths at which people can work at length. However, these technologies are expensive and have only scratched the surface of the deep ocean. The unknown status of most deep environments and many shallower ones helps explain our inability to fully understand or predict the ocean.

Especially given the many unknowns surrounding the ocean, marine reserves provide an unparalleled opportunity to study marine ecosystems in the absence of fishing pressure and other major human impacts. As such, they offer the potential to teach us a great deal about how we affect marine ecosystems, how those systems behave in the absence of major human impacts, and how we can best minimize those impacts outside of reserves. We have already learned a great deal despite the current limited size and extent of reserves. In any debate about whether to establish marine reserves, their ability to teach us about the influences we have on the ocean should be a big point in their favor. Thus marine reserves are both an important subject for future research and a key tool to enhance our understanding of marine species and ecosystems. This chapter examines research needs for the designation and management of marine reserves. This research will, in turn, enhance our understanding of the oceans.

WHAT DO WE NEED TO KNOW ABOUT MARINE RESERVES?

We know a great deal about how to design effective marine reserves and the outcomes of doing so (see chapters 4 and 5 for further discussion). Nevertheless, there are some important unknowns surrounding marine reserve effectiveness. First and foremost, we are unable to precisely predict the full suite of responses of organisms inside and outside of newly created reserves, or how people will respond to these changes. Monitoring is the key to tracking these issues and is discussed at length in this chapter. Movement of adults, larvae, and eggs is a key area where we understand relatively little and the implications are large for reserve design and function. When habitat-based these movements form one component of habitat connectivity, another relatively poorly understood phenomenon with significant implications. Finally, we discuss the range of scientific tools that can be used to map out habitat and species distributions, and thus facilitate effective marine reserve design.

Given these unknowns, it is important to consider our knowledge of marine reserves relative to other management tools for the sea and to look carefully at what we can realistically expect to know. Considering the uncertainties surrounding oceans in general, marine reserves are quite well understood. We know, for example, that marine reserves lead to bigger and more abundant populations of many types of target species within their borders (see chapter 4 for further detail). We also know that for the vast majority of species, some of that production is going to extend to fishing areas (e.g., Roberts et al. 2001). We do not know exactly how much, nor whether these enhancements will fully offset losses to fishing communities from reduced fishing grounds, especially in the short term. However, it is generally accepted and even legally mandated that some regulation is necessary to protect fished populations from overfishing. We regularly use a suite of tools to achieve this objective, including catch quotas, effort quotas, size limits, gear restrictions, closed seasons, temporary closed areas, and even stocking of fish by artificial means. None of these techniques have more scientific validation than marine reserves.

To illustrate this point, let's consider minimum size limits, a common fishery management technique that requires fishers to throw back fish if they are too small. Theory shows they can enhance catches. If fish are allowed to survive until they can reproduce at least once, they are much harder to overfish (Myers and Mertz 1998). Yet the real world provides some challenges to this theory. It is unclear how the size limits will affect fishing behavior, but people are likely to respond by fishing harder for larger fish, which research indicates contribute disproportionately to future production. Nevertheless, theoretical studies have shown that this effort shift will still result in healthier fish populations if the smaller fish are truly protected.

But, size limits might not protect the undersized fish after all nor protect the health of the ecosystems all fish require. Many forms of fishing gear have the potential to kill fish before they are brought to the surface, measured, and thrown back. Trawling—dragging nets behind a boat either in the water column or along the bottom—is one of the most common forms of commercial fishing. Fish that end up at the back of a trawl net are likely to be squeezed to death by the fish that are caught later on. It is tempting to think that this problem could be resolved through regulating the mesh size of trawls, but it is not that easy. Trawls typically catch more than one species of fish at a time. Choosing a mesh size would be tricky because different species will have different ages at maturity. A trawl net designed to avoid all immature fish would probably not catch very many adults. Moreover, once the first layer of fish is caught at the back of a trawl, the effective mesh size becomes quite small even if the initial mesh size was large.

Other gear has similar problems. For example, longlines are another common commercial fishing gear composed of hundreds of fishhooks set out along lines that can be miles long. Longlines are deployed and retrieved many hours later. Fish that bite hooks early on are unlikely to survive until the line is retrieved. Even low impact gear has a high potential to kill certain types of fish. Most deep dwelling fish have swim bladders that inflate as they are brought to the surface. Many are likely to die on the way up whether they are caught by a trawl or a by a hook. Additionally, fish caught at any depth face increased risks of (1) being eaten while they are being reeled in or are swimming back to shelter, (2) infection or other damage from the hook wound, and (3) vulnerability from shock and exhaustion from fighting. These risks are greatest for fish that live a long time and are thus more likely to be caught and released multiple times (A. Bartholomew and J. Bohnsack, personal communication, 11/19/03).

Given this information, do minimum size limits really work? Despite these shortcomings, they are widely accepted and used in management systems and probably do help in many cases. It is intellectually fascinating that many people are unwilling to accept similar sorts of scientific validation for marine reserves. In fact, when compared to other more common fishery management techniques, marine reserves may produce benefits in a more efficient manner—providing greater benefits with fewer short-term costs (Sladek Nowlis 2000).

LIMITS TO WHAT WE CAN KNOW SCIENTIFICALLY

Marine reserves are often held to a higher standard of scientific proof than other management tools. In fact, some people demand proof of marine reserve effectiveness that may be impossible to provide.

Take the issue of how marine reserves affect the ecosystems within and around them. To assess the impacts within, we could use standard scientific protocol and compare areas inside and outside of the reserve before and after the reserve designation. We would want these areas to be in the same general vicinity so they were affected by the same external events and had similar ecologies prior to the reserve establishment. If there were minimal differences prior to and many more fish in the reserve after establishment, we might conclude that the reserve was responsible for the buildup of fish. But some other phenomenon the experimenter did not notice might have been responsible—say an unusually large new cohort of fish settling in the reserve by chance.

To factor out these concerns, we should ideally use replication—examining multiple independent reserve and fishing areas. Once replicated, statistical tools can help us distinguish random effects from real effects. But replication is difficult to achieve. Reserves are rarely established as well-designed ecological experiments because socioeconomic concerns usually dictate the choice of reserve sites. Consequently, most are not replicated. When they are, a scientist might be lucky to have three or four reserves to work with. Under these circumstances, statistical tools lack the power to distinguish real from random effects unless the differences between reserve and fishing areas are tremendously large (e.g., Paddack and Estes 2000) or unless long-term data sets are available (e.g., Russ and Alcala 1996).

When reserves are replicated, it is usually as part of a reserve network where there is more interest in the effects of reserves on outside areas. Once we view the reserves as interconnected with surrounding areas, we can no longer consider them as independent. This issue throws an even bigger wrench into the scientific paradigm because the statistical tools that distinguish random from real effects require independence of sampling units. So to examine the effects

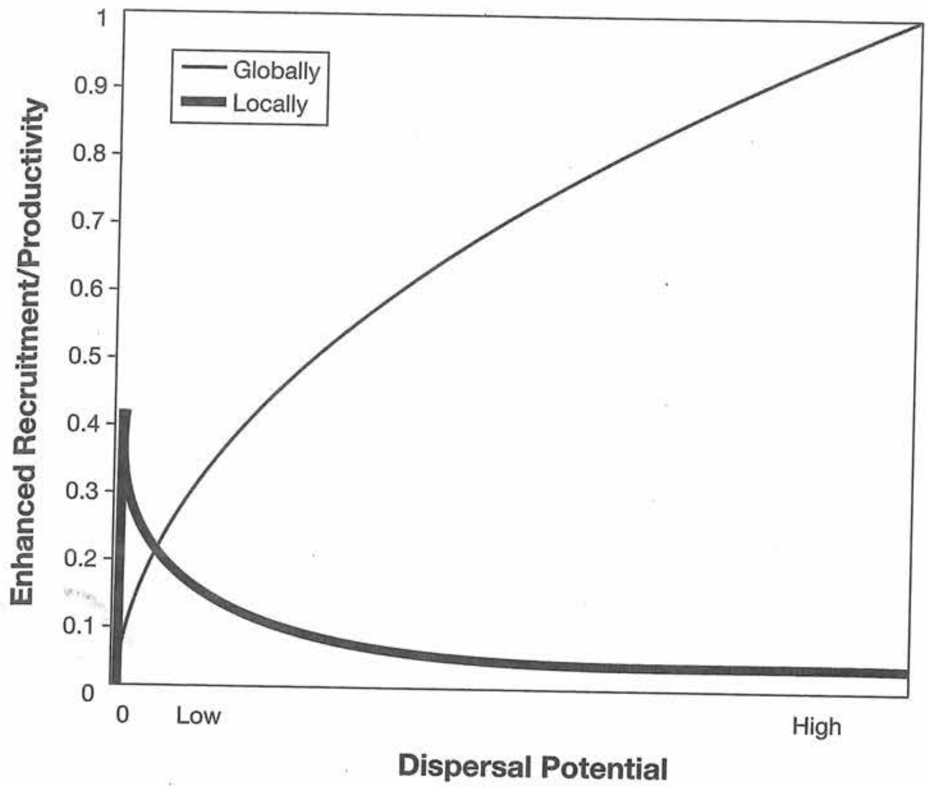

FIG. 7.1 Limits to What We Can "Prove." A simple modeling exercise of a population where adults stay in reserves and eggs and larvae vary in their dispersal potential shows a nonintuitive result. Global benefits from the marine reserve, in the form of productivity transported to fishing areas, were greatest with high dispersal potential. However, these same conditions diluted benefits so that they were small in any local area, and thus difficult to detect amidst natural variability and sampling error. Local benefits were most likely to be detected when dispersal potential was low, the conditions least likely to provide global benefits. Source: Data from Sladek Nowlis, unpublished.

of reserve networks we need multiple reserve networks and multiple areas where reserves were not established, all of which should have been similar before the reserve establishment and in close enough proximity to be affected by the same major events afterwards. Considering that a single reserve network is likely to span across an entire region, it is readily apparent that it is virtually impossible to design such an experiment in the real world (see also Fig. 7.1). These problems do not only affect marine reserves. Studies have shown that scientific proof of success may be difficult to achieve for other management tools as well (e.g., size limits, Allen and Pine 2000).

The proof we generally require of other management tools consists of logical consistency (i.e., theoretical support) combined with real-world experience where they seem to work based on anecdotal information and scientific evidence of a positive, but usually indirect, response (e.g., the average size of fish becoming larger after the enactment of a new size or catch quota limit). Reserves should not be held to a higher standard. In fact, reserves are backed by extensive theoretical support (NRC 2001) and have a strong track record for being considered effective in the real world, including not only indirect but also direct responses (e.g., Russ and Alcala 1996; Roberts et al. 2001).

MONITORING

There are a number of interesting questions about the function and design of marine reserves. Some of these questions have been examined extensively, such as those concerning how large marine reserve networks should be to achieve various objectives (see chapter 5). On other questions, the jury is still out. There are four major outstanding issues regarding the function and design of marine reserves: monitoring, movement, habitat connectivity, and mapping of habitat and species distributions.

Monitoring sounds pretty dull to most people, including many scientists, but its potential for teaching us what does and does not work in marine reserve design should not be overlooked (Carr and Raimondi 1999; Underwood 1995). Monitoring plays a crucial role in evaluating the effectiveness of a marine reserve or reserve network and is an important tool for improving the principles of marine reserve design. The ecosystems both within and around marine reserves should be the subject of monitoring (Carr and Raimondi 1999; Murray et al. 1999), but it is at least as important to monitor social attitudes toward marine reserves (e.g., Roberts et al. 2001; Russ and Alcala 1996).

Monitoring also allows us to learn a great deal about marine ecosystems because marine reserves offer less impacted systems to contrast to fishing areas. Doing so has the potential to teach us a great deal about how to better manage these systems and a better appreciation for how they operate with fewer human impacts. Here, we consider some of the questions one might answer through monitoring, and the tools and techniques available to address them.

Fundamentally, monitoring can answer the question: Is the management system working? The answer to this question will be dependent on both marine reserve performance and management goals, and monitoring systems should be tailored toward the goals of the marine reserve or reserve network. Goals will invariably have biological and social elements, and monitoring should address both. A basic monitoring system should consist of before and after results from direct or indirect counting techniques, basic ecosystem attribute measurements, and surveys of public attitudes regarding the state of the ocean and ocean resources and perceptions about marine reserves. Surveys should at minimum compare populations within the reserve to populations living in similar habitat outside. If effects of reserves on outside areas are of interest, it is preferable to include several sites inside and out that varied in their distance from the reserve center to examine the dilution of the marine reserve effect. More thorough monitoring systems could include tag-recapture studies to identify movement of adults and infer growth and survival rates, detailed study of ecosystem attributes, and examination of how fishing effort is distributed before and after the reserve is established. These additional efforts can provide valuable general information for managers as well as specifics for improving management systems.

Tools and Techniques

A monitoring program should be properly designed to ensure it is answering relevant questions, and monitoring data should be properly analyzed to ensure that efforts are directed in an efficient manner. It is also important to ensure that monitoring results are widely available to other scientists and the general public because these data are the primary means for assessing the success or failure of existing marine reserves.

What to Monitor

Monitoring programs should be tailored to focus on management issues of particular interest, but a big-picture, long-term view is also important. Obvious monitoring choices would include targeted, rare, and especially vulnerable species. Less obvious but potentially important choices could include abundance of species classified into trophic guilds (e.g., piscivores, herbivores), measures of habitat quality (e.g., structural complexity and abundance of key shelter-providing organisms), and other measures of ecosystem integrity. Finally, the human element should not be overlooked. Monitoring of fishing effort, catches, and attitudes will all help evaluate the success of a marine reserve network and potentially identify ways to improve it. We recommend at minimum a program that examines resident fish species assemblages, physical benthic characteristics (e.g., structural complexity, habitat type), benthic communities, other species of special interest, and attitudes toward reserves and about fishing success. This approach can be used to address a broad range of management issues using a few simple procedures and provides the most essential information on costs and benefits to both the ecosystem and human populations.

After deciding what to monitor comes the question of how to measure it. Regardless of reserve goals, managers will want to see whether populations are recovering from fishing pressure. Indicators of recovery could come in the form of an increase in the density of fish (number per unit area), the average size of fish, or both. Numbers may increase in the absence of fishing because of increased survival and ultimately because of enhanced reproduction. Numbers may not increase if large fish maintain territories, are predators, or otherwise keep smaller individuals out.

Size is even more likely to increase in the absence of fishing, sometimes dramatically so. Fishing pressure tends to target larger fish, which also are generally more aggressive and thus end up getting caught more often. However, even if large fish were not caught preferentially, one would expect the average size of a population to increase in response to the elimination of fishing pressure. Solely by surviving longer, fish will grow larger and average size should increase.

Numbers and sizes can be combined into a useful concept of biomass, which represents the total weight of fish in an area. It can be calculated by multiplying the number of fish in the area by their average weight. Weights can be measured directly if fish are caught, or calculated from length estimates from visual surveys using a standard length–weight conversion of the form $W = aL^b$, where W represents weight, L is length, and a and b are species-specific constants. Length–weight fitting parameters can be found for a number of species in published and Web-based sources (e.g., Fishbase at http://www.fishbase.org). In cases where length–weight information does not exist for a given species, the parameters for similar-bodied relatives can be used.

If reserve goals include the capacity to support fishing in areas outside of them, it may be helpful to monitor recruitment. Techniques for measuring recruitment will be discussed later in the context of movement of adults and their offspring.

Sampling Designs

A monitoring program, as with any scientific data collection, requires sampling because even a modest-sized management area is too big to measure in its entirety. Ideally a sampling program should aim to achieve some form of randomness so as to maximize the chance that the sample will be representative of the management area. The key to making sense of data, though, is in identifying patterns. Certain departures from randomness can help to answer key management issues (Green 1979).

Investigators may already know of some patterns prior to the study. If so, stratified random sampling is an effective way to acknowledge the known patterns and maximize the chances of identifying new ones. A stratum is a subset of the population that shares at least one common characteristic. The researcher first identifies the relevant strata (e.g., males versus females, various age classes) and their actual representation in the population. Then samples are drawn randomly from each stratum. Stratified sampling is often used when one or more of the strata in the population have a low incidence relative to the other strata or when a population is naturally divided into categories of particular interest to managers. For example, one might emphasize data collection about mangroves in a tropical reef system even though these ecosystems are often rare. Mangrove lagoons are important ecologically and rare, in part due to past human disturbances. Emphasizing their inclusion in a sampling design will help to ensure there is enough information on which to base any future decision about the management system.

A population or set of populations that spans several habitat types provides a perfect example. If habitat maps are available to guide a monitoring effort, it may be desirable to sample each habitat type multiple times, counting the density of fish and other organisms at each survey site. The manner in which habitat types are categorized, though, is crucial. If the types do not correspond to real ecological differences or are so broad that they miss such distinctions, protections may not be as effective as possible. Fortunately, evidence suggests that experienced scientists can work with their knowledge of ecosystems and existing habitat maps to devise ecologically relevant habitat types to serve as the basis for a zoning plan (Friedlander et al. 2003a). A stratified random sampling program using habitat types as strata would be an appropriate way to monitor under these circumstances.

For example, coral reef fish assemblages and biomass vary significantly among reef habitat types around Hawaii (Friedlander et al. 2003b). Within a single reef or bay, estimates of fish biomass can vary by several orders of magnitude depending on the habitat type sampled. Habitat stratified fish surveys acknowledge these major differences, and in doing so they have greater power to detect differences within habitat types based on other factors such as the presence or absence of marine reserves.

Ideally, sampling would take place across a wide range of areas inside and at varying distances outside of replicated reserves and would span a long time-series starting before and continuing well after the reserve designation. It is extremely unlikely that this ideal will be met. Politics typically constrain our ability to examine an area for much time before reserve designation and to effectively replicate reserves or comparable fishing areas. Moreover, resources often limit the frequency and extent of sampling efforts after reserve designation. As a result, important choices need to be made regarding the timing and location of sampling efforts.

An excellent example of effective sampling design was employed to survey the Dry Tortugas, Florida, prior to the creation of marine reserves in the area (Ault et al. 2002). Scientists classified habitats based on their understanding of coral reef ecology, mapped these habitats using a variety of methods, and then sampled randomly among areas of the same habitat type but ensured each habitat type was adequately sampled. If pursued on a regular basis, this sampling protocol is sure to provide insight into the changes that result from the creation of marine reserves in the Dry Tortugas.

Timing. One way to detect changes due to establishing a marine reserve is to examine the same site before and after. Although this simple analysis cannot rule out other causes of observed changes, data may be convincing if they demonstrate that changes happened in conjunction with marine reserve establishment, elimination, or both (e.g., Russ and Alcala 1999). It is preferable to know habitat qualities and fish abundances before reserve establishment as a way of showing that areas being compared were similar to start. Even if data are not available beforehand, time series can be convincing if they show a consistent trend after reserve establishment (e.g., Russ and Alcala 1996).

If data are only available from paired inside and outside areas without an adequate time span, a space-for-time substitution may be used (Pickett 1989). By looking at a number of different areas, it is possible to use space in the form of fishing and no-fishing areas as a substitute for time. However, this sort of comparison lacks statistical power unless the number of sites is quite large, so it is not necessarily recommended when other comparisons are possible.

Location. Most commonly, marine reserve monitoring programs compare areas inside to those outside the reserve (Halpern 2003). These sorts of comparisons can provide useful information about how fishing is affecting the outside areas with the reserves serving as a control. In this manner, a marine reserve monitoring program can follow a standard ecological before-after-control-impact-pairs design. These samples are paired in the sense that the control (reserve) and impact (fishing) sites are examined more or less concurrently. Replication comes from collecting such paired samples at a number of times both before and after the reserve designation. The approach is to test whether the differences between the control and impact sites changed after the reserve was established. A variety of statistical tests are available to analyze these data (e.g., randomized intervention analysis, Welch-Satterwaite-Aspin modified *t*-test, Box and Jenkins intervention analysis) and the appropriate method will depend on the behavior of the data set.

This approach can only give evidence of how reserves compare to outside areas, as opposed to how the reserve itself might be affecting areas outside. The inside versus outside approach should be used carefully. If the outside area is too close to a reserve, it is more likely to be influenced by adults and larvae spilling over and thus underrepresent the effects of fishing. If it is too far away, though, it may be influenced by different ecological processes and events, and as such be less valuable for comparison. A useful way to get around this difficulty is to look at multiple sites at varying distances away from the reserve center (e.g., Rakitin and Kramer 1996). Using this approach, one can actually look for where the effect of the reserve tails off and, in doing so, gain some insight into how organisms are moving in and out of the reserve.

Sampling Analysis

In addition to the challenges associated with the general design of a monitoring program, there are important considerations regarding analysis of sampling data. Some of these considerations are important in the design phase, whereas others are key to detecting patterns in the data after it is collected.

Sample Size and Sampling Effort. Monitoring programs are typically designed to examine more than one attribute or to look for change related to more than one factor. It is important to understand how the data will be analyzed so that the sampling effort is expended where it can achieve the best results. At the core of this decision is the issue of statistical power.

The power of a statistical test is its ability to identify a difference when the difference really exists. The trick is separating real differences from random variation. A powerful statistical test will allow an investigator to identify a real but small difference in, say, the abundance of fish inside and outside a marine reserve, whereas a low-power test might record the same difference but chalk it up to random chance.

Statisticians distinguish between two types of error. Type I errors occur when a perceived difference is identified as real when it was really just a random happenstance. Type II errors, on the other hand, occur when a perceived difference is rejected as a random effect when it was in fact real. Current management focuses on reducing the type I error because this kind of error results in catching fewer fish and can result in short-term economic loss (Dayton 1998). Ignoring type II errors, however, can result in serious long-term damage such as the collapse of fisheries or environmental damage. Dayton (1998) advocated reversing the burden of proof to require fisheries to demonstrate that their activities do not cause significant long-term ecological changes (a type II error). Consequently, increasing statistical power is important for moving management in a precautionary direction.

Three factors shape a statistical test's power to identify a difference between two populations: the number of samples taken, the actual difference between two populations, and the variance, a measure of the expected difference between any two samples within a population. The chance of detecting a difference is greater with more samples, a larger difference, and a smaller variance. Researchers can reduce the variance by pooling similar individuals through stratified sampling. Researchers can also effectively increase sample sizes by putting the monitoring effort where it can do the most good. Finally, researchers can calculate the statistical power that a test has so they can decide how likely it was that a difference existed but was simply not detectable.

Monitoring effort should be focused carefully. Within a site, it is valuable to apply enough effort so that the data collected are likely to represent the state of that site. However, extensive surveying within a sampling site at a given time is counterproductive. In the end, statistical tests will pool all of this effort into a single data point. Therefore, one is better off sampling just enough within a site to give an accurate picture of its current state and focusing the effort in increasing the number of sites and times sampled.

A Bayesian Approach. Fishery scientists have shown increasing interest in a Bayesian approach to data analysis (Thompson 1992; Walters 1986). Unlike conventional approaches to management exercises such as stock assessments, which tend to produce single best answers, a Bayesian approach explicitly incorporates probabilities into the mix. Bayesian data analysis starts with estimates of the probability of various outcomes and then modifies those probabilities based on experience (Gelman et al. 1995). These modifications represent an explicit effort to learn and improve knowledge, whereas more conventional approaches often rely on the same unreliable estimates year after year. Most importantly, the Bayesian approach provides a range of possible outcomes for any management action, with associated probabilities. These probabilities can help guide managers by highlighting the potential for bad outcomes as well as indicating which management actions might have the best chances of achieving good ones. Monitoring data can be fed back into a Bayesian adaptive management approach to marine reserve design.

Monitoring Plants, Invertebrates, and Habitat Attributes

Monitoring plants, invertebrates, and habitat attributes is often quite straightforward. With the exception of a few types of invertebrates, these things tend to stay put and are relatively easy to count and measure. The key questions with respect to monitoring them have to do with the scale of interest and the degree of physical and fiscal limitations.

When conditions permit, most plants, invertebrates, and habitat attributes can be censused visually with the use of transects—swaths of habitat of a fixed width and length. These transects may each follow a different depth contour, may be straight lines following a compass heading, or may follow a narrow patch of habitat if one is using habitat stratified sampling. Often a transect is subsampled using quadrats, a square area of habitat that is measured in its entirety, randomly chosen along the length of the transect (Davis et al. 1997; Rogers et al. 1994). Quadrats can be quantified in the field or photographs can be taken and analyzed later on land, the latter being especially useful when depth or current or other physical factors limit dive times. Alternatively, the entire transect can be sampled using a fixed distance on either side of the midline. This approach can be valuable for rare but important species (Davis et al. 1997). Quadrats are two-dimensional views and may not adequately represent the three-dimensional structure of some habitats. To measure the peaks and valleys of an underwater terrain, a chain allowed to mold to the bottom contour works well. Each link in the chain then represents a sampling unit, rather than a horizontal distance of measure. Chain link surveys can be tediously slow, though, and have the potential to cause damage to the physical structure of the habitat (Rogers et al. 1994). Recent advances in computer-aided design software have now made three-dimensional analysis possible through underwater photography (Bythell et al. 2001), but these techniques are time consuming and better suited for monitoring individual organisms rather than whole habitats.

Transects can be permanent or randomly selected. Permanent transects have the advantage that one observes the same organisms over time, allowing for detailed tracking of events. They suffer, though, from their vulnerability to chance disturbances, which could give an impression of widespread disaster when only the transect itself was impacted. Random transects cannot track the response of individuals or local biological communities to specific events but are better at putting disturbances into a broader framework.

Quadrats and transects can be performed by trained divers in the field or can be captured on film or video and analyzed later on land. Field collection has the advantage that data are available immediately without risk of loss through equipment failure. It is also easier to clearly identify species in the field than from photo or video images, although even a trained diver will not be able to replicate the measurement precision of images analyzed on a computer. Photo and video work is especially valuable in habitats that are difficult to access because of depth or currents. Images can be collected by divers in less time than would be required to count quadrats or transects, or can be collected remotely by towing a camera behind a ship or on a submersible.

There are a few invertebrate species capable of long-distance movement, for example spiny lobsters (Davis and Dodrill 1989). Lobsters are also nocturnal, making visual surveys unproductive. For invertebrates that are mobile and nocturnal, trapping can serve as an acceptable substitute to direct counting. With trapping, one loses a direct measure of density since the animals trapped represent only a portion of the population over an unknown area. Nevertheless, trapping may represent a reasonable alternative in situations where visual surveys are of limited value.

Monitoring Fish Abundance

There are a number of highly effective methods for counting fish that require disturbing them and in some cases their habitat, such as through the use of the fish poison rotenone or bottom trawling. Counting fish underwater is a valuable way to gather information on the patterns and changes of fish populations with little disruption. Underwater fish counts are known to produce underestimates of nocturnally active fish, fish that reside in crevices, and those that flee approaching divers (Brock 1982). Visual fish counts for diurnally active fish have compared well to numbers achieved using complete, destructive sampling methods (Brock 1982).

Area-Based Fish Counts. Belt transects are the oldest and most frequently used method of visually surveying fishes and invertebrates (Brock 1954). Divers swim along a transect, recording species abundance and size in a three-dimensional corridor (Bortone and Kimmel 1991). As with surveys of plants, invertebrates, and habitats, these surveys can be conducted along permanently marked or randomly selected transects. The length and width of a belt transect may vary according to the species targeted for a census but should use the same dimensions for all transects sampled. Most standard transects are 25 to 50 meters long and 3 to 5 meters wide. A narrow transect (1–2 m) may be good for small, cryptic species or newly settled fishes. Longer (100 m) and wider (5–10 m) transects may be useful for examining rare or highly mobile resource species. Any transect involves counting fish within a well-defined area and therefore provides an estimate of species density.

In the stationary point count method, a diver remains at a randomly selected fixed point and counts species within a prescribed area or volume (Bohnsack and Bannerot 1986; Bortone and Kimmel 1991). All fish species observed are listed within a 7.5 m radius cylinder for five minutes. Numbers and sizes (in separate size classes) are added following the five-minute listing period.

In interval counts, also referred to as timed swims, a diver swims in a haphazard pattern along a reef tract for a prescribed period of time, typically fifty minutes (Jones and Thompson 1978; Kimmel 1985). The time period is broken up into intervals (normally ten minutes) during which species are recorded as present or absent. Rank abundance scores are based on the number of time intervals in which the species appears.

Mark–recapture techniques can also be used to assess abundance. In this technique, a known number of marked individuals are released into a population. The population is later surveyed, and its size inferred from the proportion of marked individuals. The total population size is approximated by taking the number of marked fish and dividing it by the proportion of marked fish in the population. This technique is more time consuming than visual counting but may produce more accurate results (Davis and Anderson 1989), although inaccuracies can occur if fish move outside of the counting area or if they have discreet territories.

A comparison of sampling methods (belt, random point, and interval counts) showed that belt transects and point counts were preferable to interval counts because these methods recorded the number of species and individuals as values relative to area (Bortone et al. 1989). Because interval counts rank abundances based on frequency of encounter and disregard variations in spatial distribution, they overemphasize the importance of widespread but locally sparse fishes, while underrepresenting patchy but locally abundant species (DeMartini and Roberts 1982). Belt transects and point counts each have their inherent biases but both methods yield abundance estimates that are sufficiently robust to examine questions related to marine protected area (MPA) design and effectiveness. The applicability and limitations of various techniques for estimating reef fish abundance have been reviewed by a number of authors (e.g., Bortone and Kimmel 1991; Brock 1982). See Table 7.1 for a summary comparison.

Table 7.1 Visual Survey Methods

Method	Description	Advantages	Disadvantages	Use
Belt transects	Fish counted along transect line. Transect widths normally 1–5 m Transect lengths normally 25–100 m	Quantitative, well-defined transect boundaries, easily learned, most used method so large number of studies for comparison, can derive density estimates that are comparable among transects of different dimensions	Larger transects can span multiple microhabitats leading to inaccurate variance estimates, following behavior of some fishes causes overestimates of these species, poor at assessing cryptic species, changes in swimming speed affect estimates.	General method can sample entire diurnal noncryptic fish assemblage, good for patchily distributed species, interested in assessing large area
Variable distance transects	Variation of belt transect method. The distance and sometimes angle between the fish and the transect line is estimated	Quantitative, high precision density estimates information on behavior and vagility	Difficult to learn, high observer variability, data analysis more difficult and difficult to compare with other methods, normally restricted species list	Used for wary species, highly vagile species, and those that range widely
Point counts	Stationary diver counts within a fixed cylinder for a fixed period of time Standard method Bohnsack and Bannerot used 7.5 m radius with a 5 min count	Quantitative, ease of deployment, fast so a large number of replicates possible during a single dive, fixed time so time/space relationship unambiguous, somewhat better at detecting cryptic species particularly closer to observer, stationary observers less likely to cause distortion of abundance estimates	Small area surveyed, probability of detection decreases with distance from observer, more difficult to compare with belt transects or point counts that use different times and dimensions	Can sample entire diurnal noncryptic fish assemblage

server, stationary observers less likely to cause distortion of abundance estimates

Table 7.1 Visual Survey Methods (continued)

Method	Description	Advantages	Disadvantages	Use
Instantaneous point count	Variation of previous method but instantaneous counts made at random locations	Fast, simple, large sample size	Limited number of species can be assessed	Used for highly mobile, large species
Timed swims	Occurrence of a species is noted during a set time period, normally 5–10 min time intervals	Cover large area, high number of species detected, free moving diver can sample that are difficult to access using other survey methods, sample in currents	Qualitative, a dive usually constitutes a single sample	Interest in species richness, relative abundance estimates over large areas

Tow Boards. Tow boards allow trained divers to census organisms and classify habitats over extensive reef areas quickly. The manta tow technique is used to provide a general description of large areas of reef and to gauge broad changes in abundance and distribution of organisms on coral reefs. The technique involves towing a snorkel diver at a constant speed behind a boat (English et al. 1997). The advantage of manta tows over other survey techniques is that they enable large areas of reefs to be surveyed quickly and with minimal equipment. Studies have shown the manta tow technique to be a relatively accurate and cost effective way of determining the abundance of noncryptic crown-of-thorns starfish and corals over large areas (Fernandes 1990; Fernandes et al. 1990; Moran and De'ath 1992). This technique has, in fact, been used to assess the distribution and abundance of crown-of-thorns starfish and corals on the Great Barrier Reef for over fifteen years (Sweatman et al. 2001). Tow boards can also be used to assess the presence and abundance of large mobile species such as sharks and jacks that are often too sparse to sample with conventional diver surveys.

Deep Ocean Assessments. Scientists have recently begun using video cameras in underwater housings to monitor fish and evaluate habitat at depths inaccessible by scuba (e.g., Auster et al. 1991; Parrish et al. 1997; Uzmann et al. 1977). Video cameras can either touch the bottom or be suspended from the surface and can be used singly, arranged in arrays, or mounted on rotating platforms (similar to stationary diver census). Video cameras can conveniently take pictures at preselected intervals, allowing an extended census time, and mounted lasers can help estimate transect width as well as fish length. They can also be used alone or with bait to attract and concentrate individuals of species of interest. Video cameras towed above the bottom from surface vessels can be used to conduct belt transects. In all video censuses, low image resolution can be a problem for identifying organisms to the species or sometimes even the genus level.

Other mechanisms for surveying deep ocean environments include the use of remotely operated vehicles (ROVs) or manned submersibles. These techniques allow direct counts of organisms and habitat assessments at depths much greater than divers can reach, for longer, and in strong currents. Scientists in submersibles, using either direct observations or video, often have a much greater field of view than an ROV and are therefore better able to accurately survey the sample area. New single operator submersibles like the DeepWorker 2000, which can dive to a depth of 600 meters and allow dives of twelve hours or more, will expand current efforts to survey deeper habitats (e.g., Coleman and Williams 2002).

The development of tethered sonar mapping and imaging vehicles and autonomous underwater vehicles (AUVs) has greatly expanded our ability to observe, map, and sample the deep ocean and seafloor beyond the capabilities of ROVs and submersibles and will continue to provide new and exciting information.

Technology has also made it possible for divers to reach deep ocean environments. Divers can now breathe controlled mixtures of gases that give them greater working time at greater depths. Additionally, divers can utilize rebreathing technology, which vastly increases the supply of air they can carry with them (Pyle 2000).

Acoustic Surveys. Fish can be detected underwater using an acoustic signal because various body parts (e.g., swim bladder and muscle) have densities different from the surrounding water (Brandt 1996). A transducer mounted on a vessel sends out an acoustic signal and receives the returning echoes created when the sound reflects off the fish back to the surface (Gunderson 1993). This method should really only be used for single-species aggregations of similar size fish (Hedgepeth and Condiotty 1995), which greatly limits its utility.

Experimental Fishing. When other techniques are impractical, experimental fishing can provide useful information on fish abundance. These techniques are by nature destructive and thus at odds with the mandate of a marine reserve. They also only produce a measure of relative abundance because of differences in catchability and the lack of a defined sampling area. To the extent possible, it is better to rely on nondestructive techniques. But there are a number of environments in which visual fish counts are impractical because of great depth, poor visibility, or wave energy. Because of its ability to sample large tracts fairly quickly, experimental fishing will be especially valuable for sampling nocturnally or widely dispersed animals and for sampling large regions in a short time frame.

Many types of fishing gear can be used to sample fish, including hook-and-line gear, nets, traps, and trawls. Traps and trawls serve as a good example of the advantages and disadvantages of these techniques. Traps are mesh cages with funnels that are designed to keep individuals from getting out once they have entered. They are used around the world to capture fish and invertebrates. Trap design, volume, and mesh size can greatly influence the catch (e.g., Munro et al. 1971) and catch rates and effective area fished vary greatly depending on habitat type and reef complexity (Friedlander et al. 2002; Wolff et al. 1999).

Trawls drag a net attached to a frame either in the water column or along the bottom. Because of their efficiency, they can be a valuable tool in assessing finfish, shellfish, and other invertebrates, particularly those species exploited by similar commercial gear. They sample a discrete area or volume over a specific time and provide quantitative indices of population abundance (Hayes et al. 1996). There are a variety of trawls and dredges (bottom trawls that actually dig into the sediment) that can be used in assessing populations of marine organisms with bottom composition and target species often determining the type of gear used. Biomass and population size are the main parameters of interest during trawl or dredge surveys (Gunderson 1993). Standardized dredge surveys for Atlantic sea scallops conducted by the National Marine Fisheries Service (NMFS) off Georges Banks closely tracked landings data and have shown the effectiveness of large-scale closed areas as a fishery management tool (Murawski et al. 2000). Traps and trawls can be used as a fisheries stock assessment device but should be considered with caution due to the variations in fishing efficiency among species and gear configurations (Recksiek et al. 1991). Similar concerns surround every other form of experimental fishing.

Monitoring Eggs and Larvae

Surveys of eggs and larvae can provide a better understanding of fluctuations in the production and survival of offspring, the biotic and abiotic processes that determine recruitment, the size of the adult population, and potential sources or sinks of offspring (Gunderson 1993). Spawning and nursery areas can be identified by looking for areas with high concentrations of early eggs or larvae (Heath and Walker 1987). Spatial and temporal differences in spawning characteristics of exploited populations can be inferred from larval fish studies (Graham et al. 1984). Sample designs should take into consideration any known locations and timing of spawning and settlement.

Marine organisms have a diverse array of reproductive modes, including differential behavior and growth of larvae, spawning behavior, and habitat preferences, and these attributes make studying larvae a challenge. Studying larvae is also hampered by the fact that their concentrations are usually very low for any given species. To sample a sparse group of larvae that may vary tremendously in size, behavior, and location requires a wide variety of egg- and larvae-collecting devices.

The low densities of reef fish larvae make the study of ocean dynamics of

Table 7.2 Collection Techniques for Eggs and Larvae

Active

Plankton nets—Plankton nets are the most common gear type used and are typically towed at speeds of less than 2 m/s for periods of 30 s to an hour.

Benthic plankton samplers—Benthic plankton sleds are used to sample eggs and larvae on or just above the bottom.

Pelagic trawls—Low to moderate speed (0.5–3 m/s) midwater trawls can sample a large volume of water and are normally used to sample large larvae and small juveniles in pelagic areas. However, pelagic Tucker trawls were shown to be ineffective in estimating the density and size composition of pelagic reef fish larvae, particularly small individuals (Choat et al. 1993).

Neuston nets—These nets sample the water surface by towing the top edge of the net above the water and are ideal for surveying organisms that reside in this habitat.

High-speed samplers—Plankton nets can be mounted inside rigid cylinders and towed at speeds of up to 9 m/s. These devices can sample a large volume of water and reduce net avoidance by mobile larvae but can clog easily and damage larvae and eggs.

Pumps—Most systems involve pumping a target volume of water from an intake hose to a filter or net. Pumps provide discrete quantitative sampling that can be operated from a stationary or moving platform. Disadvantages of pumps include larvae avoidance, damage to samples, and limited volume of water sampled.

Passive

Drift samplers—Stationary sets of standard plankton nets. Useful in shallow or confined bodies of water.

Emergence traps—Demersal eggs, from fish such as salmonids, can be sampled after emergence using fixed nets with collecting bags.

Activity traps—These traps, developed for free swimming larvae and juveniles, are often used in shallow or confined bodies of water.

Light traps—Nighttime traps with artificial light sources are effective in collecting larvae that are positively phototactic (Choat et al. 1993)

the pelagic stage problematic, with different gear types selectively capturing different taxa and sizes within a taxon (Choat et al. 1993). Table 7.2 briefly describes some of the methods used to collect eggs and larvae.

Monitoring People

The monitoring of the human dimension of marine reserves is an important tool for understanding the full impact of reserves on both people and ecosystems. There are a number of different attributes that are worth consideration when designing a monitoring program.

Recreational/Subsistence Creel Surveys. The recreational fishing community is very large, particularly in developed countries. These anglers can have a significant impact on fish stocks and the economy of coastal communities. On coral reefs, the recreational and subsistence catch is often equal to or greater than the catch by commercial fishers, and these fishers also catch a wider variety of species using a broader range of fishing gear than do their commercial counterparts (Friedlander and Parrish 1997). Recreational fishing, or creel, surveys are one of the few opportunities for management agency personnel to interact with the fishing community on a personal basis (Malvestuto 1996). This allows for the collection of fisheries data as well as the occasion to gain support and educate the public on management actions such as marine reserves.

The two basic steps in developing a recreational fishery survey are (1) selecting the statistical survey design that provides the best quantitative estimates of the fishery and (2) finding the most effective method of carrying out this design with the human and financial resources available (Malvestuto 1983). Stratified random creel surveys of fishing effort provided a useful sample of almost all types of fishing activity in a small bay in Hawaii (Friedlander and Parrish 1997). Within each sampling period, census of nearly all fishing effort and more than 70 percent of all catches was possible because of favorable local geography and the small size of the bay and the fisheries associated with it. A thorough treatment of recreational creel surveys can be found in Malvestuto (1996), Guthrie et al. (1991), and Pollock et al. (1994).

Landings and Logbooks. Catches are another important measure of the human dimension of marine reserves. Fishing men and women are often most concerned about how marine reserves will affect their ability to catch fish. Commercial fishers often keep log books of what they caught by time and location, and these can be an invaluable resource. Catch data can also be collected by monitoring the amount of fish that are landed or brought back to port.

Recreational fishers also keep records in the form of record-size fish caught in different locations using various tests of fishing line. An examination of world record catch data can identify an important recreational benefit from large adult fish moving out of reserves and into fishing areas (Roberts et al. 2001).

Interviews. Whether or not scientific tools can prove that reserves enhance overall fish catches, fishers who experience reserves are bound to develop their own opinion. Interviews of this sector of society can provide very useful information about whether reserves are working from a socioeconomic perspective. Interview questions generally focus on attitudes about fish catches and efforts expended. In combination, these questions can indicate how livelihoods have changed both in terms of product gained and the time required to do so. These techniques have been used successfully even in closed, small, island communities (Roberts et al. 2001; Russ and Alcala 1996). Of course, it is crucial to supplement this information with independent scientific sampling, in part because all of us are prone to distorting our memories over time and because nonscientists rarely sample in as random or extensive a manner as scientists doing a survey.

MOVEMENT

The fluidity of marine systems via adult movement and reproductive dispersal is a major factor in marine reserve design (see chapter 5). The importance of this phenomenon to the performance and design of marine reserves warrants a fuller discussion of what we presently do and do not know on the subject, and what questions are useful to address in the future.

Adult Movement

Many fished species are incapable of adult movement. These sessile invertebrates and plants cannot cross reserve boundaries, and those in reserves will only be vulnerable to fishing in the form of poaching. On the opposite end of the spectrum, some fish are built for swimming long distances. Bluefin tuna (*Thunnus thynnus*) are huge swimming machines that cover distances measured in thousands of kilometers on a regular basis (NRC 1994) creating a management challenge requiring international cooperation.

The rare studies of species that fall in between have sometimes yielded surprising results. A Hawaiian study of the blue trevally (*Caranx melampygus*)—a fish capable of swimming tens of kilometers—used multiple methods to track movements (Holland et al. 1996). These data indicated that nearly 90 percent of fish moved fewer than 2 kilometers, although a small proportion (less than 5 percent) of fish dispersed tens of kilometers away. Similar results have been found for the galjoen (pronounced galleon, *Coracinus capensis*) in South Africa (Attwood and Bennett 1994). Over 80 percent of tagged and recaptured galjoen were caught within 5 kilometers of their release site, while others had moved as far as 1450 kilometers away. Other fish move even less. A Hawaiian study of the white goatfish (*Mulloides flavolineatus*) showed that most fish moved no more than a few hundred meters (Holland et al. 1993). Seven percent of fish were "recaptured" at a commercial fish market. Since the study area was closed to fishing, these may have migrated several kilometers out of the reserve. However, it is also possible they were poached from within the reserve.

Movements often follow patterns. A number of fish show regular movement patterns on a daily basis between resting and feeding areas. Examples include grunts (Ogden and Ehrlich 1977) and goatfish (Holland et al. 1993). Fish also move as they develop, utilizing different habitats as they grow larger (Roberts 1996). Some species also move seasonally, including moving potentially hundreds of kilometers to aggregate at specific places to reproduce (Harding et al. 1978; Johannes et al. 1999).

However, the movement of relatively few species has been studied. As we learn more about how far fish move, particularly as movements relate to habitats and seasons, we will gain valuable tools for creating better marine reserves. Until then, reserves are likely to benefit homebodies more than vagrants (Bohnsack 1996).

Reproductive Dispersal

Eggs and larvae can persist for as short as minutes or as long as months, and travel distances ranging from decimeters to thousands of kilometers (Shanks et al. 2003). The duration of the development phase may play an important role in potential dispersal distance, as may the strength and direction of prevailing currents. Eggs and larvae are generally incapable of swimming large distances themselves, at least early on in their development, so currents are the means by which they move from place to place. However, larvae may often disperse shorter distances than surface currents would suggest. Larval behavior can reduce dispersal distance by utilizing current changes that occur with depth, especially turbulence and drag that occur near the bottom (e.g., Breitburg et al. 1995). Nearshore turbulence and drag also can serve to retain larvae (Wolanski and Sarsenski 1997). And, even those larvae that do disperse face slim odds between diffusion, which may take them far from a desired habitat, and the poor survival that results (Cowen et al. 2000). These factors are probably responsible for the fact that studies of animal populations often find significant amounts of retention of eggs and larvae near the site where they were spawned (e.g., Brogan 1994; Jones et al. 1999; Swearer et al. 1999). However, local dispersal is not always the rule (e.g., the intertidal acorn barnacle, Bertness and Gaines 1993) and studies have identified what are apparently consistent patterns of larval dispersal and retention, with some sites producing great numbers of offspring and others receiving numerous new settlers (Lipcius et al. 1997).

Collectively, the body of work on larval dispersal suggests that many coastal marine populations retain some larvae locally while allowing others to disperse long distances. This strategy parallels dispersal and dormancy strategies exhibited by terrestrial and freshwater animals and plants, and in those contexts has been shown to have profoundly positive ecological and evolutionary benefits (Cohen and Levin 1987).

There are still large gaps in our knowledge about the dispersal of ocean offspring, in particular a clear understanding of what biological and physical factors influence the level of local retention of eggs and larvae (Sponaugle et al. 2002). The preceding conclusions are compatible with the data gathered in the few studies to really examine reproductive dispersal, but many more studies will be invaluable toward furthering our understanding of reproductive dispersal. Fortunately, a number of exciting new techniques now enable us to study this topic more effectively than ever before.

Key Questions

Marine reserves themselves provide a chance to study movement patterns. Study of the distribution of fish across a reserve border can give an indication of how much adults move (e.g., Kramer and Chapman 1999; Rakitin and Kramer 1996). Moreover, there is much to learn by tagging individuals within reserves and observing the degree to which they move to outside areas (Attwood and Bennett 1994; Johnson et al. 1999). In addition to learning about general patterns, reserves provide an opportunity to look at whether and how fish move differently when they are densely versus sparsely populated (Sánchez Lizaso et al. 2000).

Reserves can also be used to study larval dispersal. Tegner (1992) transplanted adult green abalone (*Haliotis fulgens*) into an area where the species had been previously extirpated but were now protected. She then studied patterns of recruitment at varying distances from the transplant site, much in the same way one could look for enhanced recruitment at varying distances away from a marine reserve.

Studies of fluidity need not rely on reserves. The same techniques to look at movement from reserves can be used more generally to understand how fish and their offspring disperse. There are a number of key questions that remain to be answered about these phenomena. In addition to filling in many gaps in our understanding of basic movement tendencies, we would benefit from having substantially more information about how movement patterns change throughout development and respond to the local density of fish in an area. We would also benefit from having a clearer picture of the degree to which offspring are retained locally versus dispersed broadly and whether current patterns and behavior result in patterns of settlement. Since these phenomena will affect how many fish and their offspring leave a reserve, it will be difficult to predict the response of populations within and around marine reserves with any real precision until they are better understood.

Tools and Techniques

Information on the movement of adult and larval marine organisms is crucial to evaluating the effectiveness of existing MPAs and determining the optimal location for establishing new ones. Local fisheries yields can be improved through export of adult biomass from protected areas to adjacent areas (DeMartini 1993; Johnson et al. 1999; Polacheck 1990; Russ and Alcala 1996), although those improvements are very small compared to the catch enhancements possible if adults stay within reserves but provide offspring to fishing areas (Sladek Nowlis and Roberts 1999). As a result, it is important to understand the dispersal patterns of both adults and their offspring.

Traditional Knowledge

Fishermen are vastly more numerous than biologists and have lifetimes of experience pursuing and capturing fish and other marine resources (Johannes 1997). This large body of knowledge is often passed on from generation to generation and can be extremely valuable in understanding the dynamics of marine ecosystems and changes that have occurred over time. Traditional knowledge, particularly the timing and location of fish movement patterns, is highly relevant to the management of these resources (Friedlander et al. 2002b; Johannes and Yeeting 2001).

An interview process can be helpful in acquiring this information for incorporation into management decisions. Maps of habitat distributions and important landmarks can engage groups of fishers and others who have spent substantial time on the water, and help them to contribute their knowledge to the process. The resultant maps can also be invaluable in guiding management decisions (Friedlander et al. 2003a; Fig. 7.2), but are only one piece of a comprehensive assessment that should also include data collection in the field.

Long-Term Tagging and Recapturing

Marking fish has already been discussed in the context of estimating abundance. The rate at which fish disperse from marine reserves can be determined

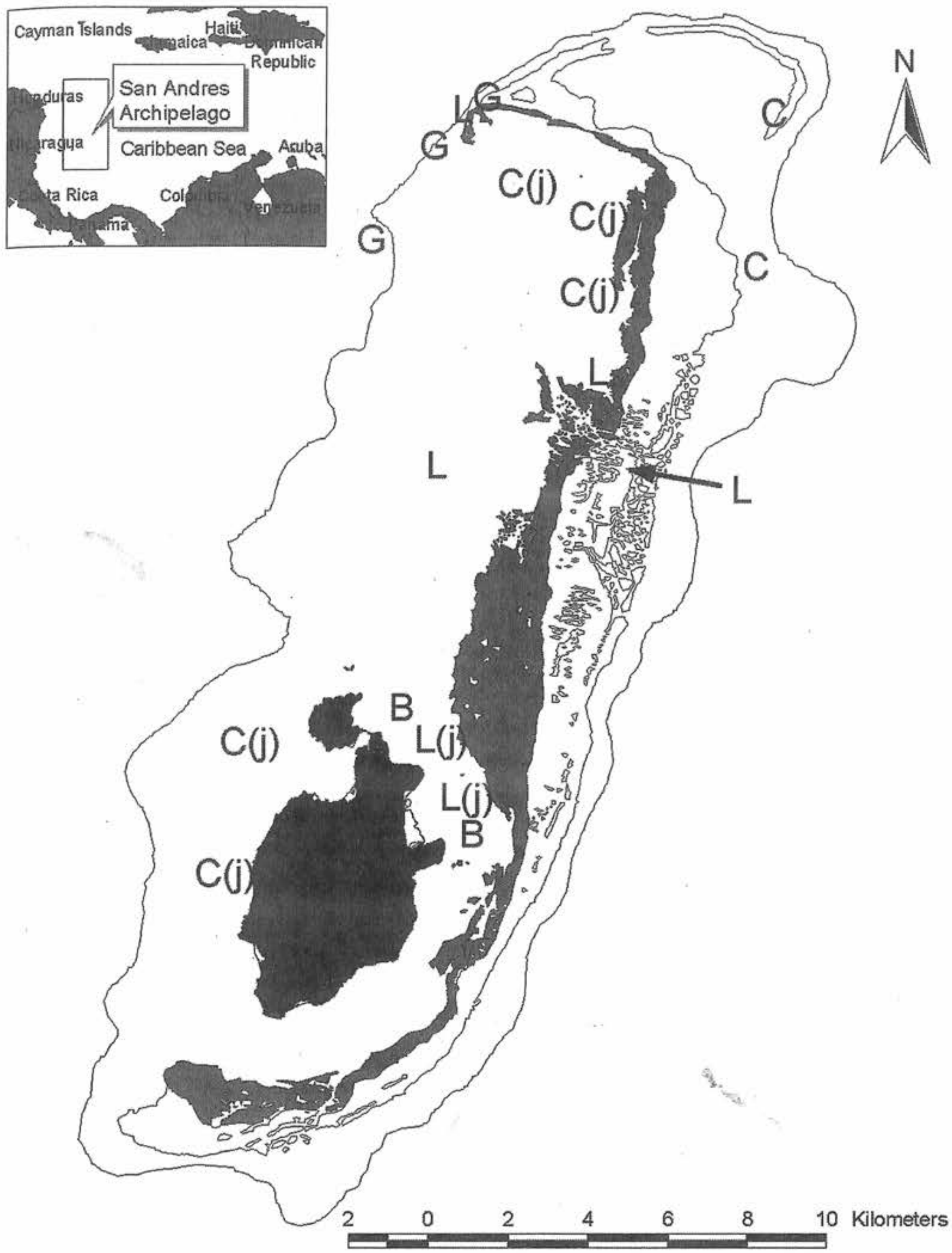

FIG. 7.2 Traditional Knowledge around Old Providence Island, Seaflower Biosphere Reserve, Colombia. Important ecological locations were identified by local fishermen on Old Providence Island, San Andrés Archipelago, Colombia. These data were collected through interviews as part of a process to zone portions of the Seaflower Biosphere Reserve. They provided useful biological information to the scientists making recommendations on zoning. Symbols: B—baitfish, C—conch, C(j)—conch juvenile, G—grouper spawning site, L—lobster, L(j)—lobster juveniles (see Friedlander et al. 2003a for more detail).

Table 7.3 Tagging Methods

Tag type	Description	Advantages	Disadvantages
External tags			
Dart and t-bar tags	External, plastic, or metal, inserted just below dorsal fin	Quick and easy to apply. Can contain great deal of information	Tag loss Abrasions
Internal anchor tags	Similar to anchor tags but inserted into body cavity	High retention rate Effective on large, wide-bodied fishes	Abrasions Difficult tagging procedure
Branding	Hot and cold branding produces scar on surface of fish	Rapid, low mortality, growth not inhibited	Short term Dangerous
Pigment marks	Dyes, stains, inks, paints, plastic chips	Simple, inexpensive	Limited number of colors Diffusion over time
Internal tags			
Visible implant tags	Elastomer tags injected with small-gauge needle	Read in live fish, inexpensive, little experience needed	
Visible implant alphanumeric tags		High retention in suitable tissue or species; low capital costs; tags detected visually and readable in live specimens; minimal impact on survival, growth, and behavior; visibility is enhanced using blue LED light; made of flexible, biocompatible material that increases retention over the original VIalpha	Retention varies among species, not usable with species lacking suitable tissue, tag readability can become occluded with time
Coded wire tags	Small (1.1 mm × 0.25 mm) magnetized stainless steel wire	Very small animals, minimal physiological impact, high retention rates, enormous code capacity, inexpensive individual tags, can scan large sample	High capital expense for tagging equipment, tags must be excised from dead fish, tags not externally visible
Passive integrated transponder tags (PIT)	Small computer chip (12 mm × 2.1 mm) that is activated by external reading device	Individual codes, live fish, no performance impact on fish	High cost, skill required for both tagging and recovering information

Sources: Guy et al. 1996 and Northwest Marine Technology, Inc. (www.Nmt.inc.com).

Passive integrated transponder tags (PIT)	Small computer chip (12 mm × 2.1 mm) that is activated by external reading device	Individual codes, live fish, no performance impact on fish	High cost, skill required for both tagging and recovering information

Sources: Guy et al. 1996 and Northwest Marine Technology, Inc. (www.Nmt.inc.com).

using "tag and release" methodology, with fish being recaptured either through fishing activity or underwater visual surveys. Resighting of marked fish underwater can also be used as a method to obtain information on the movement patterns of these marked individuals. This is particularity true when the mark possesses unique features (e.g., color, location on the fish's body, unique individual tag code) that can identify individual fish or provide information on release locations (Guy et al. 1996).

A wide range of tags are available, each of which has its own set of advantages and disadvantages (Table 7.3).

Sonic Monitoring

Acoustic telemetry is an effective way to track the daily movement patterns of individual fish. In this technique, one or more fish are fitted with a cylinder that gives off a unique frequency sound and released back into the study area (Fig. 7.3). Multiple fish can be monitored simultaneously if their transmitters use different frequencies. Scientists can track fish from boats using a hydrophone and global positioning system, or remotely using one or more stationery underwater hydrophones. Endemic Hawaiian goatfish (*Parupeneus porphyreus*) were continually monitored using an omnidirectional hydrophone for up to one month (Meyer et al. 2000). Information gained from tracking fishes can help to explain questions of immigration/emigration, residence time, habitat preference, site fidelity, and many other important life history traits, all of which have important implications for the design of effective marine reserves. Electronic tagging and tracking technologies have progressed rapidly in recent years and the tools and techniques used will vary depending upon the application and environment. Results from a recent symposium on electronic tagging and tracking of marine organisms document the current state of the art of this rapidly expanding field (Sibert and Nielsen 2001), which includes tags that record data on depth and position and then transmit this data via satellite, in some cases after the tag has deliberately popped off and floated to the surface.

Tracking and movement data can be analyzed in a number of ways, including maximum area covered (using minimum convex polygon analysis) (e.g., Klimley and Nelson 1984) and frequency of visits (using grid-square analysis). "Animal Movement" is an ArcView extension (see http://www.esri.com/) that is designed to implement a wide variety of animal movement functions in an integrated geographic information system (GIS) environment.

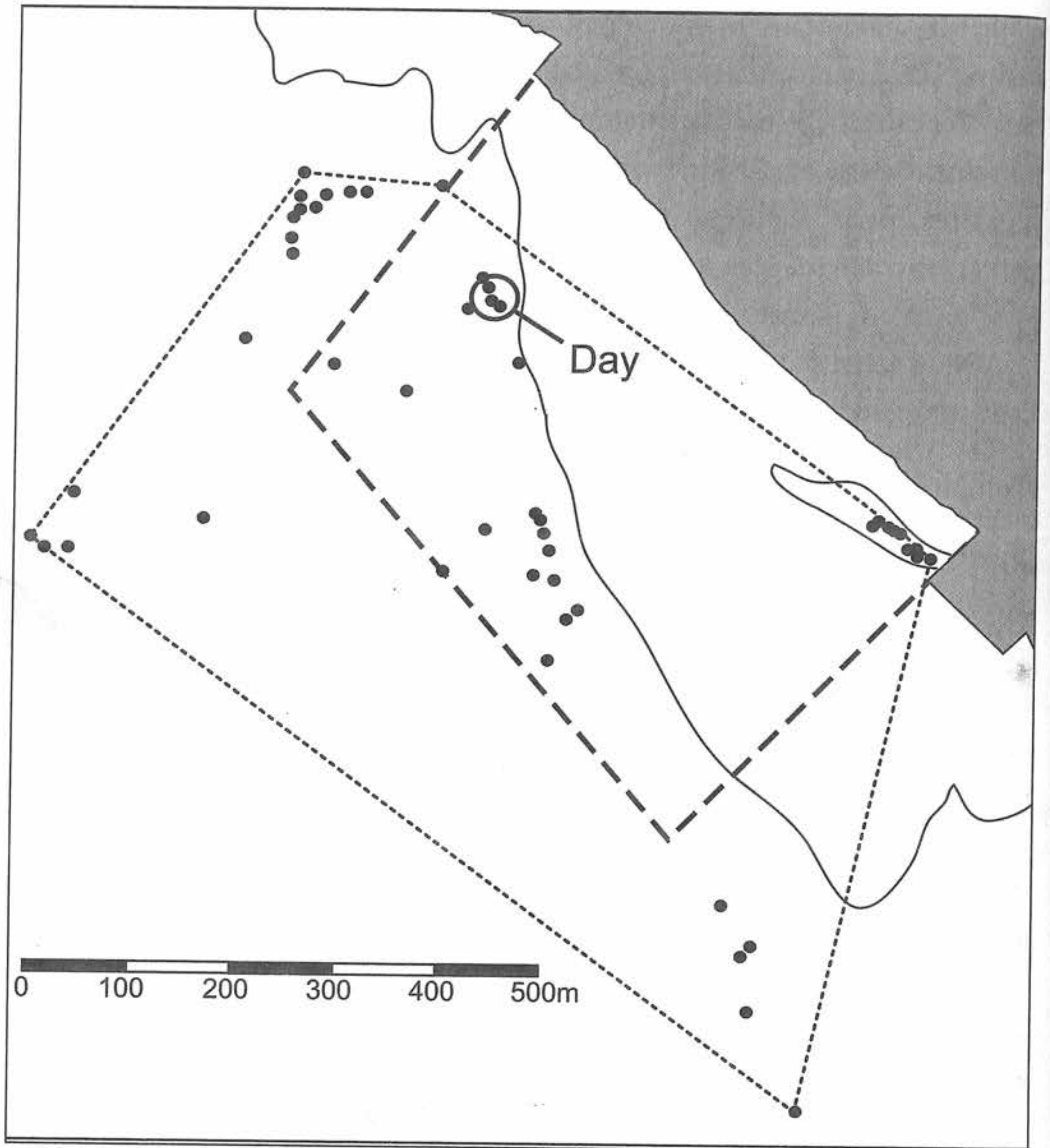

FIG. 7.3 Sonic Tag Track. Minimum Convex Polygon (MCP) home range of a 32.3 cm (Fork Length) yellowstripe goatfish, *Mulloidichthys flavolineatus,* tracked continuously for 46 h in the Waikiki marine reserve, Hawaii. Shaded area = land, solid line = 1 m depth contour, dashed bold line = reserve boundary, dotted line = MCP home range boundary, solid points = position fixes for the *M. flavolineatus*. Source: Adapted from Meyer 2003.

Inferring Larval Dispersal

By studying current patterns and larval behavior, we can get a sense of how larvae might disperse over time. Drifters are expendable systems launched from ships or aircraft into specific ocean areas. As they drift in response to ocean currents and winds, they make measurements of the atmospheric pressure, air and sea temperature, wind speed, and wind direction. Data from drifting buoys are relayed to ground stations via National Oceanic and Atmospheric Administration (NOAA) polar orbiting environmental satellites (POES). Because the great majority of tropical reef fishes have planktonic larvae, drifters are helpful in determining the settlement patterns of juvenile fish. Current patterns of the types drifters can provide have been proposed as a maximum limit on the dispersal capability of fishes from various Caribbean islands (Roberts 1997).

As we learn more about actual dispersal patterns, though, there is an increased focus on the influences of turbulent coastal current patterns (e.g., Wolanski and Sarsenski 1997) and larval behavior (e.g., Breitburg et al. 1995).

Surveying Settlement of Larvae

Monitoring of juvenile fishes will help to assess the future health and population dynamics of the assemblage. Larval fishes, which settle to local reefs, spend weeks in the plankton and are transported large distances from adult spawning sites. Therefore, local abundance of adults may not mean numerous juveniles on a specific reef. If changes in adult fish species richness or abundances are detected, settlement levels from preceding years should be examined to determine if the changes are most likely a result of settlement variation or from some other cause, like fishing level. Since most reef fishes have high site fidelity during their juvenile and adult stages, local reef fish populations must be replenished from the planktonic pool of larvae. Local settlement is highly variable over space and time and profoundly influences the population dynamics of the adult assemblage structure. Areas of locally retained larvae have obvious implications for MPA site designations. Visual transects can be used to survey juvenile fish that have recently settled out of the plankton. Typically a 50- by 2-meter strip is used (Fowler et al. 1992).

Inferring Larval Dispersal from Fish Ear Bones

Fish otoliths (crystalline structures in the inner ear) deposit new material daily and incorporate trace elements from the surrounding sea water into their structure (Swearer et al. 1999). Because productivity and trace-element concentrations differ between coastal and oceanic waters, otoliths can be used to reconstruct the dispersal history of larvae. Higher concentrations of trace-elements in otoliths should indicate faster growth rates because coastal waters are generally more productive. Trace-element concentrations in otoliths can be measured under laboratory conditions using mass spectrometers, which allows for reconstruction of past environmental conditions experienced by individual fish. The technique is proving invaluable for examining population connectivity, spawning behavior, and stock associations in a number of fish species (Thorrold et al. 1998, 2001).

Inferring Dispersal and Movement by Tracking Introduced Species

Though not a natural phenomenon, there have been and continue to be introductions of nonnative species into new ecosystems through ballast water of ships, the aquarium trade, and intentional releases to provide new recreational fishing opportunities. Some of these introduced species establish themselves and even flourish in their new environment. Tracking their spread offers the opportunity to see firsthand how far and quickly a population disperses. For example, in the 1950s and 1960s, eleven species of snapper and grouper were intentionally introduced in the waters surrounding the main Hawaiian Islands. Four of these species became established (three snappers and one grouper, Randall 1987). One snapper—*Lutjanus kasmira*—adapted especially well to its new location, and its spread along the greater Hawaiian archipelago is reasonably well documented (Fig. 7.4). Introduced in 1958 (Randall 1987), it had spread throughout the archipelago by the early 1990s (Randall et al. 1993), averaging 33 to 130 km per year. This rate of spread supports the idea that seed areas, such as marine reserves, can sustain fisheries outside their borders. However, it should be noted that such rates do not necessarily contradict the idea that much reproductive output is retained in a relatively small local area.

HABITAT CONNECTIVITY

Habitats may be connected through the flow of nutrients, through animal movements, or both. Understanding these connections is a crucial step toward designing better marine reserves. To the extent that marine reserves can encompass complementary habitat types in a connected manner, they will be more effective at retaining productive populations within their borders. Advancing our understanding of habitat connectivity will require habitat mapping exercises, habitat categorizations of ecological relevance, and direct and indirect studies of fish themselves (Christensen et al. 2003).

In a few cases, we understand the linkages among habitat types. Shallow, nearshore, tropical ocean environments, for example, are characterized by the connectivity among coral reefs, mangrove lagoons, and sea grass beds (Ogden 1988). These connections can result in different fish assemblages on a coral reef depending on whether there are mangroves and sea grass beds nearby (Appel-

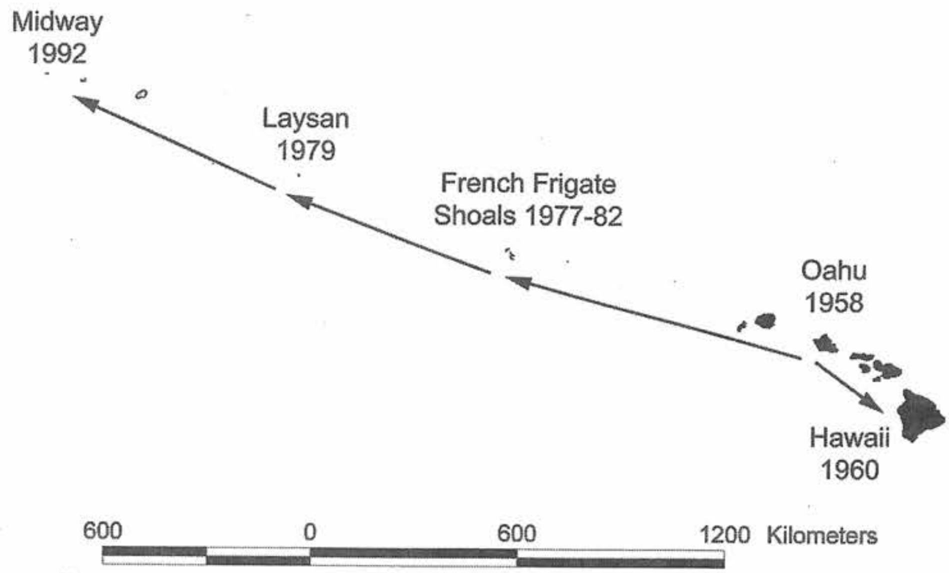

FIG. 7.4 Spread of Ta'ape, *Lutjanus kasmira,* throughout the Hawaiian Archipelago. Introduced in the 1950s, this species of tropical snapper spread through the main Hawaiian Islands and then the Northwestern Hawaiian Islands. Tracking its appearances along this island chain gives us the opportunity to measure its rate of spread and infer the degree to which the population disperses.

doorn et al. 2003; Christensen et al. 2003). Understanding these connections plays two important roles. First, it is valuable to ensure that any marine reserve or reserve network in a shallow nearshore tropical ocean environment contains reef, mangrove, and sea grass habitats because many fish species move among these habitat types as they grow, feed, and seek shelter and mates. Second, in cases where the management area includes coral reefs that are near these other coastal habitats as well as reefs that are some distance away, it may be useful to distinguish these types of reefs and ensure that both are represented in a reserve or reserve network because these reef types will have different living communities associated with them, all of which should receive some degree of protection (Friedlander et al. 2003a).

Key Questions

It is likely there are many important ecological linkages between habitat types that have not yet been recognized. At present we have only a primitive understanding of the movement patterns of ocean animals and the distribution and ecological functions of various habitat types. Because linkages may well exist that we do not yet recognize, it is important to ensure that marine reserves encompass a variety of habitat types. Also, it may be worthwhile to choose reserve sites with high habitat diversity since they are more likely to encompass connected types (Appeldoorn et al. 1997).

Habitat connectivity is a critical area of study for improving the design of reserves and reserve networks. Reserves will not necessarily aid in our understanding of this topic in the same way they can for other topics. Instead, these connections are most likely to reveal themselves through detailed studies of habitat-specific animal movements and spatial studies of nutrient dynamics.

In addition to understanding specific connections, there are some more general questions of particular interest. It has been proposed that even very small reserves can be effective if they contain a diversity of habitats because many fish will be able to meet their feeding, shelter, and reproductive needs without leaving. This hypothesis is still largely untested and would benefit from further study. We would also benefit from a better understanding of the influence of human impacts on habitat connectivity. Identifying the connections is one step in this understanding. The next step would be to examine how different human impacts are likely to affect these connections. A more thorough understanding of these connections will help to design management systems that conserve whole functioning natural systems. Finally, there has been great attention paid to the value of reserve networks, or a series of marine reserves that are interconnected through the dispersal of adults and larvae.

Tools and Techniques

In addition to monitoring and adult and larvae movement patterns, an understanding of habitat connectivity is critical in the design of marine reserves. If reserves are to maintain system integrity and structure, all components necessary to ensure system function must be included within the reserve design, either by networking smaller areas or by creating large, all-encompassing areas (Appeldoorn et al. 1997, 2003).

Mobile animals play a key role in connections among habitat types. In moving from one habitat to another, adult animals make direct ecological connections and can even shuttle nutrients from one habitat to the next (Parrish 1989). Movements throughout development also contribute to habitat connections. Finally, eggs and larvae are a means by which adult habitats connect back to nurseries via a waterborne stage. Thus we can learn a lot about habitat connectivity through the study of movement patterns, as already discussed.

Movement patterns can also be inferred by looking at changes in habitat usage seasonally or through development by studying the distribution of different size classes or at different times of year. For example, small grunts and snappers are consistently found in shallow habitat types, primarily sea grasses and mangroves, whereas larger individuals are most often found offshore on coral reefs. These patterns indicate movement tendencies from nearshore nursery habitats to offshore adult habitats as these fishes grow and mature (Appeldoorn et al. 2003; Christensen et al. 2003). Such indirect studies can provide a valuable broad-scale perspective when studying the way that habitats are interconnected ecologically. Such studies, when combined with habitat mapping exercises (discussion follows) can teach us a great deal about these connections.

HABITAT AND SPECIES DISTRIBUTIONS

Having discussed issues relevant to the performance attributes of marine reserves as a management tool, we will now describe some data requirements for designing specific marine reserves in practice and how best to collect these data. In particular, it is valuable to collect and compile data about the distribution of habitats and species in a management area. Marine reserve design can be greatly enhanced by an understanding of habitat and species distributions and interactions.

Habitat-oriented marine reserve design can achieve a wide range of potential goals (see chapter 5). Sometimes it is necessary, though, to study species distributions as a way of categorizing habitats in an ecologically relevant manner. For example, Friedlander and colleagues (2003a) used species distributions to confirm a system of habitat types they used to advise an ocean zoning process in Colombia. They recategorized habitats from existing habitat maps based on their understanding of coral reef ecosystems. They then used surveys of species distributions and abundance to confirm that their habitat type definitions were ecologically based.

Good habitat maps are rare, and even when they do exist the habitats may not be categorized in a manner conducive to reserve design. In many cases, we may need to rely on the simplest of physical features, such as separating sheltered bays from open coastlines, and nearshore from offshore areas (e.g., Ballantine 1997). Alternatively, it may be desirable to map habitats if resources are available to do so quickly. Where habitat maps already exist, they should guide marine reserve design (e.g., Friedlander et al. 2003a).

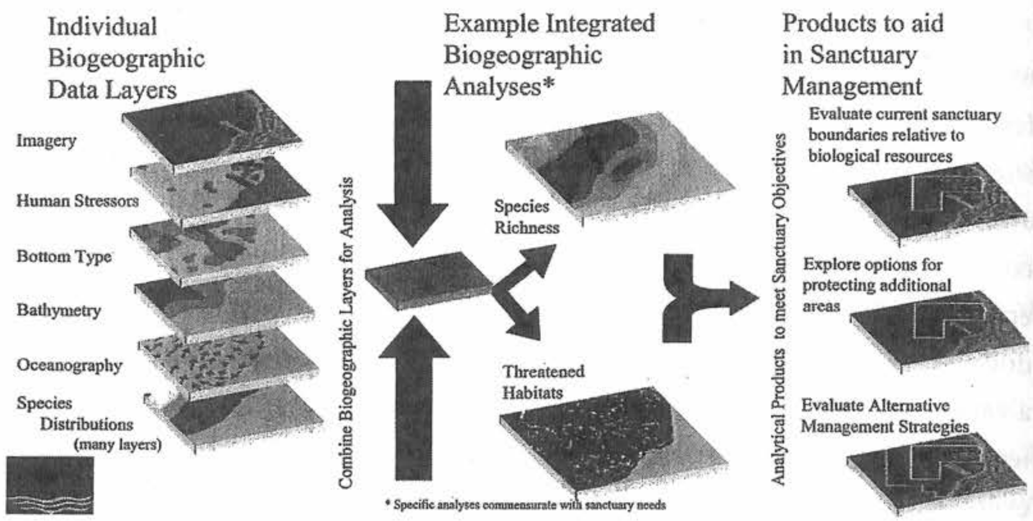

FIG. 7.5 Biogeographic Assessment for Marine Protected Area Design. A range of geographic data are collected and can be combined to gain insight into threatened habitats and other priority areas for protection. These insights can be communicated to managers through various illustrative products. Source: From Kendall and Monaco 2003 with permission.

Tools and Techniques

The quality, quantity, and distribution of habitats are some of the most important factors influencing fish and invertebrate distributions and population dynamics and thus should be considered when designing effective marine reserves.

It's important to know the exact location of habitats within a reserve because of the key role habitats play in sustaining ocean fisheries and ecosystems. Geophysical techniques, such as sideways looking sonar (side-scan) and seismic reflection profiling, which uses sound waves to distinguish among habitat types, can help to define large-scale benthic features and to map protected areas. NOAA's Biogeography Program recently produced a series of highly accurate GIS-based maps of coral reef habitats using digital georeferencing and orthorectified aerial photography (Monaco et al. 2001). These images came from photographs taken from directly above, with reference points and other measures used to remove any distortion and to link adjacent photos. The resulting habitat classifications and underlying hierarchical spatial structure were used to look at resource distribution, abundance, and habitat utilization (Fig. 7.5).

Knowing the layout of habitat types goes hand in hand with knowing the fish assemblages that use them. There is a strong link between coral reef fish diversity and physical habitat, as demonstrated by a number of authors (e.g., Luckhurst and Luckhurst 1978; Friedlander and Parrish 1998). For example, habitats with low spatial relief and limited shelter in Hawaii harbored a lower biomass of reef fishes than highly complex habitats (Friedlander and Parrish 1998). This strong link means that we must know the location, distribution, and extent of habitats necessary for successful recruitment, growth, feeding, and reproduction (Christensen et al. 2003; Friedlander and Parrish 1998). Habitats and species can be mapped using techniques already discussed in the context of monitoring, or with more sophisticated remote sensing technologies.

Remote Sensing

Different technologies allow the measurement of habitat attributes at a wide range of spatial resolutions and varying costs (Table 7.4). Habitats can be identified and mapped remotely using reflected light and sound. Light reflectance only works for relatively shallow waters, whereas sound reflectance can paint a picture of deeper areas.

High-resolution digital imagery gathered from either an aircraft or a satellite can be used to create habitat maps. Maps can be generated by either human observers or computerized image analysis software. Imagery from satellites typically has spatial resolution on the order of tens of meters of spatial resolution and hundreds of nanometers of spectral resolution (Hochberg and Atkinson 2000). The recent advent of high spatial (1-m) and high spectral (1- to 10-nm) resolution digital images should provide fine-scale identification and mapping of coral reefs and other benthic communities (Mumby et al. 1997). Aerial surveys can also be conducted at lower altitudes using conventional light aircraft, kites and balloons, remote-controlled aircraft, or ultralights (McManus et al. 1996). LIDAR (light detection and ranging) integrates light and sound signals to determine the properties and ranges of target objects. LIDAR can be mounted on aircraft to quantify bathymetry and habitat complexity over tens and hundreds of kilometers of area.

Techniques using sound reflectance are usually performed in the water using ship-based equipment. They send sound signals out and analyze the returning echoes. Sound surveys can be useful in fisheries for stock assessment (Karp 1990), for remotely sensing characteristics of bottom habitat (e.g., Able et al. 1987; Yoklavich et al. 1997), and for assessing impacts to fisheries habitat (Collie et al. 1997). Acoustic remote sensing also presents a promising independent approach to evaluate fishing effort on a spatial scale consistent with commercial fishing activities. For example, this technology can identify marks left by bottom trawls as a method of determining the frequency of impact of trawl gear over a range of depths and habitat types (Friedlander et al. 1999).

Table 7.4. Remote-Sensing Methods with Associated Resolutions and Costs.

Technology	Spatial Resolution	Spectral Resolution	Cost to Acquire
Space-based			
IKONOS	16 m^2	4 bands	\$27–62 km^2
Quickbird II	6.25 m^2	4 bands	\$30 km^2
LandSat	900 m^2	6 bands	\$0.0015 km^2
Hyperion	900 m^2	220 bands	NA
Aircraft			
Hyperspectral	9 m^2	74 bands	\$325 km^2
Color Aerial Photography	1 m^2	3 bands	\$175 km^2
Ship-board			
Multibeam	0.01–10 m^2	Bathymetry + backscatter	Shallow Water –\$27,000 km Deep Water –\$300 km
Sidescan	0.01–10 m^2	Backscatter	Shallow Water –\$24,000 km Deep Water –\$200 km

In addition to providing the basis for quantifiable, accurate determination of the coral reef ecosystem, digital maps are easily incorporated into a computerized GIS for analysis along with other map information. They can be used to support the designation and conservation of MPAs and essential habitats. They also have an important role in shaping public awareness and education (Monaco et al. 1998, 2001).

The coupling of ecology, remote sensing, and GIS technology has recently been used to map and monitor U.S. coral reefs in Florida, the Caribbean, and Hawaii (Monaco et al. 2001). Digital benthic habitat maps derived from high-resolution aerial photography have been used to help define spatial and temporal distributions by life stage of fishes and invertebrates and to determine species habitat affinities (Monaco et al. 1998). Coupling the distribution of habitats and species habitat affinities using GIS technology enables the elucidation of species habitat utilization patterns for a single species or for assemblages of animals (Kendall et al. 2003). This integrated approach is useful in quantitatively defining essential fish habitat (Clark et al. 2003) and defining biologically relevant boundaries of marine protected areas (Christensen et al. 2003). Such approaches are also critical to understanding ecological connections among habitats as already discussed here.

CONCLUSIONS

Marine reserves present an unparalleled opportunity to study marine ecosystems in the absence of fishing pressure and other major human impacts. The ocean is an inherently unpredictable place. This unpredictability makes it difficult to scientifically prove that marine reserves work, especially when it comes to export of benefits to surrounding fishing grounds. However, we do not demand such proof of other management tools we regularly enact, wisely so because it is nearly impossible to provide. Compared to other management tools, extensive scientific support backs marine reserves as an effective conservation and fishery management tool. Better still, extensive marine reserve networks can serve as an effective insurance policy against the unpredictable nature of the ocean.

In spite of their promise as a management tool, there are a number of areas where more study would enhance our ability to design marine reserves. Monitoring of existing and new marine reserves will be an invaluable tool for improving our ability to design them effectively while providing broader insight into management issues and natural systems in general. Movement of adults and their offspring is another major topic of interest related to reserve design. As we learn more about how fish move, we will gain valuable insight into creating better marine reserves. Fish movement is one crucial way in which habitats are connected, and additional study on this topic will aid greatly in designing reserves that are effective at protecting fish throughout their life cycle. One of the most important reasons that reserves are important is to protect against ecosystemwide crashes. Our lack of knowledge warrants such protection, and reserves themselves can teach us how to avoid crashes. Design of marine reserves would not be complete without habitat maps and species distributions, so these exercises will be valuable as part of a process of reserve designation in an area.

We know everything necessary to improve on current use of marine reserves. Nevertheless, a number of tools and techniques are available to enhance our ability to design and implement effective reserve networks. Reserves themselves provide an invaluable research tool and give us the opportunity to learn a great deal about areas relatively unaffected by humans. Populations of important species in many marine ecosystems are now so sparse that they cannot exert their former ecological role (Dayton 1998), and the indirect effects of the reductions of these species are unknown because no baseline data exist for comparison (Dayton et al. 1998). Modern studies of marine ecosystems began long after enormous changes in these systems had occurred (Jackson et al. 2001). Moreover, the "shifting baseline syndrome" causes people to identify ecosystems as near pristine when they first experience them, even if they may have already been severely degraded (Pauly 1995; Sheppard 1995). These problems make it difficult to determine what constitutes a natural ecosystem and how to manage these ecosystems accordingly. One irreparable consequence of overfishing and habitat destruction is the loss of opportunity to study and understand intact communities (Dayton 1998). Marine reserves can provide that baseline if the ecosystems are not already too degraded to recover.

Other tools, ranging from simple plastic tags to sophisticated satellites, can help to advance our understanding of how to design marine reserves better. In the short run, most designs will represent an improvement over present management practices. In the long run, the techniques discussed in this chapter will be vital to improving our ability to design effective marine reserves for conservation and fisheries.

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