Ecological Monitoring Design, Implementation, and Applications: *A Case Study from Channel Islands National Park, California*

Gary E. Davis, Senior Scientist

U. S. National Park Service, Ventura, California

Abstract

Conservation of biodiversity and natural resources requires advanced ecological knowledge beyond qualitative observation and simple surveillance. Resource stewards need to understand ecosystems entrusted to their care so that they can maintain the systems unimpaired. They need to know when to intervene to restore and maintain damaged ecosystems, and when to abstain from action. For these purposes, ecological monitoring programs should be designed to provide indications of ecosystem health, define limits of normal variation, identify abnormal conditions, and suggest potential agents of abnormal change. After setting program goals, the first step in design of such a diagnostic monitoring program is to develop a conceptual model from existing inventories that identifies all ecosystem components and describes their relationships. The next step is to conduct design studies that establish monitoring protocols. During these studies, experts select parameters to be measured and field test sampling, analytical, and reporting procedures for each system component. The final step in the design process is implementation, which entails obtaining sustained funding and staff, building infrastructure, executing the protocols, and applying information to relevant management issues. A successful diagnostic monitoring program at Channel Islands National Park, California, based on population dynamics and environmental factors, provides a practical example of this design process. Both management and monitoring of ecosystems need to be recognized as experimental endeavors, and approached in an iterative fashion. Using the scientific method to design monitoring reduces uncertainty and cost. Information generated by monitoring also reduces uncertainty and cost of resource management, and it reduces risks of species extinction. Information from the monitoring program at Channel Islands National Park provided early warnings of pollution and other human disturbances, guided alien species removal, revealed unsustainable fisheries, and directed restoration efforts for impaired resources.

Introduction

This chapter describes a tested process for designing ecological monitoring programs, explains by example a practical application of this process, and provides examples of how information developed by this monitoring program has been used to resolve environmental issues. The design process has four steps: set goals, develop a conceptual model, establish protocols, and implement monitoring. I have used this procedure to design monitoring programs for a dozen units of the United States National Park System, including desert, mountain, and coastal parks. The most mature program was initiated in 1980 at Channel Islands National Park, California. This park contains a wide variety of marine, terrestrial, and coastal ecosystems, and therefore provides good examples for monitoring programs in many other places.

Why Monitor Ecosystem Changes?

Why do you want to monitor? It is essential to explicitly ask and answer this simple question at the outset of the design process because the answer will largely determine what, where, when, and how you actually monitor. The world's rapidly increasing human population and evolving attitudes toward natural resources drive several major trends in biotic resources that identify generic reasons for monitoring. The pervasive unsustainable consumption of 'renewable' resources, fragmentation and loss of habitats, human alterations of air, water and soil, and the spread of alien species all require immediate attention to avert economic, social, and environmental catastrophe. A brief description of these factors will help set the stage for understanding the kinds of information that modern monitoring programs need to provide.

The **unsustainable consumption of 'renewable' resources** drives populations and communities to failure. For example, serial depletion of coastal fishery stocks and harvest of ancient forests in the 19th and 20th centuries supported economic development, but seriously eroded the biological productivity on which continued economic productivity depends. California's red sea urchin fishery, currently the State's largest coastal fishery, provides a graphic example (Dugan and Davis 1993). In southern California, commercial and recreational divers sequentially exhausted a series of five abalone species from 1950 to 1980 (State of California 1995). In the early 1970's, the commercial fishery shifted to a new resource base, red sea urchins, but was forced to expand into new territory in northern California after less than a decade, when southern California stocks began to decline in the mid-1980's. Today, diving-based fisheries must develop new markets for yet more species, purple sea urchins and sea cucumbers, to 'sustain' their income. Ironically, it takes 20,000 metric tons of urchins to provide the same economic return of 2,000 tons of abalone, so even greater biological productivity is required to support economic status quo. Now, with few new forests or fish populations to exploit, we must learn either to restore ecosystem integrity and productivity, or to live within the limits of reduced biological productivity.

High human population densities and land-use practices that destroy and fragment habitats erode society's productive resource base when native populations and communities collapse from lack of appropriate space, i.e., critical habitat (Soulé 1986). Habitat fragmentation and loss threatens not only tropical rainforests; throughout North America native ecosystems are being carved into smaller and smaller remnants. Florida's Everglades, the great Midwestern prairies, California's mediterranean ecosystems, dammed river basins, and intensively developed coastal zones are but a few examples of seriously fragmented habitats in the United States.

Habitat alterations threaten migratory birds and fisheries with loss of critical marshes and estuaries. The loss of wide-ranging predators that require large expanses of continuous habitat, such as wolves and grizzly bears, alters ecological community structure and function, thereby precipitating and accelerating loss of biodiversity.

Human alterations of air, water, and soil drive ecosystems toward unstable and less productive states. Global atmospheric changes precipitated by industrial development threaten to increase the frequency and magnitude of otherwise natural extreme events, such as tropical storms, el Niño, floods, and droughts. Pollution can simplify systems by reducing species outright, or by reducing the resources available to various populations. Productivity of individuals and ecosystems may be reduced by contamination of food and water. Pollution stress added to natural stresses, such as storms or parasites, may bring communities to crisis conditions. Diversions from surface water supplies and withdrawals from deep aquifers threaten long-term productivity of many ecosystems.

Spread of alien species causes loss of biodiversity and disrupts ecosystem structure and function. The virtual extinction of native birds on Guam, caused by introduced brown tree snakes, provides a sobering example of the serious ecological consequences of alien species. Alien species introduced by human activities, both intentional and accidental, are wrecking havoc on native flora and fauna and their associated ecosystems worldwide.

Ecological monitoring can greatly mitigate the impacts of these and other factors threatening human existence. Ecological monitoring is like health care for the biosphere, our life support system (Odum 1989). We must learn the characteristics of a healthy biosphere, recognizing that it is a dynamic system, constantly changing with normal variations. Monitoring can help identify the limits of healthy conditions by empirically measuring the variation. Monitoring can also help diagnose abnormal conditions and identify threatening situations early enough to allow for effective mitigation. Finally, monitoring should be designed to identify potential causes of abnormal change and to suggest remedial treatments.

Ecological Health Care and Medicine

Natural resource stewardship requires *teams* of specialists, as does human health care. It is important to identify the division of labor and purposes of the various team members to avoid competition and to enhance opportunities for collaboration. Effective ecological monitoring includes people who recognize overt threats to resources (such as chemical spills), take immediate actions to stabilize the situation, and protect both people and resources from further damage, much like emergency medical personnel manage an accident scene. Taking care of natural resources also requires people who act like family physicians by monitoring health, diagnosing illness, and by prescribing treatments and evaluating their efficacy. Other scientists conduct research to develop new treatments, improve monitoring protocols, and identify new diseases. Still other members of the stewardship team act like public health officials. They teach the public about the threats of alien species, habitat fragmentation, and pollution, and explain why actions to modify society's behavior are important to the general well being.

In medicine, normal limits of variation in human physiology are known. Most body functions and structures are understood, and many causal relationships between stressors and responses have been identified. Unfortunately, the current state of knowledge in ecology equals that of 17th century medicine, about when Harvey discovered the function of the heart as a pump in a circulatory system. In ecology today, the name of many ecosystem components, such as species, are known, but their relationships with each other or with the environment, are still mysteries. It is virtually impossible to mange a system with reliable certainty when we have such a poor understanding of its structure and function. Hence for most of the 20th century, people have done as well managing natural resources by guessing or relying on beliefs as they have by relying on scientific studies. The best way to improve on superstition and traditional beliefs is to begin systematically measuring the components of ecosystems by monitoring (Halvorson and Davis 1996, Sagan 1996).

The concept of ecosystem health is not dissimilar to that for individual health. A healthy individual's vital signs remain within some normal, dynamic, range and return to a nominal level quickly after perturbation. Damage to structural elements is quickly and effectively repaired to sustain normal functions. Infections (alien species) are eliminated or contained. The same attributes pertain to populations, communities, and ecosystems. Exactly what constitutes vital signs for these higher levels of ecological organization is not yet clear. As knowledge of their structure and function improve, we will be better able to identify critical parameters. Just as early physicians empirically discovered the value of body temperature, respiratory rate, and blood pressure in assessing patient health, ecologists today need to begin measuring dynamic ecosystem parameters to discover 'ecological vital signs'.

Design Process

Ecologists have devised several quite different approaches to measuring ecosystem dynamics. Theoretically, any approach would work for monitoring, but we have found that population ecology, a combination of population dynamics and physical environmental measurements, is the most practical (Davis 1989, Davis et al. 1994). Nevertheless, attributes of other approaches deserve serious consideration, depending on the specific application or purpose for monitoring. One appealing and sophisticated approach to ecosystem study is energetics. Energetics provide a single common denominator of life on earth and can be used to describe, understand and predict ecosystem dynamics (Odum and Odum 1981). However, reducing all ecosystem components to caloric values and measuring their changes over time requires a host of very complex measurements. Many of these measurements require expensive and destructive sampling unsuitable for long-term monitoring. Understanding and applying the results of energetics measures to environmental issues is frequently ambiguous and indirect.

Another sophisticated, and potentially elegant, approach is the study of biogeochemical cycles, such as carbon, phosphorus, and nitrogen (Likens et al. 1977). A virtue of this approach is the focus on a few key control points in the system with clear threshold values (Liebig's law of the minimum). Nevertheless, this strategy also requires numerous complex measurements and substantial *a priori* knowledge of system structure and function, frequently beyond that currently available. Application is likewise often ambiguous and difficult, since management controls and human impacts on ecosystems are exercised in units other than nutrients or other elemental constituents.

A popular characteristic of ecological systems is biodiversity (Wilson 1988). Monitoring biodiversity generally involves a series of repeated inventories. Diversity may be measured at several levels: genetic, species, ecosystem, or landscape, which yields information vital to conservation efforts. Unfortunately, biodiversity has two major drawbacks for diagnostic monitoring. It is extremely difficult to measure, because of the large amount of taxonomic expertise needed for even the simplest of systems. Also, biodiversity measures neither provide early warnings by forecasting future conditions, nor measure chronic, less than lethal, changes in the system. Monitoring changes in biodiversity hind-cast, rather than forecast, by measuring the addition of alien species or documenting the loss of native species.

Population ecology that measures both population dynamics and environmental factors is relatively easy to do, allows selection of key elements of the system, and provides many of the diagnostic features required to manage systems. It permits projections into the future through measures of population age structure, recruitment, and reproductive effort. Population demographic measures, such as growth rates and reproductive success, can detect subtle, chronic stresses before they become lethal for species or populations. Management control actions for mitigation and restoration often function at the population level, making application of monitoring results direct and clear. The measures of population dynamics we find most useful are abundance, geographic distribution, age structure, reproduction, recruitment, and growth and mortality rates. Population dynamics serve well as ***vital signs*** for ecosystems.

A step-down diagram is a useful way to display the steps in the design process and their relationships with each other and the program goals (Phenicie and Lyons 1973, Davis 1993). The diagram starts with the program goals at the top, and indicates on the next line below the goals all of the actions, and only those actions, required to achieve the goals. On the third line, all, and only, those actions required to affect the actions on the previous line are indicated, and continues until the details of the actions on the bottom line (lowest level of organization) are sufficient for program execution. For example, the goals of the Channel Islands National Park monitoring program are to develop and institute an ecological monitoring program to: 1) determine present and future ecosystem health, 2) establish empirical limits of resource variation, 3) provide early diagnosis of abnormal conditions, and 4) identify potential agents of abnormal anthropogenic change. The next tier on the step-down diagram indicates that if, and only if, we develop a conceptual model of park ecosystems, conduct design studies, and monitor system health will we achieve the program's goals (Davis et al. 1994). In outline form, the remaining steps are:

1. Develop a conceptual ecosystem model
    - 1.1 Set limits (boundaries) on systems to monitor
    - 1.2 Inventory natural resources
        - 1.2.1 Review literature for resources occurrence and distribution
        - 1.2.2 Conduct field surveys for inadequately known taxa
    - 1.3 Make an exhaustive list of mutually exclusive components
        - 1.3.1 Define biogeographic units, e.g., watersheds, islands, ocean currents, be sure to consider a variety of scales of time and space
        - 1.3.2 Determine appropriate taxonomic divisions, e.g., birds, trees
    - 1.4 Identify relationships among system components
2. Conduct design studies
    - 2.1 Select critical components from conceptual model
        - 2.1.1 Establish selection criteria for taxa, represent all ecological roles, special legal status, endemic, alien, exploited, dominant, common, and charismatic species
        - 2.1.2 Apply criteria to system components identified in conceptual model
    - 2.2 Set component priorities
        - 2.2.1 Review legislation, executive orders, and policies
        - 2.2.2 Consider threats to ecosystems and resources

        2.2.3 Review knowledge of each component
        2.2.4 Review monitoring technology for each component
        2.2.5 Consider other agency responsibilities and programs as opportunities for partnerships
    2.3 Design monitoring protocols
        2.3.1 Review scientific literature
        2.3.2 Select component parameters to monitor
        2.3.3 Select and test data acquisition systems
        2.3.4 Establish information management system
        2.3.5 Prepare standardized report forms
        2.3.6 Demonstrate protocol efficacy in field tests
3. Monitor system health
    3.1 Obtain funding
        3.1.1 Market monitoring needs
        3.1.2 Establish accountability for resources
        3.1.3 Obtain scientific and management review
    3.2 Obtain personnel
        3.2.1 Determine knowledge and skills required
        3.2.2 Prepare organizational plan, with position descriptions and performance standards
        3.2.3 Recruit and hire personnel
        3.2.4 Establish career ladders and training program
    3.3 Implement monitoring protocols
    3.4 Synthesize information from monitoring and apply to appropriate issues
        3.4.1 Determine historical or nominal values for monitored parameters
        3.4.2 Compare current and historical values
        3.4.3 Examine values and variations for correlated patterns in space and time with other components, events, and threats

Channel Islands National Park Ecological Monitoring Program

Conceptual Model

We used this design process to develop a monitoring program for Channel Islands National Park. First, we needed a conceptual model of the park that included its biological features, environmental setting, land and sea forms, and threats to the park's ecological integrity. Here is a brief description of the park and its environs to serve that purpose.

A chain of eight islands, shrouded in fog and surrounded by some the world's largest kelp forests, guard the last remnants of America's natural Mediterranean coast. Five of the eight California Channel Islands, and more than 310,000 ha of the surrounding sea bed, are protected by a plethora of conservation designations. The area is recognized internationally as a Biosphere Reserve, nationally as a National Park and a National Marine Sanctuary, and locally in three State Ecological Reserves and two Areas of Special Biological Concern. These islands bridge two biogeographical provinces. In a remarkably small space, they harbor the biologic diversity of 1,500 km of the North American west coast. The nearby confluence of ocean currents brings nutrients up from the dark sea bed into bright sunlight, building one of the most productive food webs on earth, with more than 1,000 species of marine fish, invertebrates, and algae. Myriad elephant seals, sea lions, fur seals, harbor seals, auklets, murrelets, cormorants, guillemots, petrels, gulls, and pelicans breed and raise their young on these islands, near abundant food and safe from disturbance on the 240 km meridian of pristine sand beaches, rocky tide pools, and shear cliffs that rings the islands at the sea's edge. Twenty-six kinds of cetaceans cavort around the islands, including vast schools of sleek pacific whitesided dolphins, families of acrobatic humpback whales, swift Orcas, and the largest animals that ever graced the earth – blue whales. A mild mediterranean climate, with short wet winters, long dry summers, and extensive coastal fog, creates a fascinating array of plant and animal communities on the islands. Isolation protects island species from competition with large diverse mainland populations and from destruction by land development. Unique island forms of majestic oaks, ironwood, torrey pine, and other trees tower above rippling grasslands interspersed with fields of coastal sage and lupine. Island wildlife is rich along the riparian corridors of more than a dozen perennial streams that dissect the gently rolling marine terraces marking ancient uplifted shorelines. Small populations and limited island habitats relegate many species to rare and endangered status, and accelerate evolution of unique life forms. Nearly 10% of island plants exist only on these islands today, while fossils record the past presence of giant mice, flightless ducks, and mammoths.

Numerous archeological sites on the islands reveal a rich human culture spanning 100 centuries. Today, the islands sit precariously at the edge of a human tide that threatens to engulf them. Nearly 18 million people live within 300 km. These people bring worldwide demands for coastal resources from 172 human cultures. The clear, cool waters of the Pacific both facilitate and limit public access to the islands. Each year, 100,000 SCUBA divers explore island reefs and kelp forests. Boaters find shelter in more than 100 secluded anchorages. Primitive campgrounds provide intrepid visitors intimate views, revealing each island's unique nature. Thousands of day-visitors glimpse island wonders and peek at marine mysteries in tide pools left by the sea's brief daily retreats. Air and water pollution from nearby metropolitan and industrial developments threaten island ecosystems. Sheep and cattle ranching on the islands introduced alien species and accelerated erosion. Island waters used to yield 6,800 tonnes of fish, shellfish, and kelp annually to commercial and recreational fishermen, producing 15% of California's nearshore harvest from only 3% of the state's coastal waters. Recent collapses of fishery-targeted populations revealed that managed traditionally, neither the fisheries nor the populations were sustainable. All of these human activities have altered native island communities, and collectively threaten their survival. Normal dynamics of these systems mask human influences and make management uncertain, at best. The ecological monitoring program, established in 1981, reduces that uncertainty by yielding knowledge of population dynamics and environmental forces. This program is the result of a remarkable collaboration of State, Federal, and private interests. The Federal government contributes scientific expertise and management oversight from the Department of the Interior's National Park Service, Geological Survey, Minerals Management Service, and Fish and Wildlife Service, from the Department of Commerce's National Marine Sanctuaries Program and National Marine Fisheries Service, and from the State Department's Man-in-the-Biosphere Program. The State of California contributes university scientists and facilities, Department of Fish and Game biologists and fishery managers, and guidance from regional water quality boards and county air quality boards. Private interests involved in the program include The Nature Conservancy, the Santa Catalina Island Conservancy, and many other local groups, such as the Channel Islands Council of Divers, Santa Barbara Museum of Natural History, and Santa Barbara Botanic Garden.

In this setting, these ecosystems produce a series of management issues, including fisheries exploitation, air and water pollution, grazing and other effects of alien species, and small isolated population adaptation and evolution. These issues, and variations in ecosystem structure and function, drive the monitoring program by determining what information is needed to address the issues, and to maintain the resources unimpaired for the enjoyment of future human generations. A step-down plan, developed in 1980, was used to identify the system components in a conceptual ecological model, show the components for which design studies were needed in priority order, and to identify the actions needed to implement a sustained monitoring program in the park (Davis et al. 1994).

Design Studies

Short-term research studies are the core design activity. We used a modified Delphi approach in the design studies. We asked groups of experts to share their conceptual models with each other in a workshop setting, and then to use that knowledge to decide what parameters to measure and how to monitor each of the selected components, such as sea birds, kelp forest, or terrestrial vegetation. Recognizing that the long-term design process is an iterative one and recognizing the limitations of our expertise (17^{th}century medical knowledge), we acknowledged that we were not trying to find a final solution, but rather to identify a reasonable starting point. The list of 12 design studies constitutes a brief summary of the collective conceptual model of the park (Davis 1989). Each design study lasted 3-5 years and addressed the same tasks: 1) select index species or factors for this component, 2) develop sampling techniques, 3) test analytical protocols, 4) develop report formats, and 5) demonstrate the efficacy of the recommended monitoring protocol by field testing all aspects of the protocol for two years.

Selecting species, or other taxa, and parameters was the first order of business for each design study. This process involved applying seven selection criteria to existing inventories. Where existing inventories were inadequate, field surveys were conducted. At Channel Islands National Park, field surveys were needed for terrestrial invertebrates, amphibians, and reptiles. Inventories of the other components were considered adequate by the experts. The first selection criterion was to assure that a representative sample of all species in the component were selected, i.e., assure that a broad array of ecological roles were represented, including primary producers and high-level consumers, long-lived and short-lived species, sessile filter feeders and mobile grazers and hunters. The next was to assure that common and dominant species that characterized communities and provided physical structure were represented. Then we wanted to make sure that all taxa with special legal status were included, e.g., endangered species. The monitoring program also had to include all endemic, exploited, and alien species. Finally, if all other criteria were equal, we selected heroic, charismatic species with human constituencies, i.e., species about which the public already cares and empathizes.

The next concern was where and when to sample. Site selection began with existing inventories. Where do the species, or other elements, of the component occur? When does reproduction occur? Monitoring sites need to provide replicate sites within the range of conditions or along gradients. For example, kelp forests in the park occur along two biogeographic and physical gradients. Kelp forest assemblages of algae, invertebrates, and fishes in the cold, nutrient-rich waters of the western islands in the Oregonian zone are quite distinct from those in the warm waters around the southeastern islands in the Californian zone and from those in the transition zone between these two extremes. Kelp forests north of the islands are buffeted by winter storms from the Gulf of Alaska, while those on the southern shores are protected from winter storms. The south coast kelp forests are strongly influenced by large summer swells generated from southern hemisphere winter storms and by seasonal upwelling from adjacent oceanic basins. These physical settings create six different kelp forest zones (3 biogeographic zones X 2 physical zones). At least two monitoring sites were established in each of the six zones. Fishery harvest has a major influence on kelp forest structure and function, and so additional monitoring sites were selected to compare fished with unfished kelp forests, yielding a total of 16 sites (Davis 1988). Just as a physician needs to put the thermometer back in the same location in the patient to get reliable results, ecological monitoring sites need to be identified so that changes in parameters reflect changes over time and not within site variation. So each site is carefully marked to assure that sampling occurs in precisely the same place every year.

Sampling techniques are often species dependent, and standard techniques need to be adapted to particular sites and situations. Resolving these matters is the main function of the design studies. Goals for accuracy and precision of monitoring at Channel Islands National Park were set *a priori* by park managers to detect 40% changes in mean values, with α=0.05 and β=0.20[1].

A variety of sampling techniques is required for each component. Again using the kelp forest component as an example, over 1,000 species of plants and animals inhabit kelp forests in the park. We selected 63 taxa to monitor at the 16 sites. Common, ubiquitous, discrete species, such as sea urchins and giant kelp, are relatively easy to sample for abundance and size with quadrats placed in a stratified random fashion. The design study resolved how many and how large the quadrats needed to be to reduce within-site variation to achieve the established statistical goals. Rare, clumped species, such as abalone and lobster, required a different sampling strategy, so band-transects were designed for that purpose. Colonial species, such as anemones and bryozoans, and algae that literally carpet the bottom require yet another technique, so we used 1,000 randomly selected points in 50 plots to estimate cover as an index of abundance. Recording observations for 15 taxa at 1,000 points at each site is a significant bookkeeping exercise for divers underwater. Another function of design studies is to develop and adapt new technologies. In this case, surface supplied diving equipment was employed to shift the record keeping activities to surface data recorders who simply recorded observations dictated to them by divers, thereby increasing speed and accuracy of the sampling. Fish are difficult to sample, because they are mobile, patchy, and sensitive to observers. Design studies also need to invent new techniques and to test old, standard, ones. We discovered that traditional, non-destructive, *in situ* fish population assessments had very low accuracy (Davis and Anderson 1989). We continue to struggle with appropriate techniques for sampling fishes (Davis et al. 1996a) and are currently testing roving-diver and timed-species counts.

The detailed monitoring protocols for each component are documented in peer-reviewed handbooks, published in loose-leaf notebook form to facilitate revisions (Davis and Halvorson 1988). Initially (1988), 12 handbooks were published for pinnipeds, seabirds, rocky intertidal ecosystems, kelp forests, terrestrial vertebrates (amphibians, reptiles, and mammals), land birds, terrestrial vegetation, fisheries, park visitors, and weather. A protocol for sand beaches and coastal lagoons was added in 1990. The protocols are to be reviewed for design performance and updated at ten-year intervals. The first design review was conducted in 1995 (Davis et al. 1996a).

Implementation and Using the Results

We designed the Channel Islands National Park Ecological Monitoring Program to identify

[1] A type I error (α) means the probability of erroneously reporting that a parameter changed when it really did not, and a type II error (β) means the probability of not detecting a change when it occurs. Probabilities are typically set at 5% and 20%, respectively, because a false report is considered more serious than failing to detect a change.

trends in ecosystem health, to empirically determine normal variation of ecological vital signs, to diagnose abnormal conditions early, and to suggest potential causes and remedies for impairment. The information generated by this program has significantly reduced uncertainty for management decisions and reduced the costs of resolving serious threats to the park's ecological integrity, but the program constitutes a significant investment in personnel, infrastructure, and operating funds.

Conserving the park, while providing for visitor enjoyment and assuring it is left unimpaired for future generations, requires a team effort by the entire park staff of some 60 people. Fewer than 12 of these people dedicate all their time to the monitoring program. They are organized into three working groups: one for marine and coastal resources, one for island resources, and one for information management. We found it difficult to maintain institutional continuity in operations and data with fewer than three people in a work group.

<u>Information Management</u>

Information is the primary product of an ecological monitoring program. How it is managed largely determines a program's efficacy, reputation for reliability, and image among critics, peers, and supporters. Each of the 12 peer-reviewed monitoring protocols in the Channel Islands National Park program includes directions for data management. In addition to the effort required to collect and record monitoring information, 35-40% of the monitoring program's resources are dedicated to managing and making available the information collected, archived, and produced (Dye in press). The usual, more theoretical, estimates of information management needs of 10-15 % seriously underestimate the effort required in practice (Royal Society of Canada 1995).

Other practical information management lessons learned during development of the Channel Islands program include using standard, commercially available, software (avoid custom programs), specifying common fields for all records that relate all databases, e.g., date and location, and planning for and embracing change. Not only are the natural systems we seek to understand through monitoring dynamic, the engineered systems we use to manage information are also dynamic. For example, we experienced 10 generations of software and operating systems in the first 16 years of the Channel Islands program, from Apple II microcomputers to Windows-95 and UNIX environments.

Annual reports for each monitoring protocol, e.g., kelp forest or island birds, describe current resource conditions, archive annual data, document monitoring activities that may vary from year to year, provide an end-point for otherwise endless monitoring activities (emotionally important for the monitoring staff), and document changes in monitoring protocols. In addition to annual reports, conducting formal peer-reviews of protocols, operations, and results at 10-year intervals helps assure program vitality and relevance. During protocol reviews, we review design criteria for accuracy and precision, analyze data for power to resolve changes, and recommend protocol revisions. This process provides a formal history of program evolution that helps assure data continuity while employing modern technologies and methodologies.

Frequent and extensive analysis and synthesis of monitoring data facilitates discovery of new features and characteristics of monitored systems. The sustained time-series data at landscape scales that monitoring programs produce permits resolution of complex environmental issues too difficult to address with typical ecological studies focused on meter-square plots for one or two seasons (Baskin 1997). Monitoring data-sets also allow exploration of new analytical methodologies. It is essential that monitoring practitioners publish results and failed efforts in peer-reviewed literature and present their experiences in topical symposia. Ecological monitoring is no longer simply a compliancemandated record of environmental parameters; today it drives explorations at the edge of conservation biology and ecology. As such, its discoveries need to be documented, critiqued and discussed widely.

Applications to Environmental Issues

The primary applied uses of ecological monitoring are to guide and evaluate resource management actions, to provide early warnings of abnormal conditions, to identify possible causes of abnormal conditions, and to help frame research questions to resolve issues. At the California Channel Islands, monitoring has helped to control and eliminate alien species, to detect and mitigate pollution, to recognize unsustainable uses and change fishery management policies, and to develop and evaluate population and ecosystem restoration methodologies.

Stewards of the California Channel Islands have used the monitoring program to direct and evaluate removal of several alien species, including burros on San Miguel Island, European hares on Santa Barbara Island, feral pigs on Santa Rosa Island, and South African iceplant on Anacapa Island. The monitoring program provided realistic cost estimates of each effort by actually measuring costs of successful partial removals and projecting total costs from empirical data, which engendered public trust in the process. Monitoring also measured progress toward the removal goal and clearly identified end-points for removals, thereby reducing the uncertainty of success.

Monitoring reproduction and recruitment in California brown pelican rookeries provided an effective early warning of pesticide (DDT) pollution, providing sufficient time to ban DDT and restore pelican productivity. Today the monitoring program indicates clearly that DDT is still a problem in coastal ecosystems as witnessed by reproductive difficulties experienced by peregrine falcons and bald eagles, but also that we are making progress which thereby encourages people (society) to continue abatement activities.

Knowing when not to intervene is another value of monitoring related to early warnings of pollution or other environmental issues. The Channel Islands National Park rocky intertidal monitoring protocol was modified and applied to Cabrillo National Monument, in San Diego, California in 1989. In 1992, when the San Diego municipal sewage treatment effluent discharge pipe broke and dumped 16 billion gallons of treated effluent into the sea less than a kilometer from the monument's tide pools over a two month period, many people were rightfully concerned about marine life in the tide pools and adjacent kelp forests. Objective information from pre-spill monitoring established clearly that the effluent had little negative effect on these resources. In fact, closing the tide pool area to visitation during those two months, in order to protect visitors from potential health hazards in the effluent actually relieved trampling and other visitor-related disturbances. The monitoring in this case saved unnecessary expensive litigation that normally occurs in the absence of actual knowledge in situations like this. It also elucidated the specific effects of visitor disturbance relative to regional environmental events, such as el Niño.

Many fisheries are managed and evaluated largely on the basis of fishery-dependent landings data that may not be related to changes in fished populations. Fishery-independent monitoring provides essential corroborative information for fishery managers. Serial depletion of five species of abalone (*Haliotis* spp.) and then a sea urchin (*Strongylocentrotus franciscanus*) to support a commercial diving fleet was obscured by ambiguous landings data in southern California before monitoring data were available (Dugan and Davis 1993). As a result, harvest exhausted abalone populations before fishery management policies could be changed, and drove at least one species nearly extinct (Davis et al. 1996b). Political systems are frequently frozen into inaction by uncertainty

(Wurman 1990). By reducing the uncertainty regarding abalone population status, monitoring allowed the political process to work. The California Fish and Game Commission and Legislature quickly closed five abalone fisheries to prevent loss of critical brood stock and to facilitate and reduce the costs of rebuilding depleted populations. Monitoring methodologies are currently being used to test a variety of different abalone restoration techniques at the California Channel Islands (Davis 1995, Davis and Haaker 1995). Ecological monitoring also provided early warning of black abalone (*H. cracherodii)* population collapse (Richards and Davis 1995). The ultimate population collapse was apparently caused by infectious disease in small, fragmented populations. Monitoring provided sufficient information, early enough, to protect disease-resistant individuals from fishery harvest and to ensure survival of another generation.

Conclusion

Monitoring won't solve all environmental issues, but it can provide a sound foundation for addressing them. Experimental, manipulative research is also needed, especially for longer periods of time and on larger areas than is customary in ecology today. Only then will we begin to understand ecosystem structure and function adequately enough to predict system behavior and responses to insults and natural perturbations. In the twentieth century, society began to change from belief-based to knowledge-based stewardship, with science providing the knowledge (Halvorson and Davis 1996). This change has been slow and opposed by many, especially those invested profitably in the old ways and threatened by the knowledge science generates. Persistence and personal experience are needed to facilitate change. Denial that we need a new approach hinders progress and threatens our own survival by hiding impacts of fragmentation, pollution, alien species, and unsustainable resource uses. As a society, we must get past this denial to shape our future. Ecological monitoring will facilitate persistence, encourage mitigation by providing confidence and reducing uncertainty, provide early warnings which reduce the magnitude of problems, and thereby reduce restoration costs. Ecological monitoring *is* expensive, but it is a good investment to assure continued productivity of natural resources, to maintain the services of natural ecosystems, and to protect biodiversity.

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