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

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In 1980 Channel Islands National Park was established to preserve unimpaired, self-sustaining examples of coastal ecosystems off the coast of southern California. The region's first conservation designation came in 1938 when President Franklin D. Roosevelt proclaimed Channel Islands National Monument to protect the islands of Santa Barbara and Anacapa. Since then, many governmental bodies have conferred a variety of conservation designations on the five of the eight California Channel Islands and the sea around them that comprise the park (Table 1). This chapter describes the design, structure, and function of a General Ecological Monitoring (GEM) program instituted to inform, guide, and evaluate natural resource preservation efforts in Channel Islands National Park, California. The National Park Service leads an informal coalition of Federal and State agencies and private interests that sponsors and funds this GEM program, each acting under its aegis.

The National Park Service mission[1], the ecology of the Channel Islands, and regional human threats to park resources combine to determine the function–and thereby the structure–of the General Ecological Monitoring program. The GEM program has four goals. It seeks to:

- identify and measure ecological vital signs of the park to determine present and future ecosystem health,
- establish empirically normal limits of resource variation,
- provide early diagnosis of abnormal conditions, and
- identify potential agents of abnormal change.

Establishing cause and effect relationships requires extensive experimental manipulation and is beyond the scope of the GEM program.

[1] To preserve unimpaired park resources for the enjoyment, education, and inspiration of this and future generations

Threats to park resources that helped shape GEM sampling design include:

- unsustainable uses, such as fishing, grazing, and disturbance by visitors;
- fragmentation of habitats, including loss of nearby mainland habitat and island erosion;
- pollution of air and water;
- spread of alien species, such South African ice plant, *Mesembryanthemum crystallinum*, Australian gum trees, *Eucalyptus* spp., feral pigs, *Sus scrofa* and sheep, *Ovis aries*; and
- loss of soil and fog-drip precipitation.

In this situation measures of population dynamics serve as good ecological vital signs, especially measures of abundance, geographic distribution, age structure, reproduction, juvenile recruitment, and growth and mortality rates. Basic environmental parameters, such as sea temperature, precipitation, and other meteorological measures are also important vital signs. Collectively, these population and environmental parameters permit projections of future conditions which provide early warnings of impending disasters. They integrate a broad variety of environmental and human induced stresses, thereby detecting subtle chronic stresses as well as defining critical acute events. They also directly measure effects of remedial actions such as alien species control or mitigation of visitor disturbances.

Identifying and measuring vital signs of ecosystems is a difficult and complex endeavor involving more than 40 discrete but interdependent activities or projects. This complexity and the magnitude of the work can overwhelm those who are faced with threatened natural resources and constrained by severely limited fiscal and personnel resources. The complexity can be reduced and organized into a three-step process. This facilitates explaining the need for a GEM program and marketing GEM to potential supporters and collaborators. This process also allows all participants and supporters to see easily how their contributions relate to the whole effort.

After setting GEM goals, as indicated above, the three steps are: 1) develop a conceptual ecosystem model, 2) conduct design studies of ecosystem components to establish monitoring protocols, and 3) implement monitoring. Decomposing the overwhelming job of designing and implementing a monitoring program into feasible tasks and fundable projects helps overcome inertia, facilitates communication among participants, and provides a record for future generations of participants to see how and why particular components and parameters were selected.

Successful conservation at the close of the 20th century requires coalitions of many interests. The example described here may appear to be an ideal, with near-adequate professional staff and funding, but it began in 1980 with one person and no other resources. Only the commitment of a park superintendent to science-based management and a single sentence in an obscure Federal law that allocated no funding but nevertheless required "an inventory of all species, both marine and terrestrial…with biennial reports…for ten years" spawned this pioneering program (16 USC 410ff).

The process used to design and implement the Channel Islands National Park GEM program was described and marketed using a step-down diagram that showed explicitly both the relationships among the 41 detailed technical program elements and between those elements and the park's mission (Phenicie and Lyons 1973, Davis 1993). A step-down diagram starts with program goals on the top line and on the line below indicates all of the actions–and only those actions–required to achieve the goals on the line above it. The actions on the second line become the goals for the next step down, indicated on the third line. This step-down process continues to decompose large complex tasks or programs into feasible actions until the actions on the bottom line are sufficiently simple to define a single research project or monitoring protocol (the process could be continued further to detail parts of protocols, such as individual sampling procedures, but then the detail of the plan obscures the relationships of actions and goals for the entire GEM program and loses its educational effectiveness).

For example, the goals of the Channel Islands National Park monitoring program are to develop and institute a General Ecological Monitoring Program that: 1) determines present and future ecosystem health, 2) establishes empirically normal limits of resource variation, 3) provides early diagnosis of abnormal conditions, and 4) identifies potential agents of abnormal change. The next tier on the step-down diagram indicates that the program can address its four goals if, and only if, we develop a conceptual model of park ecosystems, conduct design studies to develop monitoring protocols for ecological vital signs, and monitor system health (Davis et al. 1994). In outline form, the remaining steps for a three tier plan (below the program goals) 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 of the system
        - 1.3.1 Define biogeographic units, e.g., watersheds, islands, ocean currents, and 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 to develop monitoring protocols for ecosystem vital signs
    - 2.1 Select critical components from conceptual model to serve as vital signs
        - 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 General Ecological Monitoring Program

Conceptual Model

This step-down plan describes the design process used to develop a GEM program for Channel Islands National Park. The first step was to create a conceptual model of the park that all collaborators understood and accepted. It included the park's biological features, environmental setting, land and sea forms, and threats to the park's ecological integrity, e.g., alien species, unsustainable uses, and pollution. The following description of the park and its environs, combined with the step-down plan, summarizes the conceptual model.

A chain of eight islands, shrouded in fog and surrounded by some the world's largest kelp forests (*Macrocystis pyrifera*), 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 (Table 1). 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 northern elephant seals (*Mirounga angustirostris*), sea lions (*Zalophus* spp.), fur seals (*Callorhinus* spp.), harbor seals (*Phoca* sp.), Cassin's auklets (*Ptychoramphus aleuticus*), Xantus' murrelets (*Endomychura hypolencia*), cormorants (*Phalacrocorax* spp.), pigeon guillemots (*Cepphus columba*), petrels (*Oceanodroma* spp.), gulls (*Larus* spp.), and brown pelicans (*Pelicanus occidentalis*) 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 (*Lagenorhynchus obliquidens*), families of acrobatic humpback whales (*Megaptera novaengliae*), swift Orcas (*Orcinus orca*), and the largest animals that ever graced the earth–blue whales (*Sibbaldus musculus*).

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 (*Quercus tomentella*), ironwood (*Lyonothamnus floribundus*), torrey pine (*Pinus torreyana*), and other trees tower above rippling grasslands interspersed with fields of coastal sage (*Artemisia californica* and *Salvia* spp.) and bush lupine (*Lupinus arboreus*). 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 (10,000 years). Today, the islands sit precariously at the edge of a human tide that threatens to engulf them. Nearly 15 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 other alien species, greatly accelerated erosion, and reduced the height of vegetation from meters to centimeters (thereby further drying the already near-desert islands by virtually eliminating their capacity to capture moisture from the marine fog blown across them by prevailing winds). Island waters used to yield 6,800 tonnes of fish, shellfish, and kelp annually to commercial and recreational fishers, 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 conceptual model described briefly above includes biological resources (populations and communities), environmental forces (climate and ocean currents), land forms (islands and ocean basins), and management issues (fisheries, pollution, grazing, alien species, and habitat fragmentation). Specific features of the California Channel Islands ecosystem structure and function, combined with management issues, shaped the GEM program by determining what information is needed to address the issues and still maintain the resources unimpaired for the enjoyment of future human generations. A site-specific step-down plan, developed in 1980, was used to identify the system components in a conceptual ecological model, to 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).

The GEM program, established in 1981, has endured because it has proven to be a cost-effective way to reduce the uncertainty of management actions by providing reliable information about ecosystem vital signs. For example, GEM provided early warnings of exploited abalone (*Haliotis* spp.) population collapses and alien plant invasions. This warning gave resource managers and politicians time to respond before remedial actions became too expensive or impossible to enact, and provided confidence that actions were actually required. GEM information also guided feral animal eradication programs (rabbits and pigs) by revealing what efforts were most successful and by estimating time and costs required for complete eradication.

Early documented successes also encouraged many people and agencies to participate. The Channel Islands National Park GEM program is currently 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 various local groups, such as the Channel Islands Council of Divers, Santa Barbara Museum of Natural History, and Santa Barbara Botanic Garden.

Design Studies

Short-term research studies to develop

monitoring protocols are the core design activity. A modified Delphi approach worked well to identify what design studies were needed (Linstone and Turoff 1975). A group of experts on the California Channel Islands shared their individual conceptual models of the park with each other in a workshop and agreed on a generic model. They then used that knowledge to select ecosystem components to monitor, such as sea birds, kelp forest, or terrestrial vegetation, and to decide what parameters could be used as ecological vital signs.

Sub-groups of experts then discussed specific parameters and appropriate spatial and temporal scales for monitoring. For example, to meet GEM goals, plant ecologists decided that island plants needed to be sampled at three spatial scales: individual species' populations, communities, and landscapes, and at respectively increasing time scales of one to five years. It is important to recognize that the GEM design process is an iterative one, and to recognize the limitations of current ecological expertise that approximate a 17th century level of medical knowledge. Consequently, one should acknowledge that the GEM design goal is not to find a final solution in the beginning, but rather to identify a reasonable starting point.

The list of 14 initial design studies (Table 2) identified for the Channel islands National Park GEM program constitutes the skeleton of the collective conceptual model of the park (Davis 1989). Design studies, that each lasted 3-5 years, were conducted for each component and addressed the same five tasks: 1) select index species or factors for this component, 2) develop sampling techniques, 3) test analytical protocols, 4) develop report formats and content, and 5) demonstrate the efficacy of the recommended monitoring protocol by field testing all aspects of the protocol for at least two years.

Selecting species, or other taxa, and the parameters to be measured for each was the first order of business for each design study. This process involved applying six selection criteria to existing inventories (Table 3). Where existing inventories were inadequate to offer selections, field surveys were conducted. Field surveys were needed for terrestrial invertebrates, amphibians, and reptiles. Inventories of the other components were considered adequate by the experts at the design workshop. The purpose of the criteria was to assure selection of a representative sample of all species in each component i.e., to 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 step was to assure that common and dominant species that characterized communities and provided physical structure were represented. The monitoring program also had to include all endemic, exploited, and alien species as well as all taxa with special legal status, e.g., endangered 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 that included distribution maps, e.g. kelp forests (Figure 1). Where do the species, or other elements, of the component occur? When does reproduction occur (Figure 2)? 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. Biogeographically, kelp forest assemblages of algae, invertebrates, and fishes in the cold, nutrient-rich waters of the western islands in the Oregonian zone (that stretches from the park to Alaska) are quite distinct from those in the warm waters around the southeastern islands in the Californian zone (that extends southward from the park to the middle of Baja California in Mexico) and from those in the transition zone between these two extremes. Physically, 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. Fishing has a major influence on kelp forest structure and function, 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, fixed ecological monitoring sites need to be identified so that changes in parameters reflect changes over time and not within-site variation. Therefore, 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. Resolution of these matters is the main function of 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[2]. These guidelines need to be made explicit by the people who will use the information. These parameters also become important criteria for periodic evaluations of the program.

A variety of sampling techniques is required for each biological component selected for monitoring. More than 1,000 species of plants and animals inhabit kelp forests in the park. The Delphi work group selected 63 taxa to monitor at the 16 sites to examine the biological responses to global climate events, such as El Niño, and to differentiate the effects of regional pollution from those of fishing.. Abundant, ubiquitous, discrete species (non-colonial) such as sea urchins and giant kelp are relatively easy to count and measure in small quadrats placed in a stratified random fashion around a fixed 100-m long transect line. The design study resolved the minimum number of quadrats needed (20) and how large each needed to be (1-5 m^2) to reduce within-site variation and achieve the established statistical goal (to detect 40% changes in mean values) at all sites. Rarer species that tend to clump, such as abalone and lobster, required larger plot sizes to resolve the same degree of change in abundance. A different sampling strategy based on band-transects (12, 3 m X 20 m) was designed for that purpose.

Another function of design studies is to develop and adapt new technologies to provide the most accurate, precise. and cost-effective techniques. Since colonial species, such as anemones, bryozoans, and algae that literally carpet the bottom cannot be counted easily, 1,000 randomly selected points in 50 plots were used 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. SCUBA was the standard equipment used by scientists to access kelp forests, but it required extensive, slow and tedious record keeping underwater by chilled divers to record up to 15,000 observations of bottom cover at each site. Using equipment commonly used in commercial diving that provided air and communications to and from the surface allowed us to shift record keeping activities to warm, dry data recorders at the surface who, by simply recording observations dictated to them by biologist-divers, increased the speed and accuracy of the sampling. Recording bottom cover and abundance of colonial taxa required an average of seven hours at each site using SCUBA. Having divers dictate the observations to a person recording on a ship at the sea surface reduced the average sampling time to 90 minutes. Because the surface recorders were unaffected by nitrogen narcosis that plagues divers, data quality was also measurably improved.

Design studies also need to invent new techniques and to test old, standard ones. Fish are difficult to sample because they are mobile, patchy, and sensitive to observer presence. 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 and using the resulting monitoring data to evaluate the techniques.

Implement Monitoring

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 by an external review panel of statisticians and kelp forest ecologists in 1995. The review panel affirmed the original design criteria and made a few minor suggestions to improve compatibility with other kelp forest studies (Davis et al. 1996a). The statisticians on the panel asserted that a prime directive for such programs was to maintain the continuity of the data collection and make only minor changes with ample dual sampling to allow comparisons between original techniques and new 'improved' techniques to assure that calibration and correlation are valid.

[2] 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.

Using Monitoring Information to Solve Environmental Problems

We designed the Channel Islands National Park Ecological Monitoring Program to identify 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 approximately 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. Change in staff is inevitable in any long-term program, and should be encouraged in order to keep people excited about their work and growing both professionally and personally. This turnover in staff presents some special problems for maintaining continuity in data collection, archiving, analysis, and reporting because it is difficult to record every significant detail of such a complex endeavor. With at least three people on each work group, there is usually one or more experienced person available to train new staff and improve to the operation. We found it difficult to maintain institutional continuity in field operations and data management with fewer than three people in a work group.

Information Management

Information is the primary product of an ecological monitoring program. How it is managed (communicated, archived, and made available) 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 fiscal and human resources are spent on storing, communicating, and making available the information collected and produced by the GEM program (Dye in press). The usual, more theoretical, estimates that information management should consume only 10-15 % of the resources of an ecological monitoring program seriously underestimate the effort required in practice (Royal Society of Canada 1995).

Other practical information management lessons learned during development of the Channel Islands GEM program include: 1) using standard, commercially available, software, i.e., avoid custom programs; 2) specifying common fields for all records that relate all databases, e.g., date and location; and 3) planning for and embracing change. Not only are the natural systems dynamic that we seek to understand through monitoring, 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, as we evolved from Apple II microcomputers to Windows-95 and UNIX environments. To describe long-term trends in ecosystem vital signs and to determine normal variation in vital sign parameters, data collected at the beginning of the program must be compatible and comparable with the data collected and stored during the middle and the end of the program. This means that every time a computer operating system changes or the data base software changes, the entire data-base must be converted to the new system. While these changes may be inevitable, the program can be designed to maintain the continuity and compatibility of the information.

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, and document changes in monitoring protocols. The annual reports are also emotionally important for the monitoring staff and provide opportunities to market the program and its accomplishments within the funding agencies, academia, and the general public. Along with annual reports, formal peer-reviews of protocols, operations, and results at 10-year intervals helps to assure program vitality and relevance. During protocol reviews, we re-examine 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. Outbreaks of fatal new diseases, such as withering syndrome in black abalone, *Haliotis cracherodii*, were previously unknown, in part because no rigorous ecological monitoring took place before the GEM program (Richards and Davis 1993). The GEM program revealed not only that black abalone abundance collapsed in the park, but also provided a regional geographic and multi-year temporal description of the spread of excessive mortality (Richards and Davis 1993). Monitoring characterized the size structure of the surviving abalone population, which exonerated fishing as a proximal cause of the population collapse, and it also defined a density at which adult abalone populations ceased to reproduce (50%). These quantitative descriptions directed subsequent research to examine potential infectious agents, rather than toxic pollutants or poaching and other human activities, and led to the discovery of a new species of pathogen (Friedman et al. 1995).

The sustained time-series data at landscape scales that GEM programs can produce permit 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). Separating the effects of El Niño events, pollution, and fishing on coastal ecosystems so that meaningful political actions can be taken to avoid irreversible resource damage and unnecessary constraints on economic development and exploitation of fishery resources requires regional (100s km) analysis over several decades. Monitoring data-sets also allow exploration of new analytical methodologies.

It is essential that monitoring practitioners publish both positive results and negative efforts. It is important to document both techniques and designs that worked and those that did not, in peer-reviewed literature and in topical symposia so others don't have make the same mistakes again. Ecological monitoring is no longer simply a compliance-mandated 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. We need to produce models of excellence to create and sustain effective GEM programs.

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 invasive alien species, to detect and mitigate pollution, to recognize unsustainable uses, to change fishery management policies, and to develop and evaluate population and ecosystem restoration methodologies. A few specific examples are described below.

As indicated above in the conceptual model of the park, alien species constitute an ever increasing threat to the park. 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. Before instituting monitoring programs, eradication efforts were sporadic and ineffective. Numerous efforts were made to remove feral rabbits from Santa Barbara Island in the 1950s and 1960s by hunting and spreading poison bait on the island (Sumner, 1959) but none was successful until the GEM program provided specific information about the effectiveness of various population control methods (trapping vs. hunting), rabbit population trends, and reliable cost and time estimates for complete eradication. By reducing the uncertainly of success through monitoring, the eradication program gained enough support to sustain the effort long enough to succeed.

Even before the GEM program began, monitoring wildlife populations in the park provided an early warning of regional pollution with global consequences. Monitoring reproduction and recruitment in California brown pelican rookeries on Anacapa Island identified pesticide (DDT) pollution in the Southern California Bight, and provided sufficient time to ban DDT and restore pelican productivity (Anderson and Gress 1983). Today the park's GEM program indicates clearly that DDT is still a problem in coastal ecosystems as evidenced in continuing reproductive difficulties experienced by peregrine falcons and bald eagles (Detrich and Garcelon 1986). The GEM program also indicates that progress is being made which thereby encourages people (society) to continue abatement activities.

GEM programs also help to decide when human intervention in park ecosystem dynamics is appropriate, such as when to suppress forest fires or let them burn.

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 monitored tide pools over a two month period, many people were rightfully concerned about marine life in the tide pools and adjacent kelp forests (Tegner et al. 1995). Objective information from pre-spill monitoring established clearly that the effluent had no immediate negative effect on the 15 vital sign taxa monitored. 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, which was reflected by increased abundance in most vital sign taxa.

The GEM program in this case saved unnecessary expensive litigation that often occurs without actual knowledge and with a belief that damage is self-evident in such situations. The two month closure associated with the effluent spill constituted a large environmental experiment unlikely to be conducted intentionally. Since the GEM program was in place, it was possible to measure the effects of the event and separate the longer term trends in populations associated with regional environmental events, such as El Niño. For example, the chronic loss of California mussels, *Mytilus californicus*, and feather boa kelp, *Egregia menzesii*, recorded for three years before the effluent spill continued at the same rate during and after the spill, while ground cover of ephemeral algae and sea grass, *Phyllospadix* sp., increased dramatically (Engle and Davis in press).

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 (Botsford et al. 1997). 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, fishing exhausted abalone populations before fishery management policies could be changed, and drove at least one species to the verge of extinction (Davis et al. 1996b).

Political systems are frequently frozen into inaction by uncertainty (Wurman 1990). Reliable fishery independent data from GEM allowed the political process to work by reducing uncertainty regarding abalone population status. The California Fish and Game Commission and State Legislature closed five abalone fisheries to prevent loss of critical brood stock and to facilitate and reduce the costs of rebuilding depleted populations statewide only after GEM data confirmed imminent abalone population collapses (Figure 3), implied by declining fishery landings but contested by fishing interests.

GEM methodologies are currently being used to test a variety of different abalone population 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, dense but fragmented, populations. Monitoring provided sufficient information, early enough, to protect disease-resistant individuals from fishery harvest and to ensure survival of another generation.

The Channel Islands National Park GEM program has become a prototype for many other national parks and other agencies, and catalyzed a national GEM program for the U. S. National Park System. The step-down planning process described here has been used successfully in a wide variety of ecological settings with many Delphi-experts, including deserts (Organ Pipe Cactus National Park and Lake Mead National Recreation Area), mountains (Great Basin, Lassen Volcanic and North Cascades National Parks), and the New England coast (Acadia National Park). Other parks emulating the Channel Islands model include Virgin Islands (USVI), Dry Tortugas (FL), Denali (AK), Great Smokey Mountains (TN-NC), Shenendoah (VA), Olympic (WA), a cluster of small prairie parks in the mid-west, and a cluster of parks on the Colorado Plateau. Based on the experience gained in prototype park programs, the National Park Service plans to implement GEM programs in all 250 national park system areas with significant natural resources. Only with the information acquired by GEM programs can national parks be adequately understood, restored, maintained, and protected so that current and future generations can enjoy their wonders, receive their inspiration, and reap the values of their unimpaired ecosystems.

References Cited

Anderson, D. W. and F. Gress. 1983. Status of a northern population of California brown pelicans. Condor 85(1): 79-88.

Baskin, Yvonne. 1997. Center seeks synthesis to make ecology more useful. *Science* 275: 310-311.

Botsford L. W., J. C. Castilla and C. H. Peterson. 1997. The management of fisheries and marine ecosystems. Science 277: 509-515.

Davis, G. E. 1988. Kelp forest monitoring handbook , Channel Islands National Park, California. National Park Service, Ventura, CA. pp. 34.

Davis, G. E. 1989. Design of a long-term ecological monitoring program for Channel Islands National Park, California. Natural Areas Journal 9: 80-89.

Davis, G. E. 1993. Design elements of environmental monitoring programs: the necessary ingredients for success. Environmental Monitoring and Assessment 26: 99-105.

Davis, G. E. 1995. Recruitment of juvenile abalone (*Haliotis* spp.) measured in artificial habitats. Marine Freshwater Research. 46: 549-554.

Davis, G. E. and C. Nielsen. 1988. Visitor monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA 5pp.

Davis, G. E. and P. L. Haaker. 1995. A strategy for restoration of white abalone, *Haliotis sorenseni*. Journal of Shellfish Research 14: 263. [abstract].

Davis, G. E., P. L. Haaker, and D. V. Richards. 1996. Status and trends of white abalone at the California Channel Islands. Transactions of the American Fisheries Society. 125: 42-48.

Davis, G. E. and W. L. Halvorson. 1988. Inventory and monitoring of natural resources of Channel Islands National Park, California. National Park Service, Ventura, CA. pp 31.

Davis, G. E. and T. W. Anderson. 1989. Population estimates of four kelp forest fishes and an evaluation of three *in situ* assessment techniques. Bulletin of Marine Science 44: 78-88.

Davis, G. E., D. V. Richards and D. Kushner. 1996. Kelp forest monitoring design review. National Park Service, Channel Islands National Park Technical Report 96-01. Ventura, CA. 13 pp.

Davis, G. E. K. R. Faulkner, and W. L. Halvorson. 1994. Ecological monitoring in Channel Islands National Park, California. p. 465-482. *In*: The Fourth California Islands Symposium: Update on the Status of Resources W.L. Halvorson and G. J. Maender, Eds. Santa Barbara Museum of Natural History, Santa Barbara, CA.

DeMaster, D. P., R. L. DeLong, B. S. Stewart, P. K. Yochem. 1984. A guide to censusing pinnipeds in the Channel Islands National Marine Sanctuary and Channel Islands National Park. National Marine Fisheries Service Southwest Fisheries Center, La Jolla, CA. Administrative Report LJ-84-44.

Detrich, P. J. and D. K. Garcelon. 1986. Criteria and habitat evaluation for bald eagle reintroduction in coastal California. Final Report to California Department of Fish and Game C-1307. Sacramento, 32 p.

Dugan, J. E., D. M. Hubbard, and G. E. Davis. 1990. Sand beach and coastal lagoon monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA. 33 pp.

Dugan, J. E. and G. E. Davis. 1993. Application of marine refugia to coastal fisheries management. Canadian Journal of Fisheries and Aquatic Sciences 50: 2029-2042.

Dye, L. in press. Data management plan for Channel Islands National Park, California. National Park Service Technical Report 97-xx, Ventura, CA.

Halvorson, W. H. and G. E. Davis. [eds.] 1996. Science and Ecosystem Management in the National Parks. Univ. Arizona Press. 384 p.

Engle, J. M. and G. E. Davis. In press. Ecological condition and public use of the Cabrillo National Monument intertidal zone 1990-1995. U. S. Geological Survey, Biological Resources Division, California Science Center Technical Report, Davis, CA. 183 p.

Fellers, G. M. and C. A. Drost. 1988a. Terrestrial invertebrate monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA.

Fellers, G. M. and C. A. Drost. 1988b. Reptile and amphibian monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA.

Fellers, G. M., C. A. Drost and B. W. Arnold. 1988. Terrestrial vertebrates monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA. 17 pp.

Forcucci, D. and G. E. Davis. 1988. Fishery harvest monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA. 8 pp.

Friedman, C. S., G. R. Gardner, R. P. Hedrick, M. Stephenson, R. J. Cawthorn, and S. J. Upton.

1995. *Pseudoklossia haliotis* sp. n. (Apicomplexa) from the kidney of California abalone, *Haliotis* spp. (Mollusca). Journal of Invertebrate Pathology. 66: 33-38.

Halvorson, W. L. and L. Doyle. 1988. Weather monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA. 20 pp.

Halvorson, W. L., S. D. Veirs, Jr., R. A. Clark, and D. D. Borgias. 1988. Terrestrial vegetation monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA. 11 pp.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson. 1977. *Biogeochemistry of a Forested Ecosystem*. Springer-Verlag, New York.

Linstone, H. A. and M. Turoff. 1975. The Delphi Method. Addison-Wesley, Reading, Massachusetts. 620 pp.

Odum, H. T. and E. C. Odum. 1981. *Energy Basis for Man and Nature*. 2nd. ed. McGraw-Hill, New York.

Odum, E. P. 1989. *Ecology and Our Endangered Life-support Systems*. Sinauer Associates, Inc., Sunderland, Mass. 283 pp..

Phenicie, C. K. and J. R. Lyons. 1973. Tactical planning in fish and wildlife management and research. U. S. Department of the Interior Fish and Wildlife Service. Resource Publication 123. Washington, D. C. 19 p.

Richards, D. V. and G. E. Davis. 1993. Early warnings of modern population collapse of black abalone, *Haliotis cracherodii* Leach 1814, on the California Channel Islands. Journal of Shellfish Research 12(2): 189-194.

Royal Society of Canada. 1995. Looking ahead: long-term ecological research and monitoring in Canada. Technical Report No. 95-1.

Sagan, C. 1996. The demon-haunted world, science as a candle in the dark. Ballantine Books, New York. 457 p.

Soulé, M. E. [ed.] 1986. *Conservation Biology the Science of Scarcity and Diversity*. Sinauer Associates, Inc., Sunderland, Mass. pp. 584.

State of California. 1995. Pink, green, and white abalone fishery closure draft environmental document. The Resources Agency, Department of Fish and Game. np.

Sumner, L. 1959 The battle for Santa Barbara! Outdoor California 20(2): 4-7.

Tegner, M. J., P. K. Dayton, P. B. Edwards, K. L. Riser, D. B. Chadwick, T. A. Dean, and L. Deysher. 1995. Effects of a large sewage spill on a kelp forest community: catastrophe or disturbance? Marine Environmental Research 40(2): 181-224.

Van Riper, C., III., M. K. Sogge, and C. Drost. 1988. Land bird monitoring handbook, Channel Islands National Park, California. National Park Service, Ventura, CA. 23 pp.

Wilson, E. O. 1988. *Biodiversity*. National Academy Press, Washington, D. C.

Table 1. Conservation designations of the California Channel Islands in and adjacent to Channel Islands National Park.

International Biosphere Reserve (designates special recognition for conservation and education)
National Marine Sanctuary (protects seabed and air space)
National Oil and Gas Sanctuary (prohibits petroleum exploration and exploitation)
National Park (preserves island and marine ecosystems)
State Ecological Reserve (regulates fishing)

- San Miguel Island Ecological Reserve
- Anacapa Island Ecological Reserve
- Santa Barbara Island Ecological Reserve

State Area of Special Biological Significance (ASBS) (regulates water quality)

- Santa Rosa Island ASBS
- Santa Cruz Island ASBS

State Area of Environmental Concern (regulates land use)
University of California Santa Cruz Island Nature Reserve (identifies research site)
The Nature Conservancy Santa Cruz Island Project (preserves island ecosystems)

Table 2. Design studies conducted for the Channel Islands National Park General Ecological Monitoring program (GEM), in priority order as determined by the procedure described in section 2.2 of the step-down plan.

Ecosystem Component	Monitoring Protocol Reference	Principal Investigator's Affiliation
Pinnipeds	DeMaster, et al. 1984	National Marine Fisheries Service
Information Management	Dye in press	Private Consultant
Tide Pools	Richards and Davis 1993	Private Consultant
Sea Birds	Hunt and Anderson 1988	University of California
Kelp Forests	Davis 1988	National Park Service with California Department of Fish & Game
Land Birds	Van Riper et al. 1988	National Park Service
Island Plants & Vegetation	Halvorson et al. 1988	National Park Service
Island Invertebrates	Fellers and Drost 1988a	National Park Service
Island Reptiles & Amphibians	Fellers and Drost 1988b	National Park Service
Island Mammals	Fellers et al. 1988	National Park Service
Park Visitors	Davis and Nielsen 1988	National Park Service
Fisheries	Forcucci and Davis 1988	National Park Service
Weather	Halvorson and Doyle 1988	National Park Service
Beaches and Lagoons	Dugan et al. 1990	University of California

Table 3. Criteria used to select species, or other taxa, as vital signs for General Ecological Monitoring in Channel Islands, National Park, California, and assure selection of a representative sample of all species and taxa in park ecosystems.

1. Common species that dominate community structure
2. Legal status, e.g., designated endangered species
3. Park or island endemic species
4. Exploited species
5. Alien species (non-native)
6. Heroic, charismatic species with current human constituencies

List of figures