vital to sustainable management of these systems. Explicit connectivity information is needed for management planning.

Application of connectivity measurements in environmental management

If relationships with management agency personnel are managed effectively, the need to measure connectivity as a normal part of management planning will be well established in those regions where the program is based. Over time, conversations among managers are much more likely to establish that connectivity data are essential than will conversations among academic scientists, or speeches by these to managers! A major goal of the program must be to articulate the need, develop the tools and ensure the tools are in the managers' hands. The effectiveness of the collaborations built among academic scientists, students, managers, and members of regional NGOs can be best measured by how well we establish that this need is real.

Promotion of learning and capacity building

Graduate education for students from the region

The connectivity program is designed to provide opportunities for participation of graduate students from each region where demonstration projects are undertaken. Students will normally be enrolled at institutions within the region, but with scientists from outside the region serving on their advisory committees as appropriate, and with opportunities for short-term secondments to institutions outside the region as appropriate to use advanced instrumentation or learn novel techniques.

Participating students will receive an outstanding educational opportunity by being directly involved in a large-scale, international, multi-disciplinary project of very direct relevance to coastal marine management in their home countries. The direct participation of scientists from outside the region in their educational programs, and the working collaborations between faculty from within and from outside each region should also enhance the educational benefits from the project.

Academic scientists from within the regions who participate in the project also stand to receive equipment and technologies that will enhance the capabilities of their laboratories. Their collaborations with scientists from outside the region will open up new possibilities for future collaborative work using the instrumentation in distant labs to undertake important research in their home countries.

Collaborations with NGOs and management agencies

Within each region, execution of the connectivity program depends upon building sustained collaborations with personnel from management agencies and NGOs as a way of securing the participation necessary for broadly distributed field monitoring and sampling activities. In addition, the placement of sampling and experimental sites will be done in consultation with management agency personnel to maximize the possible benefits of the work for current management activities. Workshops planned in region will directly engage management agency and NGO personnel. Efforts also will be made to build links to other large projects in place in each region (such as the MBRS project in Mesoamerica, which includes development of a Synoptic Monitoring Program at a number of sites throughout the region, and development of a regional-scale hydrodynamic model).

In this way, the design and implementation of the program requires establishment of effective collaborations that will also be needed if results are to be effectively transferred to the management community where they are needed. We enhance what may be possible to achieve within the connectivity program (by sharing logistics), while building the network of trust and collaboration that will facilitate the effective sharing of information, and the raising of overall capacity within the management sector.

Communication of results

Many of the results anticipated mark fundamental advances in marine ecology, and will be reported in the international peer-reviewed journals and major symposia such as the quadrennial International Coral Reef Symposia. In addition, however, it will be important to report results by way of websites, public information documents, media releases, and workshops for management agency and NGO personnel as well as interested members of the public. The Targeted Research project will not have succeeded if the results are only reported within the scientific community

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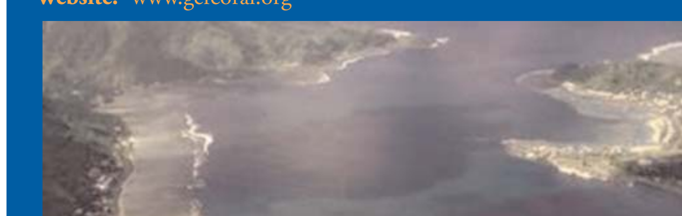

This project is part of a major initiative of the World Bank, with support of the Global Environmental Facility, to provide the best available scientific information on coral reef response to environmental disturbances and climate change. The "Coral Reef Targeted Research and Capacity Building for Management" project aims to conduct specific, targeted research to fill critically important information gaps in the fundamental understanding of coral reef ecosystems so that management and policy interventions can be strengthened globally.

Connectivity

- Bleaching
- **Connectivity**
- Disease
- Modeling
- Remote Sensing
- Restoration

Definitions

Connectivity is the flux of items between geographic locations, whether these be adjacent coral reefs, subtidal seagrass meadows, mangrove-fringed shorelines, coastal estuaries, or any other environments in the coastal marine ecosystem. Items may be sediments, nutrients, pollutants, or individual living organisms. ***Demographic connectivity*** refers more precisely to the movement of living organisms between nearby, or more distant, local populations, whether these be juveniles and adults, or, as is far more usual, pelagic eggs and larval stages. The overwhelming majority of coral reef organisms possess pelagic eggs and/or larvae, and for many the larval life lasts several weeks and the larvae are behaviorally capable, competent pelagic organisms. While connectivity of nutrients or pollutants is accomplished by purely physical (hydrodynamic) means and concerns only the transfer between locations, demographic connectivity requires that individuals not only disperse between populations, but become participating members of the populations they join, growing, surviving, and reproducing. The transfer of organisms is driven by potentially complex biophysical processes combining hydrodynamics and the behavioral responses of the organisms to the water mass in which they travel.

Statement of the problem

At present there exists very little information on demographic connectivity for any coral reef organism, yet these data are crucially important if we are to improve our ability to design and implement networks of marine protected areas (MPAs) and other spatially explicit management systems. The complexity of the tasks required to measure demographic connectivity with any precision have prevented rapid progress in building scientific understanding in this area. Hydrodynamics alone are complex and temporally variable when water driven by tidal, wind and other forces interacts with the complex topography typical of coral reefs. Larval stages, the primary dispersal agents, are tiny, released at specific times and places into the water stream, and they develop increasingly complex behavioral and sensory capabilities as they mature. The great majority of the longer-lived fish and crustacean larvae die before completing larval life, and are still small creatures when they settle and recruit to coastal populations. Observing them during larval life, tracking them, tagging them, and often, just finding and collecting them at the end of larval life are all technically very difficult, or currently impossible, tasks.

Description of the Connectivity program

The primary goal of the Connectivity program during the first 5-year phase of the Targeted Research project is to undertake demonstration projects that will make empirical measurements of connectivity for key taxa at specific locations. In doing this, it will be necessary to develop new methods for modeling local-scale hydrodynamics, and for marking and matching newly settled recruits to source populations. These new techniques will become the tools that permit additional measurements of demographic connectivity in other places and using other taxa. Three different, multidisciplinary approaches will govern the majority of components. These take advantage of particular characteristics of coral reef fauna to design experiments or monitoring regimes that will yield powerful new data. These approaches are being termed "flux" experiments, "pulse" experiments, and recruitment monitoring. We will focus on taxa that are experimentally amenable, but where possible will choose species of economic importance, or species that are important in structuring the reef community. Work will focus on selected fish, corals, and lobster, and will be initiated first in the Mesoamerican Barrier Reef Region of the western Caribbean. Subsequent work, commencing in about Year Three, will take place in the Philippines and Palau.

Some reef species characteristically aggregate to spawn at precise times and locations. Many corals closely synchronize their spawning in precisely timed so-called mass spawning events. In both cases, very large numbers of larvae are released at precise times and places. The Connectivity program will use these reliably timed "fluxes" of larvae in two experiments—one focused on grouper and snapper species, and the other using a relatively isolated patch of spawning corals—to attempt to track organisms through larval life from natal location to ultimate settlement site. In the first "flux" experiment a spawning aggregation of Nassau grouper (*Epinephelus striatus*) will be tackled in a large-scale, multidisciplinary effort involving chemical and genetic tagging of larvae, hydrodynamic modeling, tracking of water masses, sampling of the developing larvae as they disperse, and recovery of settled juveniles following completion of larval life. This high-profile experiment will develop essential new technologies for tagging and tracking fish larvae, and will provide direct information on patterns of connectivity for one aggregation of this threatened, yet commercially valuable, species of reef fish. The coral "flux" experiment will be smaller in scope only because corals have less lengthy larval lives. It will develop novel technologies for tracking water masses, and new genetic methods for identifying coral larvae, while defining the pattern of dispersal of larvae of one species (likely a Montastrea species) in a specific location. Subsequent "flux" experiments are planned for Palau and perhaps for the Philippines.

Most reef species do not aggregate to spawn, and spawn several times through the year, however, many of these synchronize spawning to lunar phases, so that cohorts of larvae are reliably produced at particular lunar phases over relatively large geographic areas. The Connectivity program includes a "pulse" experiment that takes advantage of the reliable (pulsed) production of fish larvae, by coordinating a synchronous collection of newly settled larvae (of a specific cohort) at sites scattered across a broad geographic region. Patterns in the trace element chemistry of fish otoliths (which tracks local water chemistry), and in genetics, revealed by such a geographically widespread set of collections of fish should be able to be used to reveal patterns of connectivity due to dispersal of larvae from their natal sites. The first "pulse" experiment will use the Bicolor damselfish (Stegastes partitus), a very abundant, conspicuous, and easily collected species of reef fish in Mesoamerica. Subsequent "Pulse" experiments will use other typical reef fish species in Mesoamerica and in the Philippines. "Pulse" experiments will directly engage management agency personnel in the collection of specimens so that they become members of the research team, while gaining valuable information on patterns of demographic connectivity in their immediate region.

Many reef species, regardless of their mode of reproduction, can be found as new recruits once they settle to demersal or sessile populations following the end of larval life. Such "recruitment" can be monitored by routine field surveys, and recruitment data provide valuable information on the dynamics of the local population. In addition, because recruitment at any one location results from the dispersal of larvae to that site from many natal locations, the geographic and temporal pattern of recruitment of a species in a region is the outcome of the patterns of connectivity among all populations in that region.

The Connectivity program includes projects that will build a monitoring database of recruitment in selected fish, corals and spiny lobster (*Panulirus argus*) in Mesoamerica. Comparable databases are planned subsequently for the Philippines. At each region, it will provide a valuable and unique record, on a regional scale for population dynamics of the targeted species, and in this way can become a valuable new resource for management agencies. The primary research goal in building this database, however, is to use it to test advanced bio-physical models of dispersal of typical reef species. Recruitment records are a direct result of the dynamics of larval dispersal and are perhaps the only empirically available data that could be used to test regional-scale models of dispersal dynamics. Separate components of the Connectivity program will develop new data on larval duration and behavior in corals, fish and lobster, and use these and regional-scale hydrodynamic data in developing dispersal models for selected species, to test against the recruitment database. Again, management agency personnel will be direct participants in collecting the recruitment data, will learn how to use these data for local assessment of population dynamics, and how recruitment and connectivity are closely linked. Related studies on corals will focus on the difficult transition through multiple bottlenecks between time of settlement and ultimate recruitment to adult populations, and will take advantage of the very long lives of corals to use genetic evaluations among corals of differing age to assess how connectivity patterns in a region have changed through time.

Justification for the Connectivity program

Why connectivity data are crucial for MPA design and implementation

The use of MPAs, and particularly the use of no-take fishery reserves, presupposes connectivity. Either MPAs are established at a size believed large enough to encompass all phases of the life cycle of species being conserved, or they are established at a size, and in a spatial arrangement with respect to un-protected sites, that will foster enhanced recruitment of target species to these surrounding sites due to dispersal beyond MPA boundaries. At present, MPA design and implementation use "educated guesses" to decide appropriate spatial scales and patterns of placement, and there is little information to determine whether these guesses are even approximately correct. As levels of direct exploitation of reef resources rise, and as other pressures on reefs due to expansion of coastal populations, and increased use of coastal environments increase, it becomes increasingly important that the establishment of spatially explicit management is done at correct spatial scales – ones compatible with known patterns of connectivity of target populations.

Decisions guiding the implementation of spatially explicit management actions, such as the establishment of MPAs, are currently made without any quantitative data on connectivity of target species, although the fundamental importance of such data is broadly recognized. If one or more of our demonstration projects is capable of yielding quantitative data on connectivity, the consequences for management decision-support are substantial. There will be an explicit description of connectivity for one or more target species at a particular location that could be used immediately in management decisions there. The particular results help sharpen the "best guesses" being used in making management decisions on other species and in other locations. The method can be implemented as a tool for guiding management decisions on other species and in other locations in future.

Because several components of the Connectivity program require field work on relatively large geographic scales, the sampling programs will be planned with respect to existing (or planned) sets of protected areas of various types. As well as developing new techniques, and deriving precise estimates of connectivity for particular species, this program will produce results that can be used directly to assess the efficacy of existing or planned management using MPAs. Further, because management agency personnel will be directly involved in aspects of the program, they will have full access to the data, and interpretations, and will be able to relate these to the management of areas with which they are directly concerned.

Major benefit of the program: development of new technologies

The major benefit for management arising from the connectivity program will be the new technologies that will be developed for quantifying connectivity relationships. Each method shown to be successful can be adopted for use on other species and in other sites. As further studies are done, the combined results will become a valuable database describing the variability in connectivity patterns, and relating this variability to aspects of biology, geography, and hydrodynamics. Such a database makes it possible to undertake management planning without always having explicit data from that site and target species available. Further, since nearly all MPAs are targeted at multiple species, this accumulating database will help managers develop explicit envelopes containing connectivity values for the various species of interest in each location.

The connectivity program will be carried out in close collaboration with management agency and NGO personnel, as well as with academic scientists from each region. Thus, managers will become well acquainted with the various techniques being developed, with the science requirements to permit their use, and with a cadre of professionals who will be available to assist in guiding future application of the methods. With one exception, all methodologies being considered can be undertaken with minimal upgrading of skills or equipment over that available in the better institutions in each region where work is planned. The one exception is the instrumentation needed for trace element chemical analysis of otoliths, because of instrument costs, and operating expenses. Operating expenses will fall in future years, and shipping costs to get specimens to established laboratories will be trivial. Thus our goal must be to ensure that lasting relationships are built that will link scientists in coral reef regions with personnel at laboratories elsewhere that are equipped for these advanced analyses.

Local application of results from demonstration projects

The regions where our demonstration projects will be done all possess MPAs. In most cases, plans are also in place to create additional MPAs. Thus the demonstration projects are being undertaken in places with a management imprint already in place. The detailed planning of each project will recognize and use this imprint. While it may not be possible to implement comprehensive adaptive management approaches, it will be possible, at minimum, to locate sampling sites to complement existing management boundaries. For example, the planned monitoring of recruitment in Mesoamerica will be done at sites will be chosen within and outside MPAs, and, where possible, will be co-located with sites used in the Synoptic Monitoring Program being implemented by the MBRS project. In this way, our data on recruitment patterns can be related directly to on-going monitoring programs, and can yield direct information on any difference in rates of recruitment inside and outside protected areas.

While we emphasize MPA design and implementation as a management action that should require connectivity data, we note that many fishery populations that straddle international borders are managed by the individual nations as if they were independent stocks. New information on the extent of connectivity in such "straddling stocks" will be of very direct value in improving the international integration of management policies. The spatial scale of some of the demonstration projects is such that the extent of international connectivity in certain species, such as Spiny lobster, will be documented.

The important requirement to ensure results are integrated into local management will be to ensure that detailed planning for fieldwork for all phases of the connectivity program is done in consultation with management agency personnel. In this way it should be possible to maximize the immediate benefit for management that can be gained from the project. Early workshops to introduce the project to management agency and NGO personnel are an important requirement.

Other forms of connectivity deserve attention also

Focus in this project is on demographic connectivity, however that will require the use of regional scale hydrodynamic models, their improvement, and the addition of finer-scale models to describe hydrodynamics close to reefs and coastlines. This suite of models can be used to predict connectivity relationships for non-living items such as nutrients, pollutants, and terrestrial run-off. It will be important in workshops, in public information sessions, and in other promulgation of results that the need to understand these other forms of connectivity is not forgotten. Indeed, provision needs to be made in later phases of the project for explicit investigation of some of these other forms of connectivity, probably in the locations that have been the sites of earlier demonstration projects.

One risk inherent in the general enthusiasm for establishing MPAs is that it becomes possible to forget that human impacts at some distance are not controlled at all by enforcing regulations within an MPA. A protected site remains as vulnerable to downstream pollution as it was before protection was put in place. Indeed, in many coastal locations, anthropogenic impacts on coral reefs, due to terrestrial activities (agriculture, forestry, mining, industry, and coastal urbanization) well upstream from the reef, can be as significant as over-fishing or other direct impacts on the reef itself. The understanding of physical dispersal processes that the connectivity program will build will be of great importance in extending our ability to evaluate and to mitigate such indirect human impacts on reef systems.

Policy implications

Demographic connectivity is important, and can be measured explicitly

The connectivity program must demonstrate that the explicit measurement of demographic connectivity is both an important objective, and one that can be tackled in coral reef regions. An important goal for workshops in the program will be to ensure that its importance is widely appreciated by managers in the context of management. We are not dealing with a subject of arcane academic interest, but with one