Working Group on Coral Reef Restoration and Remediation

Bleaching

Connectivity

Disease

Modeling

Remote Sensing

Restoration

Worldwide degradation of coral reefs, particularly in the last two decades, has prompted greater attention to the prospects of remediation and restoration activities. This has resulted in a wide range of initiatives broadly classified as improving the existing condition of impacted coral reefs (mainly those damaged through anthropogenic influence). Early initiatives focused more on artificial reefs where, reefs or more accurately, fish-aggregating devices, are created on non-reef platforms, mainly to enhance fisheries production. While this approach is still being expanded, more recent activities are directed specifically at restoring degraded reefs.

The diversity and scale of remediation/restoration activities vary tremendously. They cover habitat modification, coral transplantation, species re-introduction, and recruitment potential enhancement. Some of these interventions involve large-scale sub-tidal structures designed to facilitate natural colonization of reef-related species, while others use simpler and less costly approaches that local communities in developing countries can more readily replicate. Reef remediation and restoration efforts are likely to expand. However, viable approaches and technologies are in relatively early stages of development, and in most cases are currently difficult to implement on large spatial scales. Approaches to restoration are still largely based on personal experiences and there are important gaps in our scientific understanding of the complex processes of natural recovery that underpin restoration.

Reef remediation/restoration should not replace reef protection as the first management option. However, large areas of degraded reefs make it unavoidable to ignore remediation and restoration action. The loss of biological and economic services from degraded reefs emphasizes the need for maintaining the ecosystem, and where degraded, to restore its functions and services as far as is feasible. The benefits of reefs commonly include: 1) habitat for many organisms, 2) biodiversity preservation, 3) commercial and recreational fisheries, 4) diving and associated ecotourism, 5) sand supply to beaches coupled with erosion protection, and 6) source of novel pharmaceuticals.

The start of return of the sea urchin *Diadema antillarum* at Caribbean reefs, almost two decades after their collapse, and the full-scale regrowth of the coral reef in Kaneohe Bay, Hawaii provide encouragement for reef recovery. However, efforts to conserve reefs have failed to produce significant results, and rehabilitation measures have not successfully compensated for the fast degradation. The applicability of techniques such as *in-situ* coral mariculture for example, on large-scale reef areas needs further evaluation.

Enhancing Remediation Success

The diversity of current techniques notwithstanding, it is clear that for remediation and restoration efforts to be successful, causes of reef degradation should first be identified and parallel attempts made at mitigating them. In addition, remediation/restoration should be implemented only in areas that are under some effective form of management. The accepted assumption is that there is little sense in restoring a reef degraded by anthropogenic activities unless those activities have ceased or are effectively managed and the cause(s) of degradation removed.

Identification of the major questions to be addressed and development of decision-support tools should help managers to decide whether to proceed with reef restoration/remediation. At the start of the project, the working group will develop a set of protocols on reef restoration/remediation based on best available information. This will take the form of a manual on remediation/restoration for managers, which will be useful in helping them identify pre-requisites for remediation, and be aware of the available restoration/remediation methodologies. A number of important scientific questions however, remain unanswered concerning the processes that affect the ability of reefs to recover to a pre-disturbance state. These are considered in formulating the present proposed investigations. The manual will be updated towards the end of the project after derivation of new information from the intended research.

Cost Effectiveness

It is recognized that reef remediation and restoration efforts can be both costly and time-consuming (far more than mangrove or seagrass restoration) and may have collateral negative impacts on donor sites from where transplants are taken. Analysis of restoration costs based on case studies in Florida, Maldives, and Tanzania, indicated enormous variation from US$ 10,000 to 5 million ha^{-1}. To justify such costs, reef restoration must be effective. A key question is whether restoration initiatives make a significant difference to the recovery of reef systems on a 5–10 year time-scale compared to natural processes. If yes, then do the benefits justify the cost? The working group will assess and cost out a range of biological restoration interventions. Such assessments will be of immense value to reef managers and will help facilitate the decision-making process based on science.

Research Questions

The proposed investigations of the Restoration and Remediation Working Group fall into three programmes:

1. Overarching long-term research framework (integrated series of manipulative experiments involving substrate modification, larval supply, coral transplants, and algal grazing): This will address long-term efficacy and cost-effectiveness of restoration interventions as well as investigating the processes underpinning natural recovery.

2. Enhancement of larval recruitment programme

3. Coral transplantation and culture programme

Overarching long-term research framework. This seeks, via a series of manipulative experiments using a common replicated design, to discover how cost-effective a selected set of restoration interventions are in the long-term (5-10 years) at a larger scale. These restoration interventions will include selected current "best-practice" methods. Three principal types of biological

intervention will be evaluated: early stage interventions focused on enhancement of larval supply, later stage interventions focused on enhancement via transplantation and thirdly enhancement of algal grazing to assist recovery via natural recruitment. Each intervention will be compared to natural recovery without any intervention. Underlying this approach is the assumption that the long-term benefits of restoration (if any) should only be measured in terms of recovery over and above what would have occurred naturally. The effectiveness of selected repair or replacement substrates will also be investigated. Central to the overarching research framework will be continual measurement of the key processes driving natural recovery so that we can better understand why some reefs are resilient to disturbance (recover well) whilst others fail to recover.

The other two programmes will focus on a) shorter term experiments to improve our understanding of the science underpinning restoration, and b) the development of low-cost technologies to improve the cost-effectiveness of augmentation of larval recruitment and transplantation interventions.

Enhancement of larval recruitment programme. When corals mass-spawn, billions of larvae are produced, which form slicks that drift in the sea for a week or two until the larvae are ready to settle on the reef and metamorphose into tiny coral polyps. These slicks are potentially a source of huge numbers of juveniles for restoration interventions if they can be contained and directed to injured sites. Developing low-cost methods to hold the slicks *in situ* until the coral larvae are ready to settle and then to guide the larvae to target reef areas is one fertile area of investigation. Key questions include how to optimize larval supply both in terms of abundance and diversity. Another approach is to use natural chemical inducers of settlement to attract coral larvae produced by selected spawning colonies onto larval "flypapers" in low-cost land-based hatcheries. In this way, thousands of juveniles of a chosen species can be settled on substrates and subsequently deployed on the reef after a period of nursery-rearing. A key question is what is likely to be the most cost-effective size at which to outplant recruits?

Coral transplantation and culture programme. The costs of transplantation depend largely on the amount of nursery culture that must be undertaken prior to putting transplants onto damaged reefs. Thus low-cost transplantation has tended to focus on direct transplant of sizeable coral fragments or colonies from "healthy" donor sites to damaged sites in need of restoration. Collateral damage to donor colonies or donor reefs is of concern. To minimize such damage, firstly, one can source transplants only from "corals of opportunity" in donor areas. This means that only already detached fragments or colonies, which are unlikely to survive if left, are used as source material for transplants. Secondly, one can divide material into small units (small fragments or 'nubbins') and culture these in nursery areas until at a size where good field survival is likely. One can also combine the two methods, thus making very effective use of the "corals of opportunity". The key to cost-effectiveness is balancing the costs of nursery rearing and effective use of limited source material against the likelihood of survival of transplants.

A range of related experiments are planned which seek to look at the effect of the size and structure of coral fragments or nubbins on subsequent growth and survival for a range of species. Low-cost approaches involving direct transplantation will be compared to more costly and technologically demanding approaches involving periods of ex situ culture followed by in situ culture, or *in situ* culture alone prior to transplantation to damaged reefs. These experiments are designed to seek answers to a range of questions concerning the relative costs of different approaches and the benefits derived in terms of survival, growth and maximizing yields from donor material. The ultimate goal is to determine for a range of species the most cost-effective protocols at differing levels of technology.

Long-term efficacy and Cost-effectiveness of Restoration Activities

There is a need to measure the efficacy and cost-effectiveness of a range of commonly employed restoration interventions. To advise managers on the efficacy of interventions, an agreed set of a priori criteria is needed, against which the success of otherwise of interventions can be judged. Interventions need to be compared to the non-intervention case, that is, what would have happened if natural recovery processes were allowed to operate alone over a 5–10 year timescale? Cost-effectiveness is best assessed by managers and decision-makers on a case-by-case basis. What is cost-effective for one user may be completely inappropriate in another socio-economic context. However, by compiling information on both costs and effectiveness of different restoration interventions, the working group will provide the information needed by managers to assess cost-effectiveness. Economists with experience in valuing reef resources will be approached as part of the working group's coordinated investigative framework to advance management.

Although the ultimate goal of restoration is returning damaged coral reefs to the state in which they were prior to disturbance, actual biological restoration interventions usually focus on keystone species, with the hard corals that build the reef framework being foremost among these. Clearly, attaching a few corals and other keystone invertebrates to a damaged reef does not restore the coral reef ecosystem as a whole. However, the nearterm objective of biological restoration is not generally to transplant all the biodiversity back onto a damaged reef but to **assist natural recovery processes** by putting back carefully chosen keystone species that will accelerate natural recovery or "kick-start" it in those cases where the reef is thought unlikely to recover by itself. With regard to the latter, it is important that restoration is only attempted once complementary management measures have been implemented to deal with anthropogenic activities (e.g., pollution, sedimentation, or overfishing) that may be impeding natural recovery.

The working group's research is focusing on the corals because (i) they are particularly threatened at present, (ii) they provide the major accreting element for the sea-defence service provided by reefs, (iii) they provide both topographic diversity and shelter for both fishes and invertebrates, (iv) they provide shelter in particular for herbivores which can prevent algal overgrowth, and (v) there are increasing worries that phase-shifts from coral to algal dominated systems may occur on damaged reefs without intervention.

Since the natural reef is very varied and it is difficult to conduct adequately controlled comparisons using natural reef patches, the overarching long-term research framework will use replicated standardized artificial structures for comparisons. These will allow a range of long-term comparisons to be made (i) between the outcomes of natural processes and the outcomes of biological interventions and (ii) between different substrate types (embedded limestone aggregate and concrete). Criteria for assessing success, include: % live coral cover, coral size-frequency distribution and colony density, coral species richness and diversity, fish abundance and community structure, rates of herbivory, rates of coral recruitment, coral growth and survival rates, coral fecundity, and benthic cover composition. The following questions will be addressed:

- *Recovery processes on natural reef and standardized substrates.* What are natural rates of recruitment, growth, and mortality for common coral species on standardized substrates and adjacent natural reef? This will establish baseline rates of coral recruitment, growth, and mortality, as a yardstick against which biological interventions can be compared. Fish communities and grazing invertebrate populations will also be monitored as will rates of herbivory by fish.

- *Enhancing larval recruitment.* Does enhancement of spat settlement to standardized substrates lead to significantly enhanced coral communities after 5–10 years?

- *Enhancing recovery via transplantation.* Does adding transplants to standardized substrates lead to a significantly enhanced coral community after 5–10 years?

- *Providing appropriate substrates (when structural restoration is needed).* Do standardized substrates faced with limestone offer better restoration benefits than concrete standardized substrates?

- *Algal grazing enhancement.* Does the enhancement of algal grazing improve the recruitment, survival and growth rates of corals?

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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.