1 Coral Reef Restoration: The Rehabilitation of an Ecosystem under Siege

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CONTENTS

1.1 INTRODUCTION

Today, coral reefs are under siege from a number of environmental pressures. Accordingly, the management of the world's coral reef resources is the subject of some controversy.[1] General agreement exists about the value of these ecosystems in terms of ecological, social, and aesthetic benefits.[2] There is also some agreement that an estimated 24% of reefs are in danger of collapse from human pressures[3] and another 26% are under the threat of longer-term degradation and collapse. Admittedly, the numbers and percent devastation may vary regionally, yet no area untouched by humans has gone undisturbed.

Unfortunately, no consensus presently exists on how coral reef protection is to be accomplished. Coral reefs around the world have changed dramatically over the past two decades, particularly in the Caribbean and western Atlantic region.[4–11] Humans can impact reefs directly through vessel groundings, dynamite blasting for fishing and limestone construction materials, and anchor damage, to name but a few relevant activities, and indirectly through pollution, sedimentation associated with coastal activities such as dredging, and river runoff. Humans also are implicated in global warming through the emission of greenhouse gases. Although these anthropogenic impacts have affected coral reefs globally, other natural factors impact reefs as well. It is obvious that the resource needs protection and that many of the cited anthropogenic causes can be reduced, minimized, or avoided by implementing scientifically based management programs.[1,12,13]

An appropriate course of action is to repair or replace damaged and disturbed reefs at a rate resulting in no net loss of ecosystem value; the rate of reef destruction should be offset by the rate of reef repair. Because of financial considerations and logistical problems, this may not always be possible. As a practical matter, however, managers and policymakers need to understand the effects of human-induced disturbances; assess these damages properly; and develop subsequent, appropriate restoration efforts on reefs under their stewardship.[14–17] Most coral reef restoration programs have been focused on the physical damage caused by human activities. Of these, ship groundings are among the most destructive anthropogenic factors on coral reefs and form the basis for much of our present understanding of reef restoration. Some, however, view ship groundings to be only locally significant, implying that groundings do not pose a great threat to coral reef ecosystems or may even be beneficial.[18,19] The recent, staggering history of reported groundings by the Florida Marine Patrol in the Florida Keys (>600 yr^{-1}), however, reveals the significant threat to the health of the reef tract as a whole.[20] Boats of all sizes cause significant destruction.[21] In the case of large vessel groundings, destruction is usually complete and includes the direct loss of corals by dislodgment and pulverization, as well as the crushing, fracturing, and removal of three-dimensional reef structure (Figure 1.1). Secondary impacts include the scarring and abrading of previously undamaged resources as hydrodynamic forces move rubble produced in the initial disturbance. In some cases, increased sedimentation associated with the fracturing and erosion of the underlying exposed reef framework smothers living creatures. Furthermore, collateral damage caused by salvage and towing operations in removing a vessel run hard aground often increases the footprint of the initial damage scar.[15] Careless salvage efforts can destroy vast areas of coral reef unaffected by the initial accident. Fortunately, much of the physical damage caused by vessel groundings can be repaired. Using examples of reefs injured by

FIGURE 1.1 Complete devastation from the impact of a ship-grounding. Note total loss of reef structure, exposed limestone pavement, loose rubble, and residual paint from the hull.

catastrophic vessel groundings in the Florida Keys National Marine Sanctuary (FKNMS),[22–24] Precht et al.[25] developed a process-based scientific approach to coral reef restoration.

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Environmental impacts, including hurricanes, tsunamis, global climate change, coral disease, and severe ENSO events, have also impacted coral reefs. Though hurricanes and tsunamis are clearly naturally occurring events, the causes of global climate change, coral disease, and increasing severity of ENSO-related warming events are not known and may be related to human activities. Approximately 40% of coral reefs were seriously degraded by the 1998 ENSO-related warming event.[3] Coral disease has devastated Caribbean reefs and was responsible for the almost complete demise of *Acropora cervicornis* and *A. palmata* in the late 1970s and 1980s.[10, 26] If we are not able to control or ameliorate the source of coral reef degradation, no matter what the source of degradation, we cannot expect to effectively restore these ecosystems. Management to restore acroporids, therefore, will always be constrained by the boundaries of historical conditions and the scale of recurring natural disturbances inherent to the system.

Coral reef restoration will only be effective in addressing impacts that can be ameliorated and removed from affected coral reefs. Decision makers should decide on a case-by-case basis whether or not to restore a particular coral reef. While destructive and important to address, coral reef degradation through global warming, human-induced climate change, or pandemic coral diseases can only be addressed at the highest levels of government. Restoration of reefs impacted by hurricanes, climate change, coral disease, or other natural agents may be futile because there is no way to prevent the return of these agents.[27] In addition, it would be prohibitively expensive to repair reefs crippled by the negative synergistic effects of multiple types of stressors such as severe storms, global warming, and emergent diseases.

1.2 CORAL REEF RESTORATION — A GUIDE

The most widely accepted definition of ecosystem restoration is "the return of an ecosystem to a close approximation of its condition prior to disturbance."[28] This includes placing all restoration efforts in a landscape context, in which the restored patch is integrated into the ecosystem as a whole.[29] An implicit assumption is that managers and scientists understand the ecological dynamics of the restoration process itself, but most coral reef restoration efforts performed to date have fallen short of these goals.[22,30–36] Rather than being "true" restoration efforts, most of these are rehabilitation projects, with the goal of accelerating natural reef recovery to an endpoint that may or may not resemble predisturbance conditions. Moreover, efforts to evaluate the success of reef restoration projects have been complicated by a lack of scientific goal setting and by a general lack of agreement on what constitutes project success.

The goal of restoration is to restore the structure and function of a degraded ecosystem, habitat area, or site.[29,37–39] As previously mentioned, the word restoration means that you have returned something, in this case a coral reef, back to its original condition. Why then should we not expect restored reefs to look like and provide the same functions as preimpact reefs? We can, but only if we carefully select reefs for restoration. Successful reef restoration requires, first and foremost, a definitive end to impact and/or degradation. This means the agent of destruction is removed from the impacted area and will not return. A reef impacted by environmental factors may not be a candidate for restoration in this scenario because the agent cannot be permanently removed (i.e., excessive sedimentation, nutrient pollution, repeated vessel groundings in the same spot). In the case of vessel groundings secondary mitigation such as signage may be implemented to prevent future groundings. Information on the preimpact area and its species composition/structure, financial resources, and guidance on design and construction for the restored coral reef are all necessary for a successful reef restoration project (Figure 1.2). The matrix in Figure 1.2 was developed to serve as a template for coral reef managers faced with the possibility of performing restoration projects on reefs under their stewardship.

Although each restoration project is unique, they all have common elements that can be addressed before action is taken. When faced with a potential restoration site, managers can follow

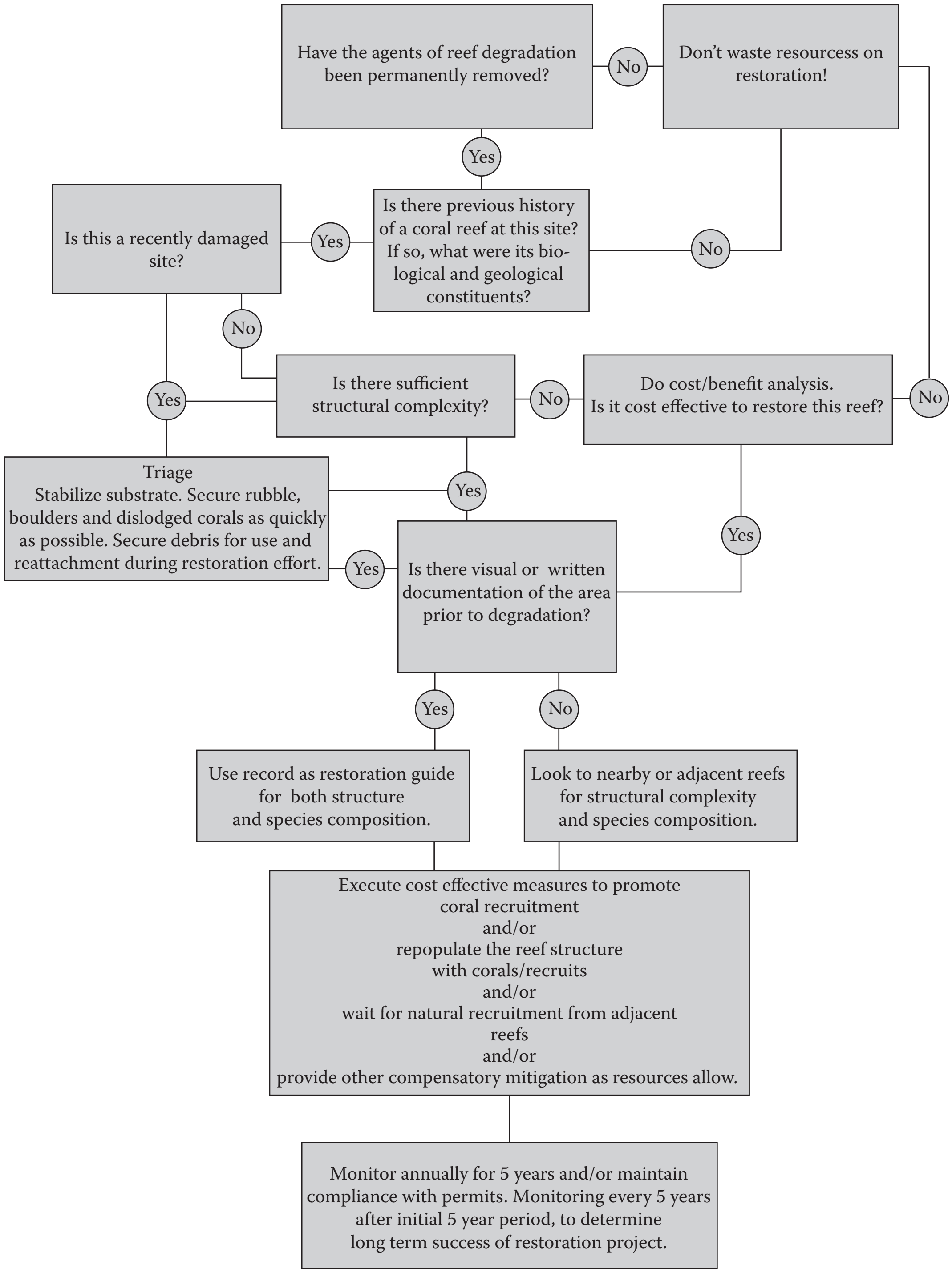

FIGURE 1.2 Coral reef restoration decision matrix.

2073_C001.fm Page 5 Wednesday, November 30, 2005 3:38 PM

a general set of guidelines, provided here, to decide on whether or not an area should be restored. The following is a narrative of the coral reef restoration decision matrix presented in Figure 1.2.

The primary consideration for managers when confronted with an injured resource of any kind is to ensure that the agent of destruction has been removed. If not, don't even consider restoration; spend your money doing something else. It is only with the permanent removal of the source of degradation that a restoration project has a chance of success. In some cases some additional action is needed to ensure that the cause of injury is not repeated. For example, the installation of mooring buoys can prevent anchor damage and small boat groundings on shallow reefs. Although this may mean spending additional resources it is imperative to include these added measures, otherwise dollars spent on restoration are potentially wasted. It is reasonable to consider not restoring a resource based on these considerations and instead focus resources elsewhere.

When the causative agent of reef destruction has been permanently removed and deemed not to return, the question then is: Was there a coral reef at the site that was injured and what were its geological and biological constituents? If there was never a reef there it is probably best to not create one as the environment (abiotic conditions) may not support a coral reef community. This is an important consideration even though it may seem obvious. To effectively restore a coral reef we must be working towards an achievable goal; therefore, site selection is vitally important. The second portion of the question should be addressed if true restoration is to be achieved. Among other things to consider are the geological constituents (the building blocks of reef framework) that are lost in addition to the biological constituents (scleractinian species, gorgonians, sponges, algae, epifauna, infauna, as well as mobile fauna). In cases where the structural complexity has been reduced or eliminated due to time or severe injury a cost–benefit analysis needs to be completed to determine the appropriate course of action. It is obvious that the more information a manager has about a site preinjury the better. Understandably, these types of records are often unavailable after an injury has occurred. However, adjacent reefs as well as their geological counterparts can be used as a guide in these circumstances. These will be discussed in more detail later in this chapter.

Timing is also critical in terms of restoration of organisms injured at the site. In cases of a recent injury, coral reef triage can be an effective tool. Triage in the form of uprighting and reattaching of corals to the substrate is only possible soon after the injury. Triage can also include large-scale stabilization of loose rubble and/or sediment left by the injury. The goal of triage is to effectively eliminate further damage and degradation to corals that were dislodged and other intact corals in the surrounding and adjacent areas. In many cases it is the most immediate and cost-effective way to begin the restoration process. Triage is a starting point in reef restoration and does not constitute restoration in and of itself. Reestablished corals may also serve as a source of recruitment in recolonizing the surrounding substrate.

Once the decision has been made to move forward with a restoration project, historical photographs and/or other descriptions of the site may be the best (and only) guide to accurately recreating the original reef structure and composition. Since such records may not be available, the adjacent reef or reefs can be used as a template for restoring the type and amount of structural complexity and species composition appropriate for the site. A cost/benefit analysis for the different restoration alternatives needs to be performed, with the knowledge that the combination of possibilities for restoration is only as limited as the imagination and resources. For true reef restoration, that is replacing the reef community structure and function, biodiversity, aesthetics, and socioeconomic value, creative as well as scientific approaches are necessary. Different projects will require varied approaches and may include various techniques including triage, adding structural complexity with reef modules or limestone boulders, stabilizing substrate with mats or cement, and importing corals from nearby nurseries, to name but a few. The solutions will depend upon the location of the site and the resources available. Once it is built, will they come? But what and how much is the question. The only way to know is through long-term monitoring.

Monitoring of restored reefs should be treated as part of the reef restoration project itself. Too often this important component is left out of restoration plans. Annual scientifically based monitoring carried out for a minimum of 5 years (preferably longer) after the completion of restoration can provide critical lessons learned, documenting successes and failures. It is only through these lessons learned that we can improve upon past technologies, techniques, and methods, bringing us closer to the restoration of complex, fully functional reef ecosystems.

1.2.1 Why Restore?

Coral reefs are some of the most productive ecosystems, providing habitat for numerous species and serving important ecologic functions. A coral reef and its specific functions may become degraded when these larger-scale processes are altered or removed. To successfully restore a degraded reef one must examine the important processes that exist within and outside of the spatial and temporal boundaries of a specific reef area. Moreover, numerous spatial and temporal scales must be examined at all stages of coral reef restoration including identification of degrading agents, selection of processes to be restored, analysis of restoration impacts on the seascape, and long-term, hypothesis-driven monitoring.

1.2.2 Identification of the Degrading Agents

The identification of the agents or actions that caused the degradation of a coral reef is the first step in conducting a restoration effort. If the causes of the reef's degradation (the stressors) are not removed or accounted for than the probability that the site will continue to be negatively impacted is high.[20,40] One must expand the scale of examination to determine whether stressors occur outside of the site's boundaries and are impacting important large-scale processes. For example, if dredging activities are occurring up current from a coral reef, then that reef system may be negatively impacted because of high sediment stress. Additionally, the loss of functioning reef systems is often the result of cumulative disturbances to the ecosystems. Coral reefs, especially those near urban settings, are subject to ongoing large-scale stresses from human activities. A multitude of stressors cumulatively influence a system at different scales and intensities, making the identification of the important degrading agents a very complex process. Many ecosystem restoration projects have failed because they have not accounted for all of the stressors that influence the system.[41–43] To properly identify the important stressors negatively affecting a coral reef ecosystem one must methodically examine the individual reef and its landscape setting at numerous spatial scales.

Coral reef stressors are imbedded at various temporal scales as well. Accordingly, the temporal scale must be considered when identifying the specific factors that caused the degradation. A stressor can occur over a short or long time period and often result in disruptions to a coral reef's function.[42,44] A historical event that occurred over a short time period that resulted in long-term impacts to a coral reef's function will not be identified if the temporal scale is not expanded beyond the current timeframe. A stressor that occurs over a long time period and has long-term impacts may be seen as a constant feature of the landscape and may not be classified as a stressor if the temporal scale of analysis is not increased. In addition, not all degrading events occur within the same time period. The severity of the impact of an existing stressor on a coral reef may not be obvious if it occurred after the site was already injured or disturbed. For instance, before the late 1970s, two species of acroporid corals were the primary builders of coral reefs along the Florida reef tract. These corals have since undergone a regional decline, with losses of 95% or more in some areas during the past few decades. Therefore, it maybe hard to determine the true extent of an anthropogenic injury on a shallow reef area that was previously dominated by acroporid corals. These confounding factors require diligence on the part of the restoration scientists.

1.2.3 A Legal Basis for Restoration

When a coral reef is injured, several federal statutes provide the United States government with the authority to recover resource damages.[45]The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 and the Oil Pollution Act of 1990 (OPA 90) are the principal federal statutes that authorize trustees to assess damages for trust resources that are lost or destroyed as a result of the discharge of oil or release of hazardous substances. The Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) was charged with developing regulations for OPA 90. The NOAA rule (15 CFR Part 990) was finalized on January 5, 1996. Many of the procedures and techniques developed for assessing natural resource damages under OPA 90 have been applied to the damages caused by the grounding of vessels on coral reefs and other significant natural resources.[46]

1.2.4 Natural Resource Damage Assessment

Natural Resource Damage Assessment (NRDA) is a process for making the public "whole" for direct injury to natural resources and/or the services of natural resources. The primary objectives of the NRDA process are to identify and quantify natural resource injury, determine the damages resulting from the injury, and develop and implement appropriate restoration actions. The primary goal of NRDA is to provide for the restoration of injured natural resources and/or services to preincident conditions.[47] This goal is achieved by implementing a plan for the restoration, rehabilitation, replacement, and/or acquisition of equivalent natural resources. In NRDA, restoring the environment after injury has two basic components. These are "primary restoration," which is the restoration of the injured resources to baseline (i.e., preimpact, unimpaired) conditions, and "compensatory restoration," which is the compensation for interim losses of resources from the time of the injury until the resources recover to the predetermined baseline. Compensation is in the form of additional restoration, replacement, rehabilitation, or acquisition of equivalent natural resources.

NOAA's NRDA rule is intended to promote expeditious and cost-effective recovery of natural resources and the services of these natural resources. Responsible trustees (e.g., authorized federal, state, Indian tribe, and foreign officials) can use the rule to recover losses of natural resources and their services. In addition, companies and/or individuals responsible for natural resource damage (i.e., responsible parties) can use the rule as guidance for determining natural resource damage and shaping proposals to the trustee to repair the damaged resource and compensate for lost services during the recovery of the resource.

The result of the NRDA process is a restoration plan that is developed by the trustee and/or responsible party with input from the public. The process has three phases:

1. Preassessment
2. Restoration planning
3. Restoration implementation

The preassessment phase involves a preliminary determination by the trustees as to whether natural resources and/or services have been injured. The result of the initial preassessment phase is a Notice of Intent to Conduct Restoration Planning, which contains:

- The facts of the incident resulting in ecosystem injury
- Trustee authority to proceed with an assessment
- Natural resources and services that are, or are likely to have been, injured as a result of the incident
- Potential restoration actions relevant to the expected injuries
- Potential assessment procedures to evaluate the injuries and define the appropriate type and scale of restoration for injured natural resources and services

The restoration planning phase includes injury assessment, restoration selection, and selection of preferred restoration alternatives. This document is often referred to as a Damage Assessment and Restoration Plan (DARP).

2073_C001.fm Page 8 Wednesday, November 30, 2005 3:38 PM

1.2.5 Crime Scene Investigation

Essentially, the trustees and the responsible party can proceed into a NRDA as partners, cooperatively developing a jointly agreeable restoration plan, or as potential opponents in a legal battle. In either case, however, any preliminary investigations should be treated as the equivalent of a crime scene investigation until the course of the NRDA is determined. Accordingly, as much physical evidence from the site as possible needs to be documented, collected, and quantified as soon as possible after the incident.[48] The evaluating scientific divers are essentially underwater detectives and must use forensic methods and protocol to accurately assess the injured resources. For a ship-grounding, these include measurements that detail both the inbound and outbound paths of the responsible vessel (e.g., hull paint scrapes, scarification and directional striations on the reef surface, keel and chine scars, direction of movement of overturned or toppled corals and/or reef rubble, etc.). There is no substitute for good scientific methodology at any time during the investigative or assessment portions of the NRDA, as they are the building blocks upon which restoration plans are based. In addition, proper chain-of-custody should be maintained at all times for samples, photographs, and other forms of data.

The decision by the responsible party to proceed cooperatively in a NRDA with the trustees will result in the development of a Memorandum of Agreement (MOA), a legally binding document, jointly developed and signed by all parties. This situation can certainly expedite the resolution of a NRDA for the responsible party and may result in a considerable reduction in the cost of assessments and restoration because interim losses can be significantly reduced.

1.2.6 Injury Assessment

Under the NOAA rule, injury is defined as an observable or measurable adverse change in a natural resource or impairment of natural resource service. The trustee or responsible party must quantify the degree and spatial and temporal extent of injuries. Immediately after an injury occurs, a detailed injury assessment should be prepared. As previously mentioned, since many of the injury actions will result in either a settlement or litigation between the trustee and the responsible party, the assessment must also substantiate or refute the description of events that caused the injury.[14] The degree of injury may be expressed in such terms as percent mortality; proportion of a species, community, or habitat affected; extent of injury or damage; and/or availability of substitute resources. Spatial extent may include quantification of the total area or volume of the injury. For a comprehensive review of the protocol detailing the field methodology for coral reef injury assessments, the readers are directed to Hudson and Goodwin[48] and Symons et al.[49]

Temporal extent or duration of the injury may be expressed as the total length of time that the natural resource and/or service is adversely affected, starting at the time of the incident and continuing until the natural resources and services return to baseline. In minor incidents this length of time is usually measured in decades. In some large disturbances, however, impacts to the "nonliving" resource may include the loss of three-dimensional reef structure and removal of vast quantities of reef substrate and sediment, eliminating thousands of years of reef development in one fell swoop. In these cases, without major intervention by humans, it is evident that the resource would not recover to its preinjury baseline for millennia.[25]

1.2.7 Emergency Restoration

Emergency restoration includes those actions that can be taken immediately after an incident that may reduce the overall extent of the injury to the resource. These actions take the form of "triage," which is defined as "the sorting of and allocation of treatment to patients … esp. disaster victims according to a system of priorities designed to maximize the numbers of survivors."[50] In the case of groundings on coral reefs, triage can be righting and reattachment of displaced or broken corals, the removal and/or stabilization of loose rubble and sediment, and the stabilization of structural fractures.[51] In some cases

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2073_C001.fm Page 9 Wednesday, November 30, 2005 3:38 PM

there may be a conflict between the evidence collection portion of the investigation and initial remedial action or reef triage efforts. Reef triage efforts must be implemented in concert with the initial damage assessment to attain maximum success in salvaging the damaged resource. However, these efforts should not be preformed in a vacuum, and collaboration among all team members is essential so as not to compromise the integrity of any of the ongoing investigative operations.

1.2.8 Economic Assessment of Damages

The following discussion is meant as a guide for evaluating the economic criteria for determining damages to injured reef resources. This discussion avoids legal analysis and liability and jurisdictional issues, and readers are directed to seek specific regulations pertaining to the complexities of individual cases or areas.[52,53] For example, in south Florida a variety of regulations pertain to the protection of reefs and corals.[14,51] In Federal waters, the National Marine Sanctuaries Program Amendments of 1988 provide that any person who destroys, causes the loss of, or injures living or nonliving resources of a National Marine Sanctuary may be liable to the United States for damages, including the cost of replacing or restoring the resource and the value of the lost use pending the replacement or restoration. The Park Service Resource Protection Act also authorizes the U.S. Secretary of the Interior to recover damages for injuries to National Park System resources.

In assessing the extent of damage from an economic standpoint, the purpose is to estimate the amount of money to be sought as compensation by the trustee from the responsible party for the injury resulting in the damage to the resource. Damages based on restoration costs may include any diminution of use and nonuse values occurring until the recovery is complete (i.e., functional success criteria are attained).

After a detailed Damage Assessment and Restoration Plan (DARP) is performed, a monetary assessment of damages based on restoration costs should be prepared and a demand for these damages presented to the responsible party. The restoration methodology should be based on the costs of the actions to restore or replace the damaged reef to its predisturbance, baseline condition. Replacement costs are the costs of substitution of the resource that provides the same or substantially similar services as the damaged resource. The restoration or replacement alternatives should be evaluated according to the DARP. The damage amount should be the amount to cover all costs related to the injury and not just limited to an amount used to restore the damaged resources, including:

- All emergency response and/or salvage efforts
- Environmental assessment and mapping of the injured resource (damage assessment)
- Implementation of emergency rehabilitation methodologies (reef triage)
- Preparation of the DARP report
- Implementation and completion of restoration through project success
- Long-term scientific monitoring studies (both functional and compliance)
- Compensatory restoration for interim loss of services

The assessment of natural resource damages requires close interaction between law enforcement officers, scientists, lawyers, resource managers, regulators, and economists. Since many damage cases result in litigation, it is imperative to get the science, law, and economics correct. Damages recovered by the trustee should then be made available to restore, replace, or create equivalent resources.

1.2.9 Selection of Processes to Be Restored

Degradation is a complicated process involving numerous changes to the function of an ecosystem; therefore, the restoration process will be at least as complex.[39] Although the identification and, if possible, removal of stressors is the first step in the restoration process, it is not the only step (see Figure 1.2). Stressors impact the function of a coral reef by altering or removing structural components and ecological processes; therefore, even if the stressors are eliminated, some components may still be absent from the restored ecosystem.[37,54,55] To develop a successful long-term solution, restoration must include the reintroduction or creation of three-dimensional structure and critical small- and large-scale processes that generate the function of a coral reef ecosystem.[54–56]

To restore the necessary small- and large-scale processes, one must first identify the function of the specific coral reef area (usually the unimpaired resource adjacent to the injured site) and by extension, the goal of the restoration project to be performed. There is currently a large debate regarding the appropriateness of restoring ecosystems to their historical functions and engineering these systems to mimic the function of reference sites.[40,42] Historical functions and reference sites can greatly assist with the restoration process but may not always be the most appropriate end goals for restoration. The landscape in which the restored coral reef exists differs from what was historically present. This is especially apparent with the ongoing global coral reef crisis, with stressors being related to coral disease and bleaching. Some stressors may not be removable, and not all of the processes that were present historically can be reestablished because the surrounding landscape has changed.[57,58] When restoring a site one must expand the spatial scale at which the reef is examined to determine which ecological process can be established and will function appropriately given the specific landscape setting of that site.[40,59]

The use of reference ecosystems is a vital component of developing success criteria in restoration programs. In coral reef systems many of these reference sites are heavily disturbed, rendering them useless as templates for the reconstruction of lost ecological services. It is possible, however, to use the paleoecologic information stored in Quaternary reefs as an appropriate analogue for placing current site conditions in context. It has been shown that, almost without exception, Quaternary fossil-reef sections exhibit species composition and zonation similar to those of modern reefs at the same location. Thus, Quaternary reef-coral communities within the same environment are more distinct between reefs of the same age from different places than between reefs formed at different times at the same location. Often, the subsurface Holocene reef history exposed by the injury itself serves as the best reference ecosystem. These Quaternary examples provide a baseline of community composition that predates the impact of humans. Most importantly, these paleoecological examples emphasize the importance of history — succession, assembly rules, and natural system variability — in structuring reef ecosystems through time and space. These fossil and subfossil reference ecosystems also form the basis for identifying desired future conditions for which the resulting restoration should aim. By identifying the ecological processes that generated a site's historical function as well as what processes are influencing other similar reef systems, restoration ecologists can begin to identify the particular large- and small-scale processes that should be established. Thus, the past should be used as a model to reconstruct the future. Because historical science is largely inductive, and interpretation of the fossil record can be highly subjective, the challenge to restoration ecologists is to combine paleoecologic data and reconstructions with reference sites, field experiments, model simulations, and long-term monitoring.

Zedler[60] has suggested that, before any project begins, those performing ecological restoration must have very clear goals for their work. Specific decisions on what aspects of the restoration will be emphasized (structure and/or function) and how those goals will be achieved must be made absolutely clear in order to promote success.[42] Specifically, restoration scientists have a series of "theoretical" decisions to make:

- Whether to use self design or engineered design (i.e., rebuild structure, actively transplant corals and other benthic attributes)
- Whether to create in-kind or out-of-kind restoration projects
- Whether to restore onsite or offsite
- How to use reference sites both as a template and as a means for evaluating restoration success
- How to evaluate/conceptualize coral reefs using hypothesis-driven monitoring programs

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Two controversial views in ecosystem restoration are ideas regarding the self design and engineered design of the injured resource. These two views have evolved from Gleasonian and Clementsian succession dynamics:

- In the Clementsian view, the community was interpreted as a superorganism. The component species were highly interactive and their distributions were strongly associated along environmental gradients.[61,62] Clementsian succession claims that the community changes as a whole through different life stages and ends up ultimately in a climax ecosystem. Species are interlinked with one another, and disturbance to the ecosystem interrupts this natural progression to the climax stage of development.[10]
- The Gleasonian model rejected the idea of tight community integration. Instead, the community was seen as a collection of independently distributed species.[63] The Gleasonian model does not exclude the possibility of succession, competition, niche partitioning, assembly rules, and other interspecific interactions. Rather, it denies interspecific interdependence as the cause of species distributions.[64,65] Gleasoninan succession claims that community change can be reduced to the responses of individual species to the environment based on the constraints of their unique life histories.[10]

The controversy of engineered design versus self design centers on the question of whether to rebuild reef structure and transplant corals at a restoration site to jump-start the recovery process or to allow the restoration site to recolonize naturally over time with little or no human intervention. The two concepts differ as follows:

- The main hypothesis of the self-design concept is that over time, a coral reef will restructure itself. The environmental condition determines what organisms will be able to colonize the site. This concept views recolonization as an ecosystem-level process. Proponents of the self-design view believe that intervention in the recovery process is not warranted.
- The main hypothesis of the engineered-design concept is that it is not a matter of time, but intervention, that determines the positive outcome of a restoration project. The most important factors in the success of the restoration project are the life histories of each organism present. The importance of the natural reproductive process (brooders vs. broadcasters) of the corals is often stressed.[66] This concept views recolonization as a population-level process.[67] It seems apparent that for coral reefs, due to the slow rates of natural recovery, intervention is not just warranted but required.[25]

Also, by comparing the restored site to an approximate reference site, restoration scientists can determine how well the restored ecosystem is mimicking the original.[41,42,60,68] However, White and Walker[68] and Grayson et al.[42] have contended that the picking of reference sites for comparison is more complicated than just looking at comparable, adjacent unimpaired settings. Specifically, Grayson et al.[42] suggest that restored sites must be compared to both nondegraded sites and unrestored degraded sites. Thus, if the restored project shows signs of success, more knowledgeable conclusions can be drawn as to whether the success has come from the act of the restoration or whether it is merely a natural response of the ecosystem (which may be evidenced by comparison to the response of the degraded unrestored site).

1.2.10 Analysis of Restoration Impacts on the Landscape Scale

Various spatial and temporal scales need to be examined to determine how the restoration of a coral reef may impact landscape-scale processes and adjacent habitats. Structural complexity has a large influence on what types of habitats are present in a landscape. Most coral reef restoration

2073_C001.fm Page 12 Wednesday, November 30, 2005 3:38 PM

projects have generally focused on reestablishing coral cover and not structural complexity at the landscape scale. We caution that if restoration is performed on a site-by-site basis without consideration of the structure, we risk a reduction in overall ecosystem function. The restoration process is a series of alterations to the current processes and patch interactions within a landscape. By altering these ecological processes, we may positively or negatively impact other ecosystem patches within a landscape.

By expanding our scale of view to the landscape or regional perspective, a restoration project can be designed so that it adds to the value or function of the entire landscape.[43,60] With the increased need for coral restoration for mitigation purposes such as in ship groundings or dredging projects, there is a danger that restoration projects will be treated as a cookbook-like process in which the same type of reef system is restored to an area regardless of its landscape context.[57] For instance, the placing of a dozen prefabricated reef modules without regard to landscape setting is hardly in-kind restoration. If all reef restoration projects are designed to be of the same type, the diversity of reef functions and habitats as well as the diversity of species within a landscape will be greatly reduced.[43] By including large-scale considerations in restoration activities, restoration projects can be designed to enhance both local and regional ecosystem functions and preserve the diversity of coral reefs present in a landscape.[37,43,54]

1.2.11 Restoration Design

In designing a coral reef restoration project, a reasonable range of restoration alternatives needs to be considered. Evaluation of the alternatives needs to be based at minimum on:

- The cost to carry out the alternative
- The extent to which each alternative is expected to meet the goals and objectives of returning the injured natural resource and services to baseline and/or compensate for interim losses
- The likelihood of success of each alternative

The extent to which each alternative will prevent future injury as a result of the incident and avoid collateral injury as a result of its own implementation

Determining the benefits of restoration to the affected environment requires an analysis of the ability of the injured natural resources and services to recover naturally. In general, factors to consider include:

- The sensitivity and vulnerability of the injured natural resources and/or services
- The reproductive and recruitment potential of the natural resources and/or services
- The resistance and resilience (stability) of the affected environment

The natural variability of the ecosystem

In the case of coral reefs, many things affect the ability of this resource to recover within a measurable time period.[25] The corals themselves are affected by human-induced and natural disturbances (e.g., near-shore pollution, hurricanes, coral diseases, bleaching due to global warming and/or ENSO events, etc.). The growth rates of most coral species are relatively slow. In addition, the distribution of gametes and larvae may affect the potential for recovery of coral species. For instance, in Florida reefs have been shown to be recruitment limited. All of these factors need to be considered during restoration planning.

Restoration ecologists also face the ethical question of whether or not it is actually possible to restore natural habitats such as coral reefs back to their predisturbed state.[69] One of the main goals of restoration ecology is to predict the results of specific restoration actions.[39] The demand for restoration guidelines has often exceeded scientific knowledge on the effects of certain restoration methods.[39] Therefore, published case studies are desperately needed to further understanding of how certain restoration practices affect coral reef ecosystems. Short- and long-term assessments of restoration projects are needed to determine the success (or failure) and function of a particular restoration method or practice.

1.2.12 Success Criteria

The word "success" has a number of meanings as it relates to restoration programs. The success of restoration projects is often evaluated as compliance success: whether environmental permit conditions were met or simply whether the stated projects were implemented or monitored. Quammen[70] distinguished functional from compliance success, noting that functional success is determined by whether the ecological functions of the system have been restored. For example, in evaluating the success of wetland restoration/mitigation projects in Florida, Redmond[71] showed that disconnected decision-making resulted in an abundance of restoration projects but failure in the sense of compliance and function: more than 80% were in noncompliance with permit conditions and/or not achieving expected ecological functions. In the past, many restoration assessments have emphasized structural rather than functional attributes. In fact, many structural attributes, such as species diversity, become indicators of function when monitored over time. The success of restoration efforts, therefore, must be determined by our ability to meet technically feasible and scientifically valid goals and focus our monitoring efforts on both structural and functional attributes. This establishment of realistic, quantifiable, ecologically based criteria is basic to the planning process for all habitat restoration and creation projects. As we have discussed, if the stated goal of reef restoration is to return the ecosystem nearly to predisturbance, baseline conditions and functions, assessment and monitoring programs must be used to evaluate and compare natural, undisturbed reference sites with disturbed and restored sites. For most ecosystem restoration programs, including reef restoration programs, functional analysis has lagged behind project compliance, with the results that goals and success criteria have generally been set ad hoc. To date, it seems as if coral reef restoration ecologists have not learned from one another, and thus the same issues are readdressed and the same problems are confronted over and over again.

1.2.13 Goal Setting

The degree of reef damage by a ship-grounding for instance may set practical limits on the viewpoint and goals of restoration. For example, radical reconstruction is required where large volumes of material have been removed, gouged, fractured, or flattened. Lesser damage may require only partial rehabilitation, such as the reattachment of damaged and overturned corals[15] and coral transplantation or reintroduction.[72–75]

Historically, successful restoration projects have been evaluated primarily by the establishment of certain attributes such as coral cover and/or the abundance of fish species. It is necessary to move beyond this tradition and focus not only on charismatic organisms but on ecosystem function.[39,76] Essentially, all definitions of success are dependent upon the likeness of the restored ecosystem (both in terms of structure and function) to comparable reference sites. However, many would still argue that no restored coral reef (or any ecosystem for that matter) will ever be as successful as the original; therefore some minor relaxations in criteria should be considered.[60] Nevertheless, without using standardized criteria, coral reef success will continue to go unassessed, which in turn may lead to continued mistakes and failures.

Compared to terrestrial and wetland restorations, which range in the thousands of implemented projects, coral reef restoration is in its infancy, with only tens of projects performed. In addition, few of these have been published or described. Therefore, at present there is little basis for

2073_C001.fm Page 14 Wednesday, November 30, 2005 3:38 PM

understanding what works, what does not, and why. Three of the most important questions that need to be addressed in all restoration programs are[25]:

1. How long will it take for natural recovery to occur at any given site without manipulation?
2. Will natural recovery converge on a community state that is different from its predisturbance state?
3. Will reefs disturbed by humans respond differently than those damaged by natural processes?

Hypothesis-driven ecological studies and quantitative, long-term monitoring programs are the only means of answering these critical questions. Formulating and testing hypotheses about the response of reefs to anthropogenic disturbances allows us to establish the scientific protocol necessary to design and implement restoration strategies, a baseline for developing quantifiable success criteria, and the efficacy of the restoration effort.[25]

1.2.14 A Scientific Basis for Restoration

Understanding whether reefs will heal through self design or need to be actively restored through manipulation and intervention (engineered design) requires a thorough scientific understanding of the recovery process. The basic principles of coral reef restoration are essentially the same as the basic principles of ecological succession. Inasmuch, we are interested in what determines the development of coral reef ecosystems from very early beginnings through senility and what may cause variation in them at points in time and space.

The essential quality of restoration, therefore, is that it is an attempt to test the factors that may alter this ecosystem development through time and space. This gives restoration scientists a powerful opportunity to test in practice their understanding of coral reef ecosystem development and functions. The actual restoration operations that are performed are often dominated by logistical or financial considerations (and possibly by government regulations), but their underlying logic must be driven by ecological hypotheses. Therefore, hypothesis-driven restoration programs are truly an "acid test" for ecological theory and practice.

Formulating and testing hypotheses about the responses of communities and whole ecosystems to disturbances and about the process of recovery will establish:

1. The degree to which the ecosystem in question has the capacity to naturally recover (self design)
2. How intervention (engineered-design) in recovery can retard or enhance the process (or have no effect)
3. The scientific protocols necessary to design and implement restoration strategies

A scientific baseline for developing quantifiable success criteria and the efficacy of the restoration effort

Using ship-grounding sites in the Florida Keys, Aronson and Swanson[16,17] and Precht et al.[25] developed and tested hypotheses that take advantage of some simple facts about major reef injuries: when ships contact reefs they break and crush coral rock, kill corals and other sessile organisms, open bare space for colonization, and eliminate topographic (habitat) complexity. Following a ship-grounding, recruitment and growth of sessile organisms can take the community in three possible directions. The first is toward the community structure of the preimpact community, usually judged from the current state of the adjacent undamaged area. The second is toward some other community structure or alternate community state.[77] The third possibility is no change at all from the initially damaged, primary substratum. The probability of the latter, "null" alternative is vanishingly small, given the inevitability of bacterial and algal colonization of primary substratum in the sea. The second alternative leads to an interesting prediction. If a ship-grounding flattens the topographic complexity of a highly structured reef habitat, and if complexity does not recover through coral growth (self design), then community structure could develop so as to converge on that found in natural hardground habitats. Hardground communities typically have low topographic complexity, consisting of flat limestone pavements with crustose coralline algae, gorgonians, and isolated coral colonies. Where ship-groundings occur in hardground habitats, recovery should be back to a hardground community structure.[25]

Aronson and Swanson[16,17] conducted a study in the FKNMS during a 2-yr period (1995-1996) that evaluated the 1984 *Wellwood* grounding site. Replicate sampling sites were established within areas of the *Wellwood* grounding site that were formerly spur-and-groove habitat. Benthic assemblages at these sites were surveyed using video techniques.[78] Two types of undamaged reference sites were also surveyed: spur-and-groove sites adjacent to the *Wellwood* site and hardground sites at Conch and Pickles Reefs. Univariate parameters of community structure and biotic composition of the ship-grounding site resembled the natural hardground habitat more closely than they resembled the adjacent spur-and-groove area. When comparing the reference sites to the impacted sites among the sampling years 1995 and 1996, hard coral cover was uniformly low in the ship-grounding and hardground surveys and higher but variable in the spur-and-groove surveys. The spur-and-groove reference sites were significantly more complex topographically than either the grounding sites or the hardground reference sites, which were not significantly different from each other. Interestingly, the Pickles Reef site, which was originally thought to represent a natural hardground, turned out to be the site of two earlier ship groundings; one of the groundings occurred circa 1800 and the other was in 1894. Debris from the two nineteenth-century groundings was still visible, but the Pickles Reef reference site was otherwise indistinguishable from the Conch Reef hardground reference site. The fact that the Pickles Reef site was similar, both visually and quantitatively, to the Conch hardground reference site is strong evidence that ship groundings do indeed produce hardgrounds.[25]

In a companion study evaluating coral recruitment success, Smith et al.[79] showed essentially no increases in juvenile coral abundance and diversity within the *Wellwood* site since 1989 and the relative absence of juveniles of major frame-building corals at all study sites. These results are an indication of recruitment limitation. Overall, this grounding study suggests that the damaged spur-and-groove habitat will not recover to its former state on a time scale of decades without substantial restoration efforts (engineered design). Multivariate analysis indicates that those restoration efforts must include reestablishment of the topographic complexity to enhance the recruitment and growth of coral species that naturally occur in spur-and-groove habitats.[16,25]

In contrast, a study of the 1989 *MV Elpis* grounding site in the FKNMS in 1995 to 1996 revealed that the damaged hardground community was statistically indistinguishable, in univariate and multivariate comparisons, from adjacent hardground reference sites. The *Elpis* site, after a decade of recovery, could not be distinguished from the surrounding hardground habitat. These results suggest that when a ship-grounding occurs in a hardground habitat, it is likely that the community will recover within a decadal time frame. Rehabilitation measures, especially substrate stabilization and coral transplantation, will likely accelerate this natural recovery.[25]

The loss of topographic complexity as a result of vessel groundings in high-relief, spur-and-groove habitats has serious implications for reef recovery. When complexity is reduced, the hydrodynamic forces change and populations of reef fish and sea urchins decrease. Both of these factors influence the trajectories of colonizing reef communities.[15,80] In addition to the lack of recovery of coral fauna mentioned above, Ebersole[81] noted striking differences between fish assemblages on undamaged spur-and-groove sites and both natural hardground and damaged sites, which were themselves indistinguishable. Restoration of habitat complexity may be the vital ingredient in the overall recovery of damaged reefs.[25]

1.2.15 Compensatory Restoration

For any given injury or disturbance on a coral reef, an interim loss of both natural resources and ecological services occurs. Ecological services refer to activities of ecosystems that benefit humans.[82] Even assuming successful recovery of the damaged resource through restoration, the repair of the damaged area alone is not sufficient to compensate for the total losses incurred due to the incident. Since restoration takes time and the resource will take years (possibly decades) to recover to a functional equivalency after restoration is implemented,[25] compensation for these interim losses must be incorporated into the estimate of the total damages. Accordingly, these interim losses of resource use are often sought as compensatory restoration. The manners in which interim ecosystem losses have been computed have been very inconsistent and have often been driven by financial and not scientific protocol.[57,83] In order to quantify the loss of use, one of the most commonly applied techniques has been a habitat equivalency analysis (HEA). HEA is a method for determining the appropriate compensation for interim loss of natural resources.[46,84,85] The HEA is an appropriate method for quantifying compensation in resource situations where substantial human use is not present (i.e., an adequate measure of human use cannot be calculated for the particular habitat). The concept behind HEA is to provide an equivalency between the ecological functions ("services" that the ecological system provides to humankind and the ecosystem) lost due to the injury and the ecological functions provided by the replacement project. The equivalency allows for the calculation of the size of a habitat replacement project necessary to compensate for the interim loss in habitat services. The HEA methodology combines elements in all components of a NRDA including the quantification of injury, the analysis of restoration projects, and the valuation of lost services.[46] For cases involving injuries to coral reefs, the ecological functions lost due to the injury and those provided by the replacement project are often calculated in terms of coral growth over time on a replacement habitat.

The injury assessment strategy to calculate interim loss on coral reefs should be based on six logical steps:

- Documentation and quantification of the injury
- Intrinsic value of damaged resource
- Identification and evaluation of restoration options
- Estimate (in years) of rates for "natural" reef recovery (self design)
- Determination of the most appropriate means of restoration (engineered design)
- Economic scaling of the restoration project over time until functional success is obtained

Interim loss-of-services is then calculated as an integral of service lost from some reference point or baseline level over time (Figure 1.3). Thus, the HEA is an economically based "model" that provides a means of standardizing computations of interim loss. Recently, Banks et al.[86,87] used a similar Habitat Equivalency Model (HEM) to assess the resource loss when the USS Memphis submarine ran aground on a reef off Fort Lauderdale, Florida. Similarly, Deis[46] reported on the use of these methods to determine adequate compensation for impacts from fiber-optic cables on coral bearing hard-bottom in the Fort Lauderdale, Florida area. When coupled with long-term scientific monitoring, these methods also provide a reasonable basis upon which to gauge compensatory restoration success (actual time to establish reef recovery and/or functional success).

In some cases, the most appropriate means of compensatory restoration is a monetary settlement, where the funds are earmarked for specific programs. These might include antigrounding campaigns; coral reef education and outreach programs; interpretive exhibits; boat pilot training; installation of mooring buoys at designated sites; increases in navigational markers; and long-term, scientifically based (not compliance mandated), monitoring studies that empirically gauge the functional success and/or failure of past restoration efforts. Other additional off-site compensatory restoration could include development of coral aquaculture programs (nurseries) and identification

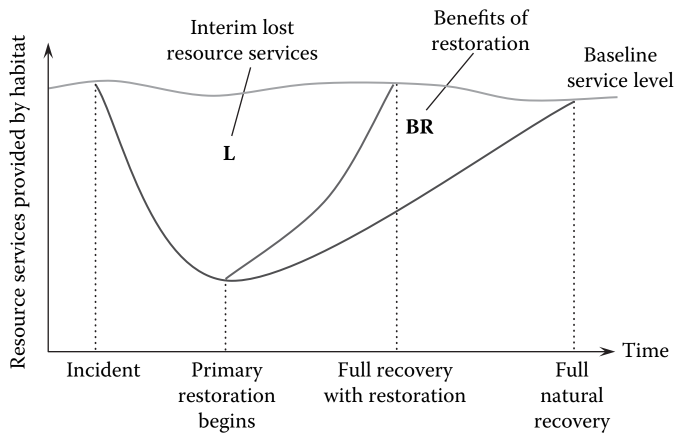

FIGURE 1.3 Graphic depiction of lost ecosystem services due to resource injury and the benefit of performing primary restoration.

of coral donor sites; artificial reef creation projects; establishment of baseline monitoring surveys of undisturbed reef resources; and restoration of damaged "orphan" sites where no responsible party had been identified, yet site rehabilitation/restoration is necessary to repair resource loss.

1.2.16 Long-Term Monitoring and Adaptive Management

After success is defined, the next step becomes working towards the realization of these goals. Specifically, restoration scientists must:[39]

1. Use preexisting ecological theory to maximize their potential for success

Periodically evaluate the project(s) via hypothesis-driven monitoring

Although often overlooked, postrestoration monitoring is very important (Figure 1.4). Pickett and Parker[88] noted that one of the pitfalls of restoration is to think of it as a discrete event when

FIGURE 1.4 Scientific diver performing long-term, hypothesis-based monitoring of reef function.

restoration is actually "an ongoing process." When required, monitoring periods typically range from 3 to 5 years, during which the site's structure and function are expected have become fully established.[41] Because of the slow growth rate of corals, this 3- to 5-year time period is often inadequate for an ecosystem to become established or to determine whether all of the reestablished ecological processes are properly functioning.[41,58] To ensure that ecological processes, especially those that function on larger spatial and temporal scales, have been properly reestablished to a system, restored sites should be monitored and managed for longer periods of time. Moreover, by monitoring restoration activities for longer periods of time, restoration scientists can assess the ability of different restoration activities to achieve desired goals and focus future research efforts where needed.[40,55,58,88]

It is easy to define a coral reef restoration project as successful merely on the establishment of coral cover. While these projects may initially seem to be successful, long-term monitoring has proven that it takes other components (and efforts) than coral cover alone to guarantee the long-term perpetuation of the coral reef ecosystem. In many cases coral reef restoration projects are not monitored at all for success or failure. Others are only monitored for a short period of time after restoration efforts are completed because (1) there is insufficient funding to support continued assessment, and/or (2) legislative regulations do not require monitoring.

Adaptive restoration begins by recognizing what we do not know about restoring a specific site.[89] The unknowns might be what ecologic targets are appropriate, how to achieve desired targets, or how to monitor the site to determine when (or if) these targets are met. For restoration to be truly adaptive, the decision-making structure must include scientists who can best explain how the knowledge can be obtained and what research can be incorporated into the restoration project, and funds need to be earmarked and made available for this strategic, applied research and monitoring effort.

Therefore, all coral reef restoration programs should be based on the following philosophy:

> ...management decisions should be treated as hypotheses of ecosystem response, and restoration programs should be designed as experiments to test them. This approach to ecosystem restoration allows management decisions to be revised (adapted) to meet project goals .

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Because coral reef restoration programs are "hypotheses of ecosystem response" based on incomplete information, uncertainty has long been a hallmark of these programs. An adaptive approach to ecosystem management, as described above, must be undertaken to ensure project success.

This progressive view of management recognizes three important principles:

- Management decisions should adapt to the results of the scientific studies and monitoring efforts.
- A multidisciplinary team of competent specialists should direct and guide all scientific studies.
- An independent Quality Assurance/Quality Control (QA/QC) team of highly qualified experts should oversee all projects.

A number of monitoring methodologies have been developed that are diverse in their application as well as their goals. These methods are used to obtain biological and ecological information for effective resource management decision-making. The synthesis of this collected information has four main objectives:

1. To prepare baseline information used in developing a restoration plan for the area being assessed
2. To study patterns and to describe trends through time
3. To determine compliance with all environmental permits
4. To determine whether the project goals have been attained

Successful adaptive monitoring programs dictate that field data must be collected in a manner that accommodates not only traditional methods of characterizing abiotic and biotic associations, but also new developments in spatial statistics. The combination of implementing proven sampling methods with cutting edge GPS/GIS methods of collecting spatially referenced data in the field meets this objective.

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This monitoring approach will allow a straightforward analysis of data and will test all the criteria stated in the restoration design plans and/or permit(s). It will also reveal biologically and statistically significant trends and patterns that could then become the focus of corrective actions in cases where restoration projects are not meeting design or permit criteria. Restoration results may vary significantly with methods and at different locations. If restoration designs are not meeting the desired objectives, modifications should be considered.

For adaptive management to succeed there also needs to be consensus among scientists, managers, and other stakeholders involved in the process, and they all must be willing to change actions in response to knowledge gained. One of the keys in this process is the input of a variety of multidisciplinary experts including biologists and ecologists, geologists, engineers, physical scientists, resource managers and economists, and others dedicated to a common vision — project success. While different experts often have divergent opinions, the Delphi technique has proven to be a successful method for developing consensus among experts. The Delphi technique is based on the following general principles:

1. Opinions of experts are justified as inputs to decision-making where absolute answers are unknown.
2. A consensus of experts will provide a more accurate response to questions or problems than a single expert will.

Part of the ability to run a successful adaptive management strategy on all environmental restoration projects is to have a QA/QC team that functions independently of all elements of the project from design through implementation and evaluation. Specifically, this QA/QC team does not overly participate in the actual project. This independence assures unbiased oversight and reviews for the benefit of the overall goals of the project and accordingly, the resource.

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1.3 CONCLUSIONS

Restoration is a relatively new and rapidly expanding discipline that combines many fields of science including ecology, geology, socioeconomics, and engineering. Although the specific goal of restoration is to restore the ecological function of a particular ecosystem, a multiscale approach is needed to ensure the successful restoration of a site, especially in the case of coral reef restoration. Those conducting restoration activities must examine how ecological processes that vary in spatial and temporal scales have influenced the function of a reef system and determine which processes need to be reestablished to restore critical coral reef functions. A multiscale approach can ensure that stressors to the reef ecosystem are removed or accounted for, that critical ecological processes have been successfully introduced, and that the restoration itself is not negatively impacting the function of the landscape. Additionally, a multiscale approach to restoration may result in greater ecological and environmental benefits because it allows for enhancement to occur at more than one scale.

Restoration is an attempt to overcome, through manipulation, the factors that impede the natural recovery of an impaired resource. For instance, when vessels run aground, they kill coral and reduce topographic complexity, thus dramatically altering the local ecosystem and its services. In these cases the ultimate goal is to restore damaged reefs that are functionally equivalent to their uninjured counterparts. To properly undertake the damage assessment and restoration strategy as outlined above requires a multidisciplinary team of individuals dedicated toward a common goal. Careful documentation of the resultant injury is critical to this planning process.[48] This approach to impact assessment and restoration planning will provide an ecologically defensible basis upon which to document the injury, set restoration goals, implement the appropriate restoration plan, and gauge overall project success. Reef restoration also challenges our understanding of reef ecosystems. Therefore, the logic underlying successful restoration must be rooted in an integrated, multidisciplinary approach that includes engineering, geologic, biologic, aesthetic, and socioeconomic considerations. The outcomes of such efforts will tell us what we know, what we do not know, and what will work in practice. While there is no cookbook for restoration, there is a general recipe.

Finally, we must glean as much as we can from the few restoration projects completed to date,[90–92] and we can profit from the vast knowledge gained in performing terrestrial, wetland, and coastal restoration.[85,93–102] Better reef restoration efforts can be achieved by setting goals based on the structure and function of local, unimpaired reefs of similar habitat type and by incorporating what we have learned from the successes and failures of earlier projects. We will learn more from our failures, because failure reveals the inadequacies in our designs.[103] Developing successful restoration efforts in the future will depend upon acquiring and applying a scientific base to this emerging discipline. In addition, because of the infancy of this enterprise, the continued sharing of information will be vital to improving restoration strategies over time. The status of coral reef ecosystem restoration has advanced a great deal in a short time. As restoration scientists and managers, we should be excited with the opportunities that lie ahead.

It is hoped that the protocol established in this document will assist resource managers in developing and guiding coral reef assessment and restoration strategies under their stewardship into the future. Conversely, better quality restoration will in turn lead to better management and more secure protection of the resource for future generations.

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