CHAPTER 3: RESTORATION MONITORING OF CORAL REEFS

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INTRODUCTION

Shallow-water coral reefs (Figure 1) are diverse ecosystems found in warm, clear, shallow tropical and sub-tropical oceans, primarily between the latitudes of 30˚ north and south, in the Western Atlantic, Indian, and Pacific Oceans. The United States has jurisdiction over an estimated 19,700 km^2 of coral reefs, not including the Freely Associated States (Turgeon et al. 2002). U.S. reefs are found in the:

- Western Atlantic
- Caribbean
- Gulf of Mexico off Florida (Florida Keys, east coast of Florida and Florida Middle grounds)
- Puerto Rico
- U.S. Virgin Islands
- Navassa Island, and
- On the continental shelf about 100 miles south of the Texas/Louisiana border (e.g., the Flower Garden Banks National Marine Sanctuary).

U.S. Pacific reefs are found off the:

- Hawaiian Archipelago
- American Samoa
- Commonwealth of the Northern Mariana Islands, and
- Guam

In the U.S. Pacific Remote Island areas, coral reefs include:

- Baker
- Howland
- Jarvis Islands (i.e. table reefs)
- Johnston
- Kingman
- Palmyra
- Rose, and
- Wake Atolls

In addition, well-developed coral reefs are associated with the Freely Associated States (Palau, Marshall Islands, and the Federated States of Micronesia).

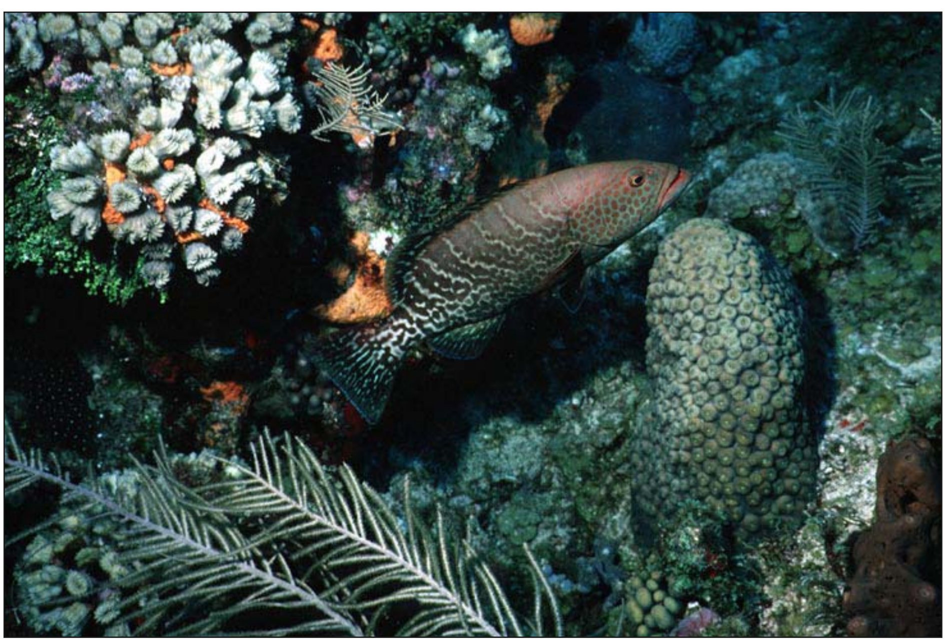

Figure 1. Star coral reef (*Montastrea cavernosa*) with a tiger grouper (*Mycteroperca tigris*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

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Coral reefs discussed in this chapter consist of consolidated limestone or unconsolidated rubble constructed primarily from the skeletal remains of invertebrates and algae. Living corals and other benthic organisms form a thin veneer that overlies a limestone framework deposited over thousands of years by their ancestors, and solidified by the combined processes of cementing coralline algae, mechanical action of waves, bioerosion from boring sponges and other organisms, and the chemical action of rainwater. Reef-building scleractinian corals are the dominant organisms responsible for most of the framework growth, followed by coralline algae on wave-exposed reef slopes, and green algae (e.g., *Halimeda*) in backreef and lagoonal depositional zones. Other important organisms contributing sediments to reef structure include mollusks, foraminiferans, and echinoderms.

Reefs can be classified according to their geological history, shape, position relative to land masses, and materials from which they are constructed. Although there is continual variation from one reef type to another, most coral reefs can be merged into three broad categories: fringing reefs, barrier reefs, and atolls. There are also several specialized reef types such as platform reefs, patch reefs, table reefs, and bank reefs. Fringing reefs are mostly located close to shore, while barrier reefs are typically offshore, at the edge of the continental shelf. Barrier reefs are separated from land by a lagoon that may contain patch reefs, mangrove islands, grass beds, and soft bottom algal flats. Most atolls are annular reefs enclosing a central lagoon that develop at or near the surface of the sea, beginning as fringing reefs around high islands and gradually becoming more distant from land as the island subsides and reefs grow upward. Bank reefs are common in the Caribbean, and formed on offshore banks or platforms in response to sea level fluctuations over the last 8,000 years since the last ice age. Table reefs are similar to atolls except they do not enclose a central lagoon.

Coral reefs contain several zones such as the backreef, reef crest, and fore reef slope that are characterized by their depth, wave exposure, structure, and biotic communities. The dominant sessile invertebrates found in all zones, except in areas of extreme wave exposure, are scleractinian corals. Scleractinian corals are similar in structure to sea anemones, with each polyp having six or multiples of six tentacles. They are unique, however, in that they produce an external calcium carbonate skeleton and often form colonies consisting of thousands of interconnected polyps. Scleractinian coral colonies may be hundreds to thousands of years old and form massive structures several to tens of meters in height. Other dominant cnidarians found on coral reefs are the octocorals, which include:

Gorgonians (e.g., sea fans)
Soft corals (leather corals)
Blue coral (*Heliopora*)
Organ pipe coral (*Tubipora*), and
Sea pens

Unlike scleractinian corals, octocorals have eight pinnately-branched tentacles, and most lack an external skeleton. *Heliopora* is the only shallow-water octocoral that forms a massive aragonite skeleton similar in structure to scleractinian corals, and *Tubipora* has a skeleton that consists of a series of parallel polyps encased in calcareous tubes of fused sclerites. Gorgonians have an internal skeleton consisting of a proteinaceous (gorgonin) central axial skeletal rod and separate embedded calcareous spicules, while soft corals possess soft, fleshy, or leathery bodies with embedded calcareous spicules. Other sessile organisms, such as sponges (Figure 2), tunicates, and bryozoans also contribute to the complexity of the reef's structure (Holliday 1989; Sorokin 1993).

The major factors controlling the global distribution of coral reefs are light and temperature, with water turbidity currents, storms, wave exposure, sedimentation, and salinity affecting

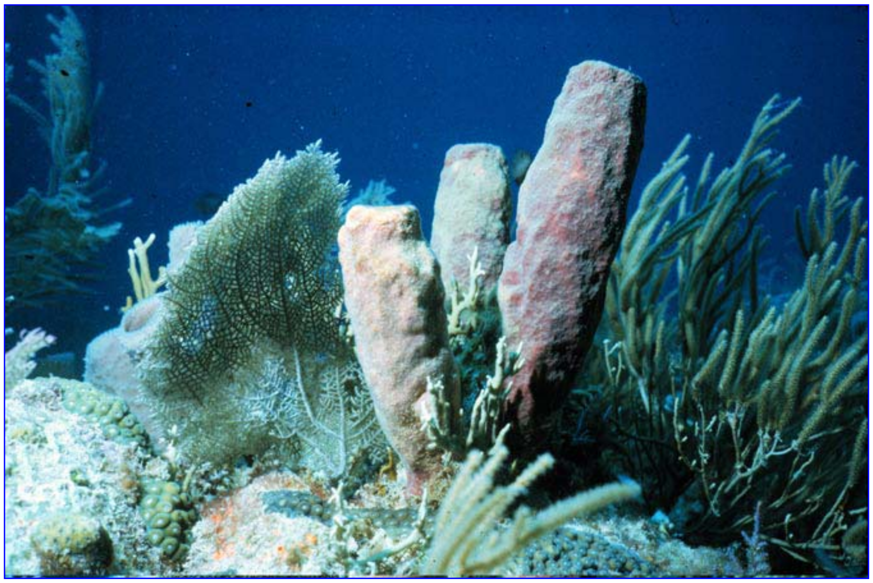

Figure 2. Sponge (Porifera) and sea fan (Gorgonia) on a coral. Photo courtesy of B. Walden, NOAA Research-National Undersea Research Program. Publication of NOAA Central Library. http://www.photolib.noaa.gov/nurp/nur03002.htm

species diversity and abundance within specific coral reef habitats. Because of the dependence of zooxanthellae on light for photosynthesis, reef-building corals are restricted to depths of about 70 m in clear water. Water temperature on most coral reefs remains fairly constant throughout the year, with optimal growth at temperatures of 22-30°C. Temperatures on some subtropical reefs, such as in the Florida Keys and Flower Gardens, will drop to 16°C in winter, and in some extreme shallow environments such as tidepools, temperatures may increase to over 34°C. While certain corals can tolerate even lower temperatures for short periods, rapid declines in temperature or prolonged colder than normal temperatures may result in extensive coral mortality. Heat stress can also lead to colony death. Temperature increases of 1-2°C above the long-term average for one to two weeks is known to trigger bleaching, causing corals to turn white due to the loss of the symbiotic zooxanthellae (Hoegh-Guldberg 1999; Westmacott et al. 2000; Salm and Coles 2001). Other stressors such as high levels of ultraviolet (UV) radiation, reduced salinity, and low temperatures also cause localized bleaching, although temperature increases are believed to be the most critical factor responsible for global and regional bleaching events (Wilkinson 2004). Although corals can recover from bleaching, prolonged higher than normal temperatures and other stressors may increase susceptibility to disease and can result in partial to total colony mortality.

ECONOMIC VALUE OF CORAL REEFS

Coral reefs provide economic and environmental services to millions of people by protecting shorelines; providing sources of food, building materials, and pharmaceuticals; and creating employment, recreational, and tourism opportunities. The estimated global economic value of coral reef ecosystems is about $375 billion per year (Costanza et al. 1997). In 2000, an estimated 10.5 million people resided in U.S. coastal areas adjacent to shallow-water corals reefs and another 45 million tourists visited these reefs (Turgeon et al. 2002). In addition, the annual ex-vessel[3] value of commercial fisheries associated with U.S. coral reefs is estimated at over $137.1 million (NMFS 2001). In southeast Florida, 18 million people participated in reef-related activities during 2001, and these reefs are estimated to have an asset value of $7.6 billion (Johns et al. 2001). Recreational fishers, divers, and snorkelers that use the natural reef in Broward County, Florida are willing to pay $83.6 million per year to maintain their natural reefs, $55.9 million per year to maintain the

[3] When a commercial fishing boat lands or unloads a catch. For example, the price received by a captain for the catch is known as the ex-vessel price.

existing artificial reefs, and $15.7 million per year to add new artificial reefs (Johns et al. 2001).

HUMAN IMPACTS TO CORAL REEFS

Coral reefs are declining in many areas of the world due to steadily increasing threats from direct human pressures and indirect effects of global climate change. The three major human stressors to corals reefs worldwide are overfishing, sedimentation, and land-based sources of pollution, exacerbated locally by other stressors such as:

- Destructive fishing practices
- Oil, metal, and/or chemical pollution
- Coral mining
- Uncontrolled tourism, and
- Physical damage from ship groundings and anchors

There are various natural stressors that also impact coral reefs and are discussed primarily in the structural and functional characteristics sections of this chapter. Some of these natural stressors include outbreaks of coral eating predators (e.g., crown-of-thorns sea star), coral diseases, bleaching, tropical storms and hurricanes, and unusual rainfall events. Until recently, most reefs recovered fairly rapidly from these natural stressors. When combined with cumulative human pressures, however, recovery may be significantly delayed or prevented. Once human impacts are removed ecological recovery may still take many years, depending on the extent and type of damage, duration of the impact, and diversity and complexity of the affected ecosystem.

Despite the longevity and apparent natural resilience of corals and the reefs they construct, both are extremely vulnerable to destruction by human activities, either gradually through degraded habitat quality, or suddenly through catastrophic damage from vessel groundings, toxic spills, or habitat destruction. In some cases, degraded reefs have undergone phase shifts from highly productive coral-dominated systems to algal reefs that persisted for more than 20 years. In these situations, ecological recovery may be facilitated through mitigation or restoration efforts. However, for restoration to be effective, it is imperative that resource managers:

1) Understand the causes and effects of human-induced disturbances
2) Properly assess these damages
3) Eliminate or reduce the stressors that contribute to the decline, and
4) Develop a subsequent restoration approach that addresses the specific needs of the particular site, prior to undertaking restoration efforts

Finding appropriate solutions to a particular damage scenario is often hampered by an incomplete understanding of the ecological effects of human impacts as well as processes and factors that contribute to natural reef recovery. Hypothesis-driven ecological studies and quantitative, long-term monitoring programs are important to answer these critical questions. Baseline monitoring data can be used to help identify and develop appropriate components of the restoration approach, develop quantifiable success criteria, and evaluate the efficacy of the restoration effort. This chapter presents a brief overview of human-induced stressors that impact reefs, management and restoration actions that may be undertaken to mitigate the impacts associated with these stressors, and monitoring approaches that are currently being used to document coral reef condition and effectiveness of management and restoration actions.

Pollution

Land-based sources of pollution

Pollution, including eutrophication and sedimentation associated with land-based activities, has been associated with the degradation of water quality and coral reef health and diversity (Lapointe et al. 2000). Some of the sources of pollution include improper coastal development; dredging and beach renourishment; land clearing for agriculture; discharge of untreated sewage, industrial waste, agrochemicals, and pharmaceuticals; and chemical and oil spills. Potential impacts to coral reef ecosystems from these stressors include:

- Poisoning sensitive species
- Altering species composition and distribution due to smothering and reduced light penetration
- Disrupting critical ecological and endocrine functions such as reproduction, coral/zooxanthellae symbiosis, and photosynthesis
- Impeding the settlement, growth, and survival of stony corals and other benthic invertebrates
- Enhancing the growth of competitive macroalgae and phytoplankton, and
- Increasing the prevalence and virulence of disease-causing pathogens and reducing the resistance and resilience of reef-building corals

Marine-based sources of pollution

In addition to land-based sources of pollution, marine pollution can kill existing benthic communities and retard recruitment. Excessive sedimentation generated by offshore dredging; ocean dumping; oil, gas, and mineral extraction; and certain types of fishing gear such as bottom trawls can cause increased turbidity as well as physical injuries, burial, and smothering of corals (Blair et al. 1990; Lirman et al. 2003). Numerous chemicals can enter coral reef habitats through industrial effluent, vessel discharge, and oil and chemical spills. Many reefs are also inundated by large amounts of human-made debris lost by commercial fishing operations or emanating from other marine and terrestrial sources. These objects degrade reef health by abrading, smothering, and dislodging benthic organisms and entangle marine mammals, turtles, birds, and pelagic fishes.

Coral reefs are increasingly vulnerable to invasion by alien species introduced via discharge of ballast water, releases from aquaria and aquaculture operations, and fouling organisms on ships hulls and marine debris. Alien species invasions have led to fundamental changes in natural communities as a result of their superior competitive ability, lack of predators, and introduction of parasites and diseases that commonly accompany them. One of the best examples of alien introductions into coral reef communities is in Hawaii, where several species of invasive, nonindigenous marine algae were introduced for commercial aquaculture and subsequently abandoned, yet are proliferating throughout shallow environments and pose a severe threat to nearshore reefs (Squair et al. 2003). As alien algae spreads, it smothers areas dominated by corals and native algae, and reef habitats rapidly shift from diverse coral communities to monotypic stands of alien algae. The loss of corals may affect fish diversity and abundance, and without intervention, a once healthy reef may become a highly degraded system with few surviving corals and fish (Stimson et al. 2001).

Overfishing and Destructive Fishing

Coral reef fisheries support and sustain communities by providing food and income, and play a central social and cultural role in many island communities. Recently, many fisheries have become unsustainable due to human population growth, the emergence of export fisheries, and use of more efficient fishing equipment. Overfishing of high-value species has been documented on nearly all U.S. inshore reefs. Localized depletions of key species such as groupers, snappers, and parrotfish may have impacts on other members of the reef community. In particular, overfishing of herbivorous fish has been linked to "phase-shifts" from high-diversity, coral-dominated systems to low-productivity, algal-dominated communities (Fossaa et al. 2002; Turgeon et al. 2002). Excessive fishing pressure on predatory fish may also accelerate bioerosion of corals by releasing their invertebrate prey (e.g., corallivorous snails and sea stars) from predation pressure. Destructive practices, such as cyanide and dynamite fishing and the use of small mesh gill nets and bottom trawls, can damage reef habitats by breaking and dislodging corals and other sessile invertebrates, resuspending sediments, and increasing turbidity.

Recreational Overuse

Coral reefs are a major water attraction for tourists visiting the tropics and subtropics, and their presence contributes significantly to the economy of many coastal communities. In many countries, including the United States, coral reefs have been exploited to support the growth in tourism. The impacts include increased development in the form of hotels, marinas, restaurants, roads, airports, and consequently increased sedimentation as a result of beach nourishment and channel dredging projects, and nutrient input from septic systems, golf courses, and gardens associated with hotels (Sudara and Nateekarnchanalap 1988; Hawkins and Roberts 1994; Turgeon et al. 2002). Most tourists also visit popular dive, snorkel, and fishing sites, which may lead to increased boating accidents, habitat damage from anchors, trampling and diver contact, illegal and damaging fishing practices (e.g., spearfishing), increased trash, and removal of shells and corals for souvenirs and curios.

Physical Damage

Commercial and recreational vessels striking coral reefs cause localized damage to shallow coral reefs. Impacts include fracturing and removal of the three-dimensional reef structure, thereby crushing and dislodging corals and other sessile invertebrates, uprooting seagrasses and displacing resident fishes (Precht et al. 2001). Propeller scarring and other physical impacts from small recreational and fishing boats and anchors is more frequent and, cumulative damage to corals and associated seagrass beds can be significant in areas of high recreational use. Although less frequent, large vessel groundings cause more insidious damage, including the fracturing of the underlying reef structure as well as collateral damage during salvage and removal of the vessel which may increase the footprint of the original scar. Secondary impacts may also include scarring and abrading of previously uninjured resources and increased sedimentation (sedimentation discussed in 'Marine Pollution' section) as waves and currents disperse rubble produced in the original grounding. Some affected habitats will not recover without direct, and often expensive, human intervention, for activities such as direct removal of debris or vessels, emergency triage of injured animals, and other restoration strategies to enhance recovery of benthic communities (Precht et al. 2001).

RESTORATION EFFORTS

Most previous restoration projects in the United States have focused on physical damage caused by humans, including vessel groundings, harbor dredging, and other discrete shoreline modification projects. Emergency restoration efforts associated with vessel groundings should be taken as soon as possible following an incident to reduce the overall extent of the injury. This may include righting and reattachment of displaced and broken coral (Figure 3), removal and stabilization of loose rubble, and repair of

Figure 3. A diver prepares to reattach an elkhorn coral fragment on Mona Island, Puerto Rico. Photo courtesy of Erik Zobrist, NOAA Restoration Center. http://www.photolib.noaa.gov/habrest/r0000732.htm

structural fractures (Precht 1998). The degree of damage by ship groundings or other physical disturbances may set practical limits on the scope of the restoration. Factors that should be considered when designing a restoration strategy include the:

- Costs to conduct various alternative approaches
- Extent to which each alternative will prevent future injury
- Likelihood of success of each alternative, and
- Extent to which each alternative is likely to return the injured natural resource and services to pre-damage state (Precht et al. 2001)

As Federal resource trustees for United States coral reef environments, the National Oceanic and Atmospheric Administration (NOAA) has been involved in a number of major ship grounding restoration efforts within Federal waters (especially in national marine sanctuaries). NOAA's Office of Response and Restoration and the NOAA Restoration Center, in partnership with Federal, state, and local agencies as well as non-governmental and non-profit organizations, have also assessed damaged reefs caused by hazardous material spills, recreational and commercial vessel groundings, and anchor damage, and implemented coral reef restoration projects in attempt to speed up recovery of the structure and function of the reef after these impacts. These efforts have often spanned years and required large sums of money that may be recovered from responsible parties. Restoration efforts involve activities ranging from initial response to damage assessment, litigation or cooperative settlement for damages, restoration planning, emergency repairs, and subsequent compensatory restoration activities. NOAA continues to provide financial and technical assistance for various restoration efforts in coral reef and other coastal habitats throughout the United States and its territories.

Several Federal statutes provide the United States government with the authority to recover resource damages caused by the grounding of vessels on coral reefs. A natural resource damage assessment (NRDA) process is used to identify and quantify natural resource injury, determine damages, and implement appropriate restoration actions (Mauseth and Kane 1995). Monitoring data can provide a defensible basis upon which to document the extent of injury and loss of natural resources and ecological services (impact assessment), set restoration goals, implement a restoration plan, and gauge the overall success at restoring ecosystem structure and function (Hudson and Goodwin 2001; Precht et al. 2001). One of the weaknesses of NRDA settlements associated with ship groundings, however, is that monitoring is not required by law to be part of the settlement, and is therefore not typically included. Responsible parties tend to be apprehensive to include monitoring in the settlement because they fear that additional compensation could be sought based on monitoring results. Thus, it has been difficult to gauge the effectiveness of these types of restoration efforts and the outcome is often unknown or inadequately studied (Miller and Rogers 2000). Because coral reef restoration is in its infancy, greater emphasis needs to be placed on hypothesis-driven restoration projects with detailed monitoring to determine the most cost-effective and ecologically beneficial approaches to restore the environment. The following section provides an overview of scientific monitoring approaches for coral reefs, with emphasis on application of these approaches to coral reef management and restoration.

MONITORING

The overall success in conserving coral reef ecosystems depends on the ability of managers to apply proactive, precautionary management measures that are successful in mitigating stressors, halting decline, and improving the overall health of the ecosystem. In some cases, this may require active restoration of reefs to prevent further degradation or to advance the natural recovery process in injured or damaged habitats. Developing the best strategy for conservation requires an understanding of the status of reefs, causes of decline, and impacts of natural and anthropogenic stressors. Because each reef is unique and cumulative stressors differ among sites, this information can only be acquired through monitoring and research at the specific sites of interest.

Coral reef monitoring involves the repeated surveys of organisms and environmental parameters (ecological monitoring) and the people who use coral reef resources (human dimensions monitoring) to provide information on abundance, diversity, and condition of particular species or their habitats, human use patterns, and changes to the ecosystem over time. Monitoring is fundamental to understanding the history, documenting the current state, and predicting the future condition of coral reef ecosystems. In addition to basic information on status and trends of coral reef resources and where they are located, long-term monitoring data can be used to guide decisions on whether and how the coral reef community needs to be managed or restored. A monitoring program can provide data to support effective management by:

- Providing baselines to enable early detection of change in coral reefs over time
- Identifying the controlling factors contributing to the stability, decline, or recovery of coral reefs
- Distinguishing the effects of human activities on ecological processes from natural changes
- Determining the response of coral reefs to management actions undertaken to reduce threats
- Evaluating the natural recovery and restoration of injured or degraded reefs, and
- Providing information necessary to adapt restoration and management activities to maximize recovery potential and conservation benefits

The design of a monitoring program will vary depending on the specific objectives and information needed to maintain, conserve, or restore particular coral reefs. The objectives may be very specific or more general, as determined on a case by case basis. A manager, for instance, may have a general objective to compare the condition of a reef under stress from human activities with a remote, undisturbed reef, or a more specific objective of determining the impact of a particular stressor, such as sedimentation associated with a coastal development or dredging project. Carefully thought-out objectives will help guide decisions on monitoring locations, frequency and duration of the monitoring program, specific biological and physical variables that need to be examined, detail (e.g., taxonomic resolution) of those variables, and appropriate scale of measurement. The most appropriate monitoring method will also depend on the available time, financial resources, equipment, and skills. Prior to undertaking monitoring, the restoration practitioners also need to consider how they will validate, analyze, and archive the data and communicate the results (Hill and Wilkinson 2004).

The primary ecological monitoring methods emphasize assessment of water quality, benthic communities (living and non-living components), motile invertebrates, and fishes. Baseline data are used to characterize the condition of a reef as it currently exists and address two questions:

1) What is the composition of the community? (This includes measures of species composition and abundance, total cover, cover of individual species, population densities and size frequency distribution, dispersion patterns, etc.), and
2) Are different communities, habitats, or populations correlated with or being affected by specific environmental and anthropogenic parameters?

Quantitative data on the ecological characteristics allow more standardized and accurate descriptions of the reef community, including comparisons of different reef areas and various zones within a reef. In addition, this type of information will provide a baseline against which to identify and quantify natural resource injury associated with physical impacts or other disturbances.

The primary focus for a monitoring program designed to evaluate a coral reef restoration project is to determine if the restorative measures are performing to an identified standard. For instance, at Western Sambo in the Florida Keys, a 200 m^2 reef crest environment dominated by elkhorn coral (*Acropora palmata*) was damaged by ship grounding. Detached corals were placed into cylindrical cement reef crowns and attached to the substrate which occupied a total of 20 m^2. After three years, the size, condition, and survivorship of restored fragments were examined and the resulting live cover was compared with surrounding unrestored habitat and a neighboring undamaged reference site (NOAA 2005). Using these monitoring data, the undamaged reference site could be compared with the restored area using the Bray-Curtis similarity coefficient (Bray and Curtis 1957) to determine whether the restored area has recovered to the pre-damaged condition.

Restoration efforts following impacts from the *Fortuna Reefer* ship grounding off Mona Island, Puerto Rico further illustrate the importance of monitoring in guiding future actions. Emergency restoration involved securing fragments of elkhorn coral (*Acropora palmata*) to the reef and to dead standing elkhorn skeletons using wire (NOAA 1997). A comprehensive monitoring program initiated two years after the grounding incident identified a major weakness that manifested over time - chronic failure of the stainless steel wire used to initially secure the fragments (Bruckner and Bruckner 2001). Data collection and analysis helped identify a mid-course correction to restabilize remaining fragments, resulting in maintenance of restored coral fragments on site that would have otherwise been lost. In addition, monitoring data on elkhorn coral survivorship over time are contributing to the development of new and improved techniques for restoring this species, including optimal placement, size, and orientation of fragments to maximize survivorship (Bruckner and Bruckner (a), *in press*).

STRUCTURAL CHARACTERISTICS OF CORAL REEFS

Although there are numerous reef types, such as fringing, barrier and atoll, they show certain similarities in structure and profile determined primarily by the physical environment, underlying topography, geological history, and the type of structure-forming (e.g., framework) organisms present. On the seaward side of the reef, the reef front or fore reef slope rises from lower depths to a shallow reef flat or reef crest. The inclination of the reef slope varies from gentle to steep, may be interrupted by one or more terraces, and often forms a vertical wall in deeper areas referred to as the drop-off. The shallow fore reef often has a series of finger-like projections that extend seaward and alternate with deeper sand channels (e.g., spur and groove formation). The reef crest is typically the area exposed to highest wave energy and may be partially exposed, especially at low tide. The reef crest separates fore reef habitats from calmer back reef environments.

The occurrence of particular scleractinian coral species and their development into coral reef communities is dependent on the availability of suitable substrata, thermal and light regimes, variations in salinity, levels of sedimentation and nutrient input, and local oceanographic conditions (e.g., wave exposure, storm frequency and intensity, and current patterns). Environmental factors, and consequently the species of corals and other animals found within a coral reef, vary depending on the reef zone. For instance, branching acroporids and pocilloporids typically dominate on the shallow fore reef and reef flat in areas of low to intermediate wave exposure. On the reef slope at intermediate depths, there is a high diversity of massive and columnar species, while plate-like species predominate in deep reef environments (Goreau 1959). In addition to the presence of distinct assemblages within reef zones, some species will overlap but exhibit wide variations in morphology. Because of these unique differences among zones, an understanding of the environmental attributes, structural features, and species composition is integral to the design of a restoration project as well as the particular method chosen to monitor the efficacy of the project. Factors that influence the structure and diversity of coral reefs may affect the design and assessment of a restoration project and include:

Biological

- Habitat created by animals[4]
- Biological controls
- Coral recruitment
- Diseases

Physical

- Bathymetry/topography
- Sediment (e.g., sedimentation rate)
- Turbidity and light availability
- Temperature

Hydrological

- Currents and wave energy
- Water sources (e.g., upwelling nutrients, land-based sources, etc.)

Chemical

- Nutrients (i.e., nutrients provided by algae and epiphytes)

Since many of these parameters can influence coral recruitment, survival, and growth, causes of site degradation must be understood and remediated as a first step in restoration. Appropriate species and growth forms must be carefully considered based on the physical attributes optimal for the target organisms.

BIOLOGICAL

Habitats Created by Animals

Scleractinian corals are considered foundation species, as they are a major source of three-

[4] Animals that form these habitat types are corals.

Figure 4. Shallow reef environment dominated by *Acropora palmata* and *A. cervicornis*. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

dimensional structure and topographic complexity which provides habitat for diverse community assemblages (Bruno and Bertness 2001). Reefs are also colonized by other sessile organisms that contribute to the reef's topographic complexity and diversity, such as:

Algae (crustose coralline, macroalgae, turf algae, and cyanobacteria)
Sponges
Other cnidarians (e.g., octocorals, hydrozoan corals, anemones, and false corals)
Tunicates, and
Bryozoans

Scleractinian corals secrete skeletons of calcium carbonate to form the basis of the reef structure (Wells 1956; Zann and Bolton 1985; Sorokin 1993). Rates of expansion of coral reefs require constant deposition of calcium carbonate, infilling of pores by sediment, and cementation by coralline algae at rates that exceed physical, chemical, and biological destructive processes.

Most reef-building corals as well as other cnidarians, tridacnid bivalves, and a number of other reef organisms have a symbiotic relationship with single-celled algae or dinoflagellates called zooxanthellae. The zooxanthellae give corals their characteristic yellow, green, golden brown, or brown coloration and they contribute to coral growth, calcification, and processes of physiology and reproduction (Glynn 1996; Brown 1997). Coral colonies are modular organisms composed of many interconnected polyps of identical genetic composition. Colonies grow by progressively accreting more skeleton. Corals have a wide range of life histories that allow them to inhabit specific zones, and modify the habitat to support other organisms. At one extreme are relatively short-lived and fast-growing corals such as the branching *Acropora* spp. (Figure 4) and *Pocillopora* spp. These species allocate considerable energy to growth and reproduction, but little towards maintenance. Growth (linear branch extension) rates can average 10-15 cm per year, but colonies are particularly susceptible to physical disturbances (e.g., hurricanes) and are preferred prey of *Drupella*, *Acanthaster,* and other corallivores. Other corals, such as *Porites* and *Agaricia* are opportunistic species. These exhibit high rates of recruitment and are among the first species to recolonize an area after a disturbance, but they are poor at repairing injuries and have short life spans. Massive faviids (e.g., *Montastraea* spp.) are long-lived and slow growing (1 cm per year), and can form colonies several meters in height. These species often exhibit low reproductive success, but they are resistant to many stressors and devote much of their energy towards colony maintenance.

Corals can build complex structures variable in shape, size, and designed to meet the demands of the reef's variable environmental conditions. Their differently shaped skeletons also influence the distribution of other organisms that co-occur in reef environments. Corals can be classified into ten general growth forms (branching, digitate, encrusting, table, foliose, massive, submassive, mushroom, flower, and solitary). Specific growth forms are primarily species specific, although the exact kind of coral can look very different from one place to the next. Some of the variation is genetically programmed, while the degree of light attenuation and symbionts clade[5] occupying the coral host, the biological environment (e.g., degree of competition), and other environmental factors such as wave exposure also cause variation. Corals on the upper slope and reef crest of exposed windward reefs are small, often encrusting or massive, and solidly constructed. In deeper reef environments, as wave action declines, corals become progressively larger and more delicate, and include diverse growth forms. In addition, many massive corals, such as *Montastraea annularis* (species complex), *M. cavernosa*, *Diploria strigosa,* and *Colpophyllia natans* that form hemispherical heads in shallow water have a plating morphology in deeper, low light environments as a strategy to maximize light absorption and particle capture.

Coral Recruitment

Regional recruitment patterns are controlled by a number of biological and physical factors such as larval supply, dispersal patterns during the planktonic period, substrate availability, and post settlement survival, as well as the local abundance, fecundity, and life history strategies of adults (Edmunds 2000). Patterns of settlement and survival of coral recruits may provide an indication of the vitality of reef communities and the potential for natural recovery of degraded areas (see Figure 5 for coral recruitment). In addition, knowledge of the effects of depth, physical relief, and various environmental parameters on juvenile coral survival may further explain the dominance of species in certain habitats (Bak and Engel 1979; Chiappone and Sullivan 1996) and assist in selecting appropriate species for transplantation.

Most studies of coral recruitment involve either field surveys of natural substrates or

Figure 5. A Mountainous star coral (*Montastrea faveolata*) colony that experienced about 90% mortality from disease. Exposed skeletal surfaces were subsequently colonized by coral recruits. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

[5] A group of species with a common evolutionary ancestry.

the use of settlement plates deployed before major reproductive periods and subsequently removed and analyzed several months later in a laboratory. Most field surveys target juvenile corals that are 0.5-4 cm in diameter and several months old because of limitations in identifying recruits due to:

1) The small size and low visual contrast of newly settled coral recruits; and
2) The difficulty in detecting small juvenile corals in more cryptic and architecturally complex habitats.

An emerging technology that may facilitate characterization of early patterns of coral recruitment involves the use of fluorescence to locate coral recruits because most corals contain pigments that fluoresce in a color differing from background algae fluorescence.

Biological Controls

There are a number of biotic agents that affect the settlement, growth, and survival of scleractinian corals, including coral diseases, bleaching, and predation by corallivores, competitors, and bioeroders (e.g., grazers, etchers, and borers). Biotic agents often weaken the substrate and make it more susceptible to physical and chemical erosion. Grazers, including echinoids and fishes, graze live or dead coral substrates, encrusting coralline algae, and filamentous algae. These activities typically generate large amounts of new sediment that may fill in spaces in the reef structure and become cemented in place, or be carried from reef substrates into sand channels and lagoons. Annual rates of parrotfish bioerosion in the Caribbean are estimated to be 40-490 g/m^2 (Ogden 1977; Frydl and Stearn 1978). Other community effects of predation include increased species diversity due to the removal of dominant preferred taxa. For instance, corallivores often feed on fast growing corals such as *Acropora*, and their removal may enhance the persistence of slower growing corals. Coral predators may also prevent recovery after a hurricane or other disturbance due to a concentration of predators on remaining prey, or they may open up substrata that are rapidly colonized by non-calcifying organisms, thereby reducing the potential for larval settlement and recruitment (Glynn 1988).

Diseases

Since the early 1990s, scientists have documented a rapid emergence of diseases among corals, with increases in the number of diseases reported, coral species affected, geographic extent, prevalence and incidence, and rates of associated coral mortality (Richardson 1998; Epstein et. al. 1999; Knowlton 2001; Sutherland et al. 2004). A survey of the coral disease literature conducted by Green and Bruckner (1999) described 29 differently named diseases on 102 scleractinian coral species. At least 12 new syndromes have since been reported, with a dramatic increase in observations from the Indo-Pacific. More than 150 species of zooxanthellate corals, including scleractinian, gorgonian, and hydrozoan taxa are now known to be susceptible to diseases (Green and Bruckner 2000; Sutherland et al. 2004).

Coral diseases may be caused by:

- Pathogens such as bacteria and fungi (infectious diseases)
- Stresses like elevated seawater temperatures and increased UV radiation
- Poor nutrition
- Genetic mutations (non-infectious diseases), or
- Possibly a combination of these factors

Increased sedimentation, nutrients, and pollutants may also be responsible for the proliferation of pathogens, or they may alter coral defense mechanisms and immune responses. Some disease-causing pathogens are thought to have been introduced into the marine environment as a result of human activities such as improper treatment and discharge of sewage, runoff associated with land clearing, dredging, ballast water exchange, and introduction of non-native species. This includes a soil fungus that is responsible for a disease in sea fans, and a bacterium found in the human intestine that has been identified as the causative agent of white pox, a disease affecting elkhorn coral (Sutherland et al. 2004). Alarmingly, more and more reefs in unpopulated areas are also being impacted by diseases, despite the absence of most major human impacts in these areas.

The most common diseases that affect scleractinian corals include black-band disease, white-band disease, white plague and yellow-band disease. In addition, a number of other conditions have been recently observed. The characteristics of the four major diseases are presented below to aid in the identification and monitoring of these conditions.

Black-band disease

Black-band disease (BBD) (Figure 6) forms a crescent-shaped or circular band that separates live, normally colored green, brown, or yellow-brown coral tissue from white, exposed skeleton. The band is maroon to black in color due to the photosynthetic pigments of the cyanobacteria (blue-green algae), it often has a white dusting of filamentous (sulfide-oxidizing) bacteria, and it is loosely anchored in living tissue and is easily dislodged by water motion. The band can range from a few millimeters to several centimeters wide, and may be over 2 m in length on large colonies. Over days to months, BBD slowly spreads in a line across the coral, advancing 2-3 mm per day or more, to a maximum of 2 cm per day. In the western Atlantic, 16 species of massive and plating corals are affected, as well as other types of stony coral, sea fans, and branching gorgonians. Boulder star coral (*Montastraea annularis* complex) and brain corals (*Diploria* spp. and *Colpophyllia natans*) are most commonly infected, while staghorn and elkhorn coral have not been observed with BBD.

White-band disease

White-band disease (WBD) (Figure 7) typically starts at the base of a colony and progresses towards its branch tips, causing tissue to peel off the skeleton at a fairly uniform rate. WBD occasionally initiates in the middle of a colony, especially where a colony branches, and then advances toward the branch tips or the base of the branch. Affected colonies have a distinct

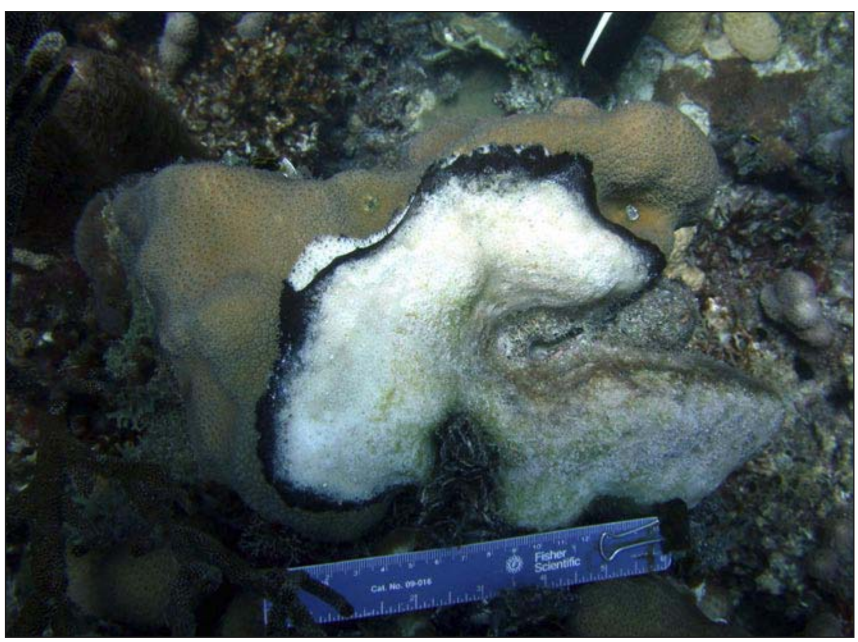

Figure 6. Coral infected by black band disease. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

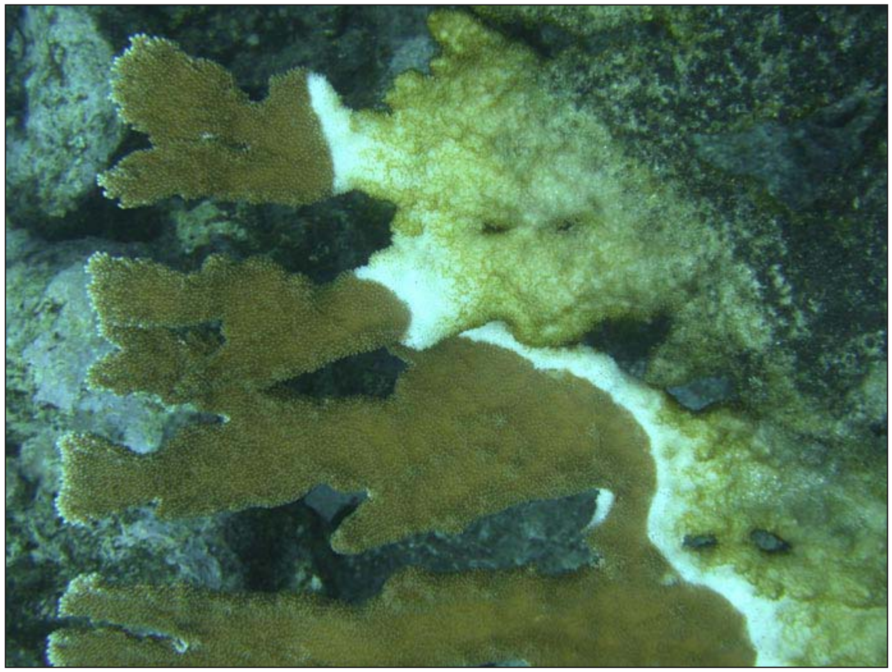

Figure 7. Coral infected with white-band disease. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

margin or band of white, recently exposed skeleton ranging from a few millimeters to about 10 cm in width. Exposed skeleton is colonized by green filamentous algae within days, and this band progressively grades into other algal successional stages towards the base of the colony. Tissue loss averages at about 5 mm per day, but it can occur much faster. In some cases, tissue adjacent to the exposed skeleton forms a jagged margin as small patches of tissue are sloughed off into the water. WBD is known to affect only the acroporids in the Caribbean and is believed to be largely responsible for the decline of two of the dominant reef-building corals on shallow western Atlantic reefs (*Acropora palmata* and *A. cervicornis*) during the 1970s and 1980s (Antonius 1981 (a); Gladfelter 1982; Aronson and Precht 2000). In most locations, populations of *A. palmata* and *A. cervicornis* have failed to recover and remaining colonies are being affected by a host of new diseases including white pox. Due to the threats that these species face, and their potential for extinction, both species are now being considered for listing on the Federal Endangered Species Act (Bruckner 2002).

White plague

White plague (WP), a disease first reported from Florida in 1977, emerged in a more virulent form (Type II) in 1995 on the same reefs and is now recognized as one of the most destructive diseases in the western Atlantic. WP Type II causes tissue losses at a rate of 1-10 cm per day and can kill several meter tall colonies within weeks to months (Dustan 1977; Antonius 1981 (a) and (b); Harvell et al. 1999). WP is similar in appearance to WBD, but it affects massive and plating corals rather than branching acroporids. Tissue loss begins at the base or margin of a colony, or next to a previously killed area, and quickly spreads upward or outward in a band. In affected corals there is the appearance of a sharp line separating healthy coral tissue and bare coral skeleton, but there is no visible mat of organisms at the disease front as is observed with BBD (Richardson 1998). It now affects nearly 40 species of reef-building corals in the western Atlantic, with outbreaks observed in the Florida Keys, southwestern Puerto Rico, U.S. Virgin Islands, Bonaire, Curacao, Panama, Colombia, and other locations.

Yellow-band disease

Yellow-band disease (YBD) (Figure 8) begins as a pale yellow, circular blotch of tissue in the middle of normal, dark green to brown tissue, or as a narrow band at the edge of a colony. Affected tissue is translucent, and still contains symbiotic algae (zooxanthellae), although the algae are reduced in number. As YBD advances, the leading edge of the band (area closest to the normal tissue) becomes a light pale yellow or lemon color, while tissue behind the disease front gradually darkens and then dies. The band advances at up to 1 cm per month. Because the spread is relatively slow, colonies with YBD rarely have a prominent area of white, exposed skeleton. Typically, recent tissue mortality is restricted to small (5-10 cm^2) irregular blotches. Although the rate of tissue loss is much less than that observed in other coral diseases, this disease can affect individual corals for many years and will eventually kill them. Boulder star corals (*Montastraea annularis* complex) are most frequently affected by this condition, but cavernous star coral (*M. cavernosa*) and boulder brain coral (*C. natans*) have also been seen with YBD (Bruckner and Bruckner (b), *in press*).

Diseases can affect coral reef organisms directly and indirectly by altering both reef community structure and function. Coral diseases are playing an increasingly important role in regulating coral population size, diversity, and demographic and other structural characteristics (Antonius 1985; Aronson and Precht 2000 and 2001; Porter and Tougas 2001; Bruckner 2004). *Acropora palmata* and *A. cervicornis* were the two dominant space occupants and most important framework builders in reef crest and fore reef habitats on Caribbean reefs until the late 1970s, when outbreaks of WBD, hurricanes, and other factors decimated populations, leading to large losses of live coral cover throughout the region (Richardson and Aronson 2002). More recently, boulder star coral (*Montastraea annularis* complex) populations are experiencing significant declines as a result of multiple diseases including BBD, YBD, and WP (Antonius 1973; Santavy et al. 2001; Garzon-Ferriera et al. 2001; Kuta and Richardson 2002; Bruckner and Bruckner 2003 and 2004).

Measuring and Monitoring Methods

Sessile Invertebrates and Algae

Sessile benthic invertebrates and algae can be assessed using transects, quadrats, manta tows, and other methods including line intercept, point intercept or belt transects, visual or

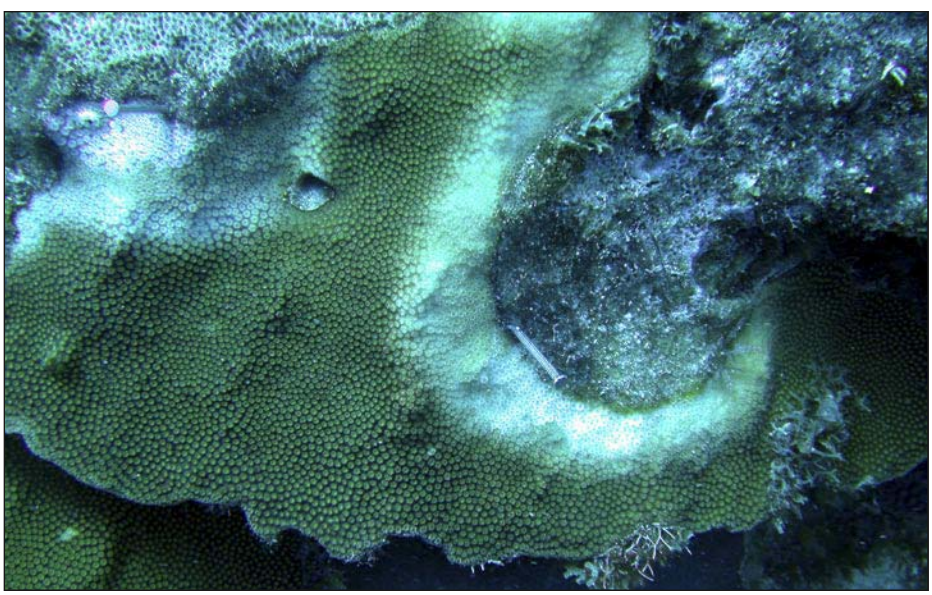

Figure 8. Coral infected with yellow-band disease. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

photoquadrats, video transects, or colony-level monitoring (Table 1). The method chosen depends on the level of detail desired. Broad-scale methods such as a manta tow or timed swim are most useful for assessing broad changes in benthic communities over large areas at lower resolutions. The manta tow technique enables visual assessment of large areas of reef in a short amount of time, and can be used to determine the effects and large-scale disturbances. Manta tows can also assist in identifying sites of interest for more detailed monitoring. Medium-scale methods, such as visual or video transects, are typically used to monitor at the scale of an entire reef. Quadrats are typically used to measure smaller areas in more detail and can provide high resolution data on coral recruitment and growth, as well as biomass of various algal groups (Hill and Wilkinson 2004).

Once the method is selected, one must determine the appropriate scale of measurement, such as the length of transect and size of quadrat, as well as the number of replicates and placement of these replicates (e.g., random or haphazard placement). The chosen monitoring method and protocol depends on the scale of the area to be monitored, level of detail desired, type of reef habitat, and precision of data required. The appropriate size and amount of replication can be determined through a pilot study that examines the size, spatial abundance, and diversity of organisms. Typically, abundant, large organisms located within a smaller area and/or sites with low diversity or low spatial heterogeneity require fewer and shorter transects, while detection of rare or smaller organisms or assessment of high diversity sites require additional, longer transects that cover a larger sampling area. Sufficient replication is also necessary to understand the extent of variability within a coral reef ecosystem and to collect information that is representative of the area of interest and/or abundance of the target organism.

Linear transects - Linear transects (Figure 9) are used to collect baseline information on sessile benthic community structure and changes over time. Linear transects are generally extended parallel to the reef crest along depth contours, although they may be extended perpendicular to depth contours to characterize different habitat types and changes in species composition along a gradient extending from the shore to deeper

Figure 9. Linear transect running through staghorn coral (*Acropora cervicornis*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

water. Data collection can include substrate types (hard substrate, rubble, sand, dead coral, etc.) and major life forms or growth forms of corals and other organisms, although identification (rather than collection) of each organism to the species level is preferred.

Line intercept transects - Line intercept transects focus on the horizontal plane of the reef and data are collected along the entire length of the line. The cover of a particular organism is defined by the fraction of the line that is intercepted by that organism. A variation of this is the point intercept method, where biotic or abiotic components are recorded at specific intervals below the line (Chiappone et al. 2001). If a researcher uses replicate 30 m transects and records the substrate type or organism every 0.5 m, then a total of 60 data points will be collected per transect. The total number of points occupied by a certain species divided by the total points examined for all transects performed in one site is an estimate of the percent cover of that species.

Chain transects - Chain transects measure benthic cover and species composition in a three-dimensional plane as the chain follows the contour of the reef. Chain transects provide details on rugosity (i.e., roughness - Figure 10). In addition, the presence/absence of particular taxa or abiotic substrates can be recorded under every link or a certain percentage of the links (similar to the point intercept method) to provide estimates of cover.

Belt transects - Belt transects (Figure 11) are similar to line transects, but examine a wider area and are used most frequently to:

1) Assess populations when examining whole colonies to obtain information on species composition, size and condition, and spatial distribution of corals or other taxa
2) Quantify the prevalence of bleaching, disease, and other stressors, and
3) Count mobile invertebrates and fishes

The optimal width of a belt transect will depend on the parameter monitored. For example, a narrow belt (e.g., 1 m) may be adequate for a very abundant organism, while wide belt transects (e.g., 3-5 m) may be necessary to accurately estimate abundance of rare taxa.

Quadrats - Quadrats (Figure 12) can provide data on percent cover, frequency of occurrence, and species diversity, abundance, density, and size for small to medium-sized organisms (Matta 1981; Laydoo 1990; Chiappone et al. 2001).

Figure 10. Divers monitoring coral along a chain transect. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

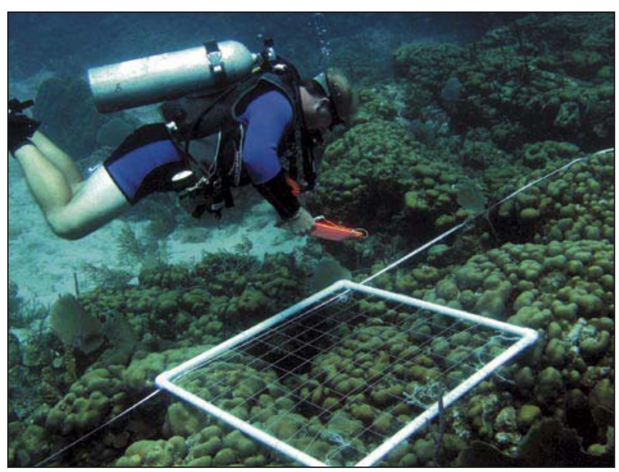

Figure 11. Diver assessing coral reefs along belt transects using quadrats. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 12. Photoquadrat (70 x 100 cm) and algae quadrat (25 x 25 cm) placed along a transect to monitor benthic communities. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Quadrats are most often used to assess coral recruitment patterns, coral growth, and algal composition and biomass. Quadrats are typically divided into a number of smaller squares (e.g., a 1 m^2 quadrat may be divided into 100 squares) to increase accuracy of coverage estimates for visual counts. Visual estimates using quadrats may require time intensive counts which limit the number of replicates. It is also possible to bias data by selecting particular areas of interest (e.g., areas of high cover or the presence of a certain taxa, disease, or other feature) instead of randomly placing quadrats throughout the survey area. This can be avoided by placing quadrats along linear transects at set intervals, with the appropriate interval determined on land prior to conducting the survey, and also by increasing the sample size and area evaluated.

Photoquadrats and video transects - Photoquadrats and video transects provide a permanent record of benthic communities, allow rapid data collection, and require minimal taxonomic expertise for field work (Bohnsack 1979; Maney et al. 1990; Meier and Porter 1991; Mumby et al. 1995; Ninio et al. 2000; Motta et al. 2001). Video data collection can be used to monitor and assess macroalgae and coral reef health, growth, abundance, and percent cover before, during, and after restoration efforts (Dartnall and Jones 1986; Maney et al. 1990; Ninio et al. 2000; Jaap and McField 2001; Rogers et al. 2001). In general, photoquadrats provide higher resolution than video transects, although data are collected at a smaller scale. Photographic images can be analyzed using random points (for video, individual frames must be grabbed prior to analysis) or by digitizing the planar area of organisms to provide an accurate percent cover and size estimates. Digitized images can be used to compare fine-scale changes in benthic communities over time. The major disadvantages with underwater photography include equipment costs, time required for image processing and analysis, possible loss of resolution, and inability to detect cryptic organisms (Jaap and McField 2001).

Tagging - Coral tagging[6] allows a comparative evaluation to be performed of the degree of impact on coral health over time. For example, some stressors such as disease, predation, algal overgrowth and bleaching that affect the health of the coral can be monitored via tagging.

Coral Recruitment

Coral recruitment is an important parameter to monitor at reef restoration sites in order to document whether structural modifications, such as the removal of sediments and rubble

[6] This method involves marking and monitoring specific individual corals at designated sites.

or stabilization of the substrate, were adequate to enhance settlement. Dead pieces of coral skeleton may be secured to natural substrate in order to increase the availability of settling surfaces for coral recruits. In addition, artificial surfaces, such as terracotta tiles, can be used to 'collect' crustose coralline algae, a preferred substrate for coral settlers (Mundy 2000; Heyward et al. 2002).

Visual quadrats and photoquadrats - Visual quadrats and photoquadrats are used most frequently to evaluate patterns of survival and growth of juvenile corals on natural substrates, and these types of studies often also assess the quality and availability of substrate, topographic complexity, grazing rates, and variations in light and nutrients (Sammarco 1980; Wittenberg and Hunte 1992). Quadrats are typically smaller (e.g., 0.25 m^2 or less) than those used to examine adult corals, although some researchers have used larger quadrats (e.g., 1 m^2) to survey both juvenile and non-juvenile corals simultaneously (Bak and Engel 1979; Chiappone and Sullivan 1996).

Underwater photography - Underwater photography is also used in recruitment studies, although close-up photographs of small areas are necessary to maximize resolution and obtain sufficient contrast to identify recruits. Patterns of recruitment on denuded coral surfaces, for example, can be examined using a Nikonos V camera fitted with a close-up lens that photographed a 16.5 x 23.5 cm area (Edmunds 2000). This method allows identification and quantification of corals ranging in size from 4 -40 mm. Quadrats may be placed in specific locations or randomly along transects, or be permanently fixed to the substrate. Fixed quadrats can provide information on temporal changes in recruitment, growth, and mortality, while random quadrats provide an indication of spatial distribution of juvenile corals.

Artificial settlement plates - Artificial settlement plates provide data on patterns of early recruitment, including the relative abundance in space and time. Recruitment can be monitored using unglazed, flat terracotta (ceramic) tiles (approximately 10 x 10 cm and 1 cm thick) that are either attached directly to the coral reef substrate or to wire racks secured to the bottom. Multiple tiles (generally 20-50 tiles per site) are positioned at various angles and distances from the substrate and in areas of differing topographic complexity. While brooding species may reproduce on a monthly to seasonal basis, tiles should be placed in the field 4-6 months before the mass spawning event (e.g., July - September in the Caribbean) to detect broadcast spawners by allowing them to acquire a rich fouling community and crustose coralline algae. A portion of the tiles are removed at various intervals (e.g., monthly to quarterly) and replaced with new tiles. In the lab, a microscope is used to count the number of recruits per tile, size and number of polyps per recruit, position of settlement (e.g., top or underside of tile; edge or middle of tile), and relationships between settlement and presence of other invertebrate or algal colonizers (Mundy 2000; Hill and Wilkinson 2004).

Coral Diseases

A variety of approaches have been used to identify the prevalence (i.e., number of affected corals divided by the number of corals examined) and incidence (i.e., number of new colonies with disease occurring in a population over a given time divided by the number of unaffected individuals at the beginning of the time period) of coral diseases, including quantitative, semi-quantitative, and qualitative surveys (Table 2). Many monitoring programs rely on repeated sampling of permanently marked transects, quadrats, or radial study sites. Detailed monitoring of particular reefs, through the establishment of permanent sites, can provide information on disease incidence. In addition,

Table 1. Advantages and Limitations of Methods to Monitor Benthic Coral Reef Communities

Methods	Advantages	Limitations
Linear transect	Useful in continuous reef areas.	Not suitable for patchy environments due to limitations on number of replicates.
Line intercept transect	Measurements taken along entire line instead of random or fixed points.	Focuses on horizontal plane of reef.
Point intercept transect	Rapid determination of species diversity and cover.	Does not allow examination of whole organism.
Chain transect	Enables determination of structural complexity.	Can be used to measures of cover, diversity, and abundance but requires large number of time consuming transects.
Belt transect	Assesses whole colony health and specific impacts such as disease; counts motile invertebrates and fishes.	May be time consuming, especially in areas with high abundance of corals.
Video transect	Permanent archive; does not require user to be able to identify species; rapid, easy to use, and allows survey of large areas.	Limited resolution; cannot distinguish small corals and algae; high relief octocorals may overshadow underlying benthic community; requires user to stay at fixed distance from substrate and repeat photographs must be taken from exactly the same angle; analysis is time consuming and requires considerable expertise and expensive equipment.
Quadrat	Fine-scale monitoring of coral recruits and algae; permanent quadrats offer high precision. Suitable for patch reefs and other discontinuous environments.	Visual estimates may have significant user variation and bias depending on placement.
Photoquadrat	High precision and detail for measures of percent cover. Allows analysis in lab using point count or planar area.	Planar view only; repeat photographs must be taken at the same angle/distance for comparisons.
Tagging coral colonies	Most specific detail on individual corals and impacts of stressors such as disease.	Time consuming. May be difficult to relocate corals. Cause and effect studies require frequent monitoring.
Recruitment tile	Collects information on new recruits. Higher detection than from photoquadrats or visual quadrats. Can be analyzed in the laboratory.	Very small scale. Tile composition and placement may affect recruitment patterns.
Timed swim	User covers larger area than possible with transect or quadrat methods. Useful for detecting rare organisms or large-scale phenomena like bleaching; can estimate species cover and diversity over large areas.	Low precision; limited to areas where divers look.
Manta tow	Best suited for examining widely spaced organisms or providing an overview of large areas; allows determination of appropriate sites for monitoring. Can be combined with video.	Area examined controlled by boat operator and not diver. Can only collect limited data at low precision.

long-term monitoring of individually tagged colonies affected by microbial pathogens can provide detailed information on the duration of infections, frequency of reinfection, and effect at the species level. Because diseases often occur at a low frequency or they exhibit a clumped distribution, a large number of transects may be required within each reef to accurately estimate disease prevalence. To obtain a more realistic measure of disease prevalence overall at a larger (nationwide or regional) scale, and to determine factors responsible for the increase and spread

Table 2. Monitoring and Assessment Techniques for Coral Diseases

Monitoring Approach	Condition Examined and Technique Description	Author(s)
Timed swim	All syndromes. Diver swam for 30 minutes along a single depth gradient and examined all corals in a band approximately 2 m wide, recording the type of disease, species, and number of affected corals. Disease occurrence categorized as rare (1-3 cases), moderate (4-12 cases), frequent (13-25 cases), abundant (26-50 cases), epidemic (51-100 cases), or catastrophic (greater than 100 cases).	Antonius 1995
Radial site	Prevalence and incidence of BBD. Total number of infected and uninfected colonies of each species present was recorded within a circular area (10 m radius; 314 m^2).	Edmunds 1991; Kuta and Richardson 1996; Bruckner et al. 1997a
Radial belt transect	All diseases on stony corals and gorgonians. Total number of affected and unaffected colonies of each species present was recorded within the outer 8-10 m of an arc radius (circular area, 10 m radius; 314 m^2).	Santavy et al. 2001
Linear transect	A. Changes in composition, size, and cover. Twenty 25 m transects on reef from 0.3-21 m depth. Permanent transects were extended parallel to each other to subdivide an area approximately 25 m x 300 m. Mean colony size (length under the transect line) and distance between colonies were recorded; colonies were inspected for signs of mortality (disease, physically damaged areas, sediment covered tissue, or other blemishes). B. Condition of stony corals. Minimum of ten 10 m transects per reef/depth used and surveys at 3 m and 10 m depth conducted; species, size, percent recent, and old mortality of all colonies that touch the transect line were recorded; whole colony examined for diseases or other sources of mortality.	A. Dustan 1985 B. AGGRA 1998
Belt transect	A. Sea fan disease. One or two 4 m x 12.5-50 m transects per country used. B. All diseases - corals and gorgonians. Ten 10 x 2 m belt transects (level 1) and three 20 m x 2 m belt transects per depth used; minimum 9 transects at each site (level 2) used. C. Reef condition. Three 20 m x 5 m transects per reef used; divers noted presence and proposed type of disease and affected species, but did not collect quantitative information.	A. Nagelkerken et al. 1997 B. CARICOMP 2001 C. Hodgson et al. 2004

Table 2. Monitoring and Assessment Techniques for Coral Diseases (cont.)

Monitoring Approach	Condition Examined and Technique Description	Author(s)
Quadrat	A. BBD in gorgonians. Prevalence measured using three 100 m x 250 m quadrats per reef; incidence measured using one 10 m x 10 m quadrat per reef.	A. Feingold 1988
	B. Sources of mortality. Two photostations of 2 m x 2.25 m established per reef; examined two reefs to identify sources and amount of mortality over time, complemented with permanent chain transects extended over 25 m to measure changes in percent coral cover, diversity, and colony size.	B. Porter and Meier 1992
	C. Coral reef monitoring. 160 stations, each 2 m x 22 m, were sampled at 40 sites in the Florida Keys National Marine Sanctuary. 15-minute survey of each quadrat conducted to complete a species inventory, identify species affected by bleaching or disease, and record the type of disease. No data collected on disease prevalence. Also ran video transects. Sites re-examined once per year from 1996-2000.	C. Jaap et al. 2000

of diseases, a repeated measures approach consisting of multiple random belt transects positioned throughout each reef environment is necessary (Bruckner 2002).

PHYSICAL

Topography/Bathymetry

Bathymetry is the science of measuring the depths of the oceans and mapping the corresponding topography, or physical features, of those depths. Accurate geo-referenced information on the location of specific natural resources, depths, topography, and corresponding habitat types is important for effectively managing marine habitats. An understanding of the bathymetry can assist in:

1) Creation of accurate baselines for long-term monitoring
2) Characterization of habitats for place-based conservation measures such as marine protected areas
3) Enhancement of scientific understanding of the large-scale oceanographic and ecological processes affecting the health of reef ecosystems, and
4) Identifying changes in topography associated with physical impacts and structural restoration efforts

Comprehensive maps can also be used to illustrate trends in coral reef health over time by providing a geo-referenced tool to track disease and invasive species and documenting loss of habitat and reef-dependent species.

Shallow-water coral reefs are generally restricted to depths of about 160 ft, with distinct depth-related zonation patterns exhibited by corals and other sessile invertebrates. Reef topography and bathymetry also vary among reef types, thereby creating unique zones that support different marine organisms or life history stages by providing shelter, feeding grounds, breeding areas, or substrates for attachment (Holliday 1989). Topographic complexity of a reef can be altered due to natural events such as a severe hurricane that dislodges, shatters, and removes branching corals. Human activities, such as the grounding of a vessel, can crush and detach coral colonies and fracture the reef surface, while dredging, beach nourishment, and shoreline modification projects can bury reefs under a layer of sediment. A number of destructive fishing practices, such as dynamite fishing and the use of bottom trawls, can also reduce the three-dimensional heterogeneity of coral reefs by pulverizing the corals that provide the structural framework. The broken coral has a low potential for survival, and the skeletons become a shifting, unstable rubble field that inhibits new coral colonization (Fox et al. 2001).

One of the primary goals of coral reef restoration is to stabilize the substrate and quickly reestablish the spatial heterogeneity as a first step to restoring ecological function. Topographical information about the site prior to the injury or the surrounding undamaged area can provide information on the extent of structural restoration necessary as well as a reference to gauge recovery within the restored area.

Measuring and Monitoring Methods

Seafloor characteristics, including habitat types, bottom features, bathymetry, substrate type, thickness of deposits, and cover of certain dominant groups of organisms can be assessed and monitored using a variety of remote sensing tools (e.g., satellite and aerial photos), acoustical systems (e.g., side-scan sonar and echosounders) (Dustan et al. 2001; NOAA Center for Coastal Monitoring and Assessment 2002; Mumby et al. 2004), in-water imaging (e.g., video or still photography), and coring.

Remote sensing - Remote sensing involves the measurement of electromagnetic radiation reflected from or emitted by the Earth's surface using satellite or aerial photographs, and then relating these measurements to the spatial extent and distribution of different habitat types, water quality, and in some cases (depending on the sensor and its resolution), the cover, composition, and/or condition of dominant organisms. Satellite imagery and aerial photography are limited by environmental conditions such as water turbidity, sun angle, cloud cover, and surface waves, and are generally useful in clear tropical waters to depths of 60 ft. Acoustical systems towed behind a survey vessel (e.g., multi-beam echosounder) or deployed closer to the bottom (using a side-scan sonar) can be used to characterize the seafloor in deeper or turbid areas.

Satellite imaging, aerial photographs, and acoustic technologies are often used to create detailed maps of the spatial dynamics and distribution of coral reef ecosystems, and are particularly useful for large or remote areas. In addition to documenting baselines for long-term monitoring, accurate geo-referenced information can be used to illustrate community-scale trends in ecosystem condition, characterize habitat types, and understand large-scale oceanographic and ecological processes affecting reef health (Riegl et al. 2001). Maps created using these technologies can also assist restoration practitioners in assessing the severity and spatial extent of impacts and developing restoration strategies. Some of the newer sensors are able to discriminate between common coral reef features when using the proper algorithm, such as live coral versus algae-covered dead coral, bleached corals, and other organisms (Holden and LeDrew 2001). Aerial photographs provide a much finer scale than satellite images, but without the spectral resolution and measure of absolute radiance. Using a digital scanner, aerial photographs can be converted to RGB digital imagery at resolutions of 25 cm and may be comparable to line transects and underwater quadrats. Multispectral cluster analysis then transforms the image into the geographical information system domain, and after appropriate groundtruthing and geo-referencing, the cover of corals and other large organisms can be calculated (Riegl et al. 2001). Sonar uses sound not light and measures distances based on how much time it takes for a sound signal to reflect back to the source and the strength of the returned signal. This indicates what type of material reflected the signal. For example, mud absorbs much of the sound signal, providing a weak echo, while rock reflects most of the sound, providing a strong echo.

While remote sensing and acoustic technologies are an excellent option for consistent, repetitive monitoring of coral reefs on a large scale, there are limitations to each remote sensing method used (see Table 3). These technologies are particularly useful for a general survey of a reef, can assist in selecting study sites for more detailed analysis, and provide a record of large-scale changes. While these approaches can assist in identifying major zones and habitats, they have a limited ability to document changes in the condition or abundance of particular organisms. Other factors that limit the accuracy of remote identification of individual organisms include the effects of water column transparency on optical reflectance characteristics of the organism (Holden and LeDrew 2001). It may also be difficult to estimate depths and structural relief using remote sensing techniques, as certain "dark" areas such as grassbeds may appear much deeper than lighter colored sand flats. These limitations can be overcome using snorkel or scuba diving to groundtruth the images. Detailed bathymetric and topographic information can be collected using underwater photography and video and chain transects to groundtruth remotely-sensed images.

Video monitoring - Video monitoring allows divers to sample larger areas of the reef in less time than non-photographic *in situ* reef monitoring techniques but it covers a smaller area than remote sensing or acoustic technologies (Dartnall and Jones 1986; DeCouet and Green 1989; Jaap and McField 2001; Rogers et al. 2001). Digital video data offer a visual representation of the sampled area that can be archived and shared electronically. It can be used to document the effects of a variety of stressors that cause conspicuous changes in the appearance of coral colonies, such as breakage from hurricanes and boat anchors, diseases, and bleaching. They can also show recovery of reefs following damage. The main disadvantage, in terms of reef structure, is that videos provide a planar view of the reef surface instead of the three-dimensional complexity, thus organisms located on the sides and undersurface of rocks and corals are missed, and the resolution decreases with distance from the substrate.

Chain transects - Chain transects are the most accurate and widely used method to monitor structural complexity at a smaller scale, such as an individual reef or habitat where restoration was conducted. Measures of rugosity (spatial index or the ratio of reef surface contour distance to linear distance), provide a way to quantify changes in topographical complexity of the reef. Other non-photographic techniques such as the visual assessment of quadrats and linear transects generally require more time in the water, and may not provide data on spatial complexity of a habitat.

Sediment

Sediments exert marked biological and geological effects on reefs. High rates of sedimentation can affect coral settlement, growth, and survival as well as the distribution and composition of sessile invertebrate assemblages through burial, smothering, shading, and abrasion. Sediments suspended in the water column also effect light penetration due to absorption and scattering of light. The ability of corals to withstand sedimentation varies considerably among species and is affected by their growth form and the ability of sediment rejection mechanisms (e.g., polyp distension, ciliary action, and mucus production) to remove foreign material from the colony surface (Hubbard and Pocock 1972). Reefs with high sediment loads are characterized

Table 3. Advantages and Limitations in Broad-Scale Remote Sensing Techniques to Map and Characterize Coral Reef Ecosystems

Methods	Advantages	Limitations
Satellite imaging	Measures wavelength and intensity of reflected radiation to differentiate habitat types like sand, seagrass, and coral-dominated areas. High resolution satellites can distinguish objects as small as 1 m, but these are costly and may be unavailable.	Difficult to differentiate shoreline features from shallow-water areas because reflection through water produces similar signatures; sun glare causes interference; cloud cover blocks reflected light; inappropriate for turbid areas
Airborne hyperspectral imaging	Visible and infrared light spectrum split into many narrow bands allows finer resolution than satellite images. Can be used to monitor oil spills, schools of fishes, and effluent, and can provide a detailed view of benthic habitats and habitat features. Can gather information from depths approximately three times greater than standard aerial photography.	Only works in shallow, non-turbid water. Limited by environmental conditions including water turbidity, sun angle, cloud cover, haze, and surface waves.
Aerial photography	Allows for broad-scale habitat mapping, delineation of habitats over wide areas, and detection of features smaller than 1 m.	Accurate spatial data requires geo-referencing. Limited by environmental conditions including water turbidity, sun angle, cloud cover, haze, and surface waves.
Hydrographic Light Detection and Ranging (LIDAR)	Used for detection and mapping of bottom topography in inshore areas. Can be used to determine depth (by recording the time it takes for the reflected signals from the surface and seafloor to return to the aircraft). Can be used to about 50 m depth in clear water.	Provides a good compliment to acoustic techniques, which cannot be used in shallow water, but is limited by water clarity.
Acoustic in situ methods	Unlike remote sensing, these tools are not limited by water turbidity.	They provide information on sediment surface, but must be combined with sub-bottom profiling systems to characterize sub-surface sediments.
Single-beam echosounder	Collects discrete data points along survey track lines.	Very portable and inexpensive, but lower resolution than multi-beam.
Multi-beam echosounder	Collects continuous high resolution bathymetry data throughout the survey areas and may measure strength of reflected sound (backscatter), allowing differentiation of soft and hard bottom substrates.	Can accurately detect features as small as 1 m.
Side scan sonar	Can identify different substrate types, such as mud, sand, and rock. Provides for continuous characterization of seafloor at all depths.	Because the sonar emitting and receiving device is towed underwater, closer to the surface of the ocean bottom, there is less signal attenuation and a lower angle of viewing differences in topography.

by lower diversity, lower percent coral cover, reduced rates of reef accretion, small colony sizes, compressed reef zonation patterns, and a predominance of sediment-resistant species. For example, the large star coral (*Montastrea cavernosa)* in Puerto Rico was found to be the dominant scleractinian coral in turbid water, primarily due to its efficient sediment rejection capabilities, while *Montastraea annularis* dominates in clear water (Loya 1976).

Grain size, composition[7], and depositional environment

Most coral reef sediments can be grouped into terrigenous sediments and biogenic sediments. Terrigenous sediments have been eroded from land and carried into the marine environment by rivers, wind, and runoff. Terrigenous sediments generally travel large distances from places where they are eroded before being deposited. During this transport, the composition, sorting, shape, and size of original grains may be significantly altered. Biogenic sediments are derived principally from precipitated skeletal material (calcium carbonate and silica) and usually have been broken down by physical and biological erosion. Sources of biogenic sediments on reefs include fragments of corals, coralline algae, green calcareous algae (*Halimeda*), foraminifera tests, mollusk fragments, echinoderm spines, sponge spicules, and other skeletal remains (Mckee et al. 1959).

The deposition of carbonate sediments is affected by hydrodynamics (currents, waves, and tides), gravitational deposition, and biological processes (death and bioerosion). Much of the reef carbonate is deposited very near its point of origin, thus the distribution of sediment-producing organisms has an impact on the distribution of sediments. Carbonate sediments, however, have variable grain shapes that are determined by the skeletal architecture of the organisms from which they are derived (e.g., spherical and disc-shaped forminiferans versus elongate sponge spicules) and have a high porosity (e.g., *Halimeda* consists of thin plates with pores and chambers), making them more susceptible to transport than terrigenous grains of a similar size. Once deposited, these sediments may be further modified through bioturbation by deposit-feeding sea cucumbers and burrowing shrimp (*Calianassa*). While normal wave and tidal conditions are responsible for resuspension of small or buoyant carbonate particles, the efficiency of wave and tidal transport is related to the water depth and size of the waves. Most large pieces of reef debris, such as reef blocks, boulders, and large coral fragments are moved only by high energy storm waves. Storms may also remove enormous volumes of sediment from reef ecosystems and keep this sediment in suspension for extended periods.

In spite of the complexity of reef sediments, sedimentary assemblages are characteristic of particular zones in a reef. The sediment produced by physical and biological destruction of calcium carbonate skeletons accumulates as aprons around the base of the reef or on lagoonal floors, filters into the reef framework, and fills in holes and crevices. In reef flat environments, course sediments consisting of coral fragments, mollusk shells and foraminiferan tests accumulate in shallow grooves on the pavement, while coral areas typically contain smaller fragments of coral and coralline algae, *Halimeda* plates, and echinoid spines. Sediments in the backreef may be a mixture of skeletal sand produced by the disarticulation of organisms that live there under normal conditions, gravel or cobbles washed in from the adjacent reef crest during storms, and carbonate mud produced through biological breakdown. In deeper, low energy lagoonal environments, accumulations of fine sediments contain high concentrations of organic matter, and grain size progressively decreases with depth. Patch reefs further modify sediment composition of adjacent lagoons by affecting water circulation patterns and introducing coarse reef debris.

[7] Sediment grain size and composition is associated with the reef's geomorphology.

Sediment composition varies geographically and across large spatial scales due to differences in physical and biological processes and the availability of various sediments. Oceanic reefs are almost entirely composed of calcium carbonate of local origin, while reefs near continents may have a significant terrigenous component. Furthermore, *Halimeda* and coral fragments are the most important sediment constituents of Caribbean reefs, while sediments of Indo-Pacific reefs are often dominated by encrusting coralline algae fragments and benthic foraminiferans.

Sedimentation rates and quality

Levels of sediment runoff from many high islands and continental areas have increased in recent decades due to human-induced changes in adjacent watersheds and increased soil exposure associated with forest clearing, agriculture, coastal development, and dredging. By understanding rates of sedimentation and sediment composition it may be possible to differentiate impacts of natural processes from human activities, such as the effects of dredging operations, coastal runoff, and land erosion (Babcock and Davies 1991; Philipp and Fabricius 2003; Torres et al. 2001). Terrigenous sediments create an unsuitable environment for corals in at least three ways:

- Unconsolidated sediments provide an unstable substrate for coral settlement
- Acute sediment stress associated with a storm event or runoff during unusual rainfall events may smother corals through rapid deposition or resuspension, and
- Chronic sediment stress resulting from elevated suspended sediment loads reduces water clarity and light levels, and may raise a coral's energetic cost of cleaning its living surfaces (McLaughlin et al. 2003).

Sediment constituents may be a useful indicator of the general condition of reef ecosystems, on a scale of years to decades (Lidz and Hallock 2000). Sediments dominated by identifiable skeletal fragments of mixotrophic organisms indicate low nutrients, while calcareous algae and gastropods are important constituents of sediments in higher nutrient environments. Sediments consisting of coated grains and difficult to identify debris are indicative of high rates of bioerosion. Findings from Florida suggest that sands dominated by coral grains reflect areas with poor coral health, while sediments consisting primarily of *Halimeda* and mollusk fragments occur in areas with better coral health (Lidz 1997). A greater volume of coral sands may be produced when corals are weakened by disease, turbidity, contaminants, mechanical damage, or other environmental and physical factors, and their injured skeletons are increasingly eroded by parrotfish, *Diadema*, boring algae and sponges, and other bioeroders.

Knowledge of the sediment load being transported from coastal areas, the spatial impact of terrigenous sediments as you move further away from the point source, and the relative proportion of terrigenous versus carbonate sediments can help determine the suitability of particular sites for coral transplantation and selection of particular species for transplant based on their sediment rejection capabilities. In addition, areas dominated by unstable coral rubble may need to be stabilized to increase survivorship of transplanted corals and new recruits.

Sampling and Monitoring Methods

Monitoring methods for sediments include measures of sediment composition within reef environments; sediment discharge, loading, and settling rates; and various water quality parameters including turbidity, water transparency, and temperature.

Light

The intensity and quality of incident light[8] is the most ecologically-limiting, physical environmental parameter in coral reef ecosystems, due to the critical role that incident light plays in rates of zooxanthellae photosynthesis and coral calcification. Reef-building corals are able to grow under a wide range of different light regimes, although the greatest densities of zooxanthellate corals are found in shallow, illuminated waters less than 30 m deep. Corals that are restricted to shallower depths in coastal areas, particularly near urban areas may be exposed to increased levels of sediments transported in from upland sources, resulting in higher sedimentation rates as well as reduced light transmission (Sheppard 1982). Reduced light levels have a profound affect on shallow water reef community structure and zonation patterns, with deeper water corals adapting to diminished light through changes in morphology (e.g., plating growth forms) or hosting a different genetic clade of zooxanthellae. Zooxanthellae also adapt to lower light by increasing the concentration of chlorophyll a and/or the relative composition of other pigments (e.g., beta-carotene, perdinin, and diadinoxanthin) (Hoegh-Guldberg 1999). Additionally, other factors can reduce light transmission reaching corals such as algal overgrowth (see section titled water sources). While turbidity may not be a critical characteristic to be monitored in many coral restoration projects, projects located near urban or agricultural areas may need to consider adding the characteristic as a monitoring variable based on local conditions or causes of decline.

Sediment composition - Spatial variability in the composition of sediments can be determined through the analysis of replicate cores collected in various locations within a particular coral reef and its associated habitats (USEPA 1985; Radtke 1997). The samples are subdivided into fractions based on their position within the core and analyzed in the lab to determine the relative proportion of carbonates and terrigenous components, specific constituents of the carbonates (e.g., amount of coral versus algal fragments), and the size of the grains (Sheldrick 1984; Pope and Ward 1998). For grain size analysis, sediment is dry sieved on a shaker through a standard sieve set, separating components into the following size fractions according to the Wentworth scale:

Sediment Type	Size Fractions
Pebbles	4-16 mm
Granules	2<4 mm
Very coarse sand	1<2 mm
Coarse sand	0.5<1 mm
Medium sand	0.25<0.5 mm
Fine sand	0.125<0.25 mm
Very fine sand	0.0625 <0.125 mm
Silt and clay	<0.0625 mm

The distribution of sediment types throughout the survey area is compared using a cluster analysis and dendrograms.

Sedimentation rates - The collection of samples at and above the substrate can provide an estimate of the amount of sediment being transported along the bottom as well as the sediment that is settling out of the water column (Rogers et al. 2001). Sediment traps (Figure 13) passively collect sediment that drops out of suspension over time (Baker et al. 1988; Rogers et al. 2001). These can be left in place for extended time periods to determine total sediment input, or more importantly over shorter, predetermined intervals to allow differentiation of acute sedimentation rates (e.g., sediment input associated with an unusual rainfall event) from chronic or seasonal patterns of sedimentation. Important considerations in the design of sediment traps include the distance that collection bottles are placed above the substrate, type of collection bottle (and size of opening), and duration between sampling events. Most sediment traps are constructed of multiple PVC pipes or jars attached to a steel rod and positioned at varying distances above the substrate. Each of the collection jars has a lid to seal it before removal and baffles at the top of

[8] Light that falls on a surface.

Figure 13. Diver installing a sediment trap. Photo courtesy of Kathy Price, NOAA Center for Coastal Environmental Health& Biomolecular Research (CCEHBR).

the jar to prevent entry of unwanted organisms. These are placed in replicate at various depths and collected typically on a weekly to monthly basis. Samples are filtered, dried, weighed, and analyzed in a laboratory.

In addition to the collection of sediment samples at the study or restoration site, discharge rates of sediments from streams and catchments can be measured using cutthroat flumes or open-channel stream gauging stations using automatic samplers or hand-held depth integrated samplers.

Suspended sediments - The amount and type of sediment and organic matter in the water column can be measured through the collection of water samples, followed by filtration and quantification in a laboratory. In many oligotrophic coral reef locations, the amount of suspended particles is very low and analysis requires the collection and filtration of large volumes of water.

HYDROLOGICAL

Currents and Wave Energy

Currents, wave action, and tidal changes have profound influences on reef distribution and also define coral zonation and distributional patterns within a reef. Water movement affects all aspects of the life history of coral reef organisms, including fertilization success, settlement, growth and mortality, and feeding success. Water motion also affects the supply of plankton and particulate matter, availability of dissolved nutrients, metabolic gas exchange, and removal of wastes, sediment, and excess mucus. In general, calcification rates are higher in areas of high water flow, although linear extension rates may be lower than in areas of reduced water flow.

Individual coral colonies display different and often distinctive growth forms, such as a branching, plating, crustose, or massive morphology, that are determined partially by their physiological and structural tolerances to water movement. Flow rates also influence the orientation, shape, and size of branches, with corals exhibiting reduced spacing and more robust, shorter, and thicker branches in areas of high wave exposure (Graus et al. 1977). Corals found on the windward side of islands, which are routinely exposed to strong waves, winds, and the full brunt of storms, tend to be stronger and hardier, but they may be less abundant and consist of fewer hardier species. Leeward reefs are protected from storm waves and the pounding surf, and tend to have higher diversity communities dominated by fragile, branching, and plating species. Distinct zones within a reef are defined by water motion in combination with other limiting factors such as temperature, salinity, food availability, depth of light penetration, and other factors. The reef crest, for example, is nearest to the water's surface and is constantly subjected to pounding waves, strong currents, and high light levels. As a result, reef crest environments are often dominated by small polyp-encrusting and robust branching corals and certain massive corals that can withstand extreme wave forces.

Water motion also plays a major role in the production, transportation, deposition, and resuspension of sediments, as well as the formation and stability of coral islands (i.e., cays). High water flow and turbulence is responsible for the transport of nutrients in sediments and detrital material out to sea or into back reef and seagrass environments. Reefs in embayments with restricted circulation are likely to experience nutrient build-up and may become eutrophic if they are adjacent to human population centers or agricultural areas. Storm waves are also important in preventing the burial of reefs by sediments, although the movement of sand and rubble can negatively impact sessile organisms through abrasion, dislodgement, and fragmentation, and may result in increased turbidity.

Hurricanes and tropical storms can have catastrophic impacts to coral reefs, though the extent and type of damage varies on small spatial scales. The amount and type of destruction are generally more severe in shallow, exposed habitats, but they also depend on the severity and duration of the storm, benthic community composition (e.g., fragile branching corals are likely to sustain greater injuries than robust, massive corals), and amount of time since a previous storm (Lirman 2001). Damage and mortality may result solely from the physical forces of hurricane-generated waves or from a combination of factors such as:

1) Abrasion and burial from transported sediments and coral fragments
2) Turbidity associated with resuspension of sediments and increases in plankton standing stocks
3) Decline in salinity with high sediment and nutrient loads associated with heavy rainfall and runoff from land, and
4) Rapid drop in temperature

Recovery of affected reefs following the passage of a hurricane may be rapid in communities dominated by branching corals, provided that detached and fragmented corals are deposited within the surrounding area and that they exhibit high rates of survival, reattachment, and regrowth (Highsmith 1982). Compounding factors such as additional storms, outbreaks of coral disease, intense predation on surviving corals, algal overgrowth, and a variety of human impacts may, however, delay natural recovery (Knowlton et al. 1990; Rogers et al. 1991).

The degree of wave exposure and frequency of storms has major implications for all aspects of coral reef restoration including restoration planning, implementation, and monitoring. In Florida, several restoration projects in response to major ship groundings required substantial structural reconstruction and stabilization to prevent expansion of the injury due to erosion during periods of high wave energy (Bruckner and Bruckner 2001).

Sampling and Monitoring Methods

There are several methods available to assess current patterns, wave exposure, surge, tides, and upwelling.

Current meters - Commercially available current meters (e.g., InterOcean S4 recording current meter) can be placed near the bottom or suspended in the water column to continuously sample water flow and record flow speed, direction, and pressure.

Clod cards or plaster blocks - Low cost methods that may be used to quantify water motion include clod cards or plaster blocks. Such methods provide a measure of overall water motion (mass flux) by monitoring the dissolution (e.g., loss of mass) over time. Clod cards or plaster blocks are appropriate for use in the evaluation of biological processes relevant to bulk water motion such as filter feeding rates, larval settlement rates, fertilization success and passive dispersal. One limitation is that the loss of mass is affected by bulk movement of water past the object as well as turbulence, making it difficult to quantify water movement (Bell and Denny 1994).

Recording spring scale or dynamometer - A recording spring scale or dynamometer may be used to estimate the direction and maximum magnitude of wave-induced forces. These instruments typically consist of a small ball attached to a spring that is secured to the substrate. With each passing wave, the motion of water generates drag on the ball, causing the spring to extend. By recording the maximum extension of the spring, an estimate of the maximum hydrodynamic force can be made (Bell and Denny 1994). Knowledge of the maximum velocity to which organisms are exposed allows predictions of the degree of hydrodynamic disturbance (e.g., likelihood of dislodgement of sessile organisms) and could help develop possible restoration alternatives, such as the appropriate organisms to transplant at the site.

Wave characteristics, including wavelength (length between successive crests), height (vertical difference between trough and crest), steepness (ratio of height to length), amplitude (half of the wave height), period (time between successive waves passing a fixed point), and frequency (the number of occurrences within a given time period) are measured using a variety of methods. These include pressure gauges placed on the sea floor, accelerometers attached to buoys on the sea surface, and remote sensing from satellites. Other methods for measuring wave energy, direction, height, and periods are discussed in Draper et al. (1974); Middleton et al. (1978); Fu et al. (1987); Brumley et al. (1983); AshokKumar and Diwan (1996); Tortell and Awosika (1996); Terray and Brumley (1999); and Yang et al. (2004).

Temperature

Most coral reefs occur in areas where temperatures rarely drop below 16°C or exceed 30°C, with an optimal range of 26-29°C. Although there are regional differences in the minimum temperature tolerance of some species, very few zooxanthellate corals tolerate temperatures below 11°C over prolonged time periods (Veron 1995). Water temperature limits the occurrence of reefs and reef-building corals through interactive ecological processes where the energy demands of reef construction become progressively less competitive against macroalgae-dominated ecosystems as temperatures decline (Veron 1995). Low temperature is one of the main environmental factors responsible for the absence of coral reefs in areas of intense upwelling along the western margin of continents, and growth rates of corals are correlated with temperature. Growth rates of corals in the Caribbean are greater than their members of the same species or genus further north, with declines observed during cold water periods and on high latitude reefs subject to greater temperature and light variations (Lewis et al. 1968; Gladfelter 1984). Estimates of mean growth of *M. annularis* in Barbados and Jamaica surpassed estimates from Florida by 1.8-2.4 times, and growth rates for *A. cervicornis* in these countries also exceeded Florida by factors of 1.3 and 2.3, respectively (Shinn 1966; Lewis et al. 1968). Furthermore, the occurrence of periodic cold fronts has limited the distribution of certain species, has been associated with partial to total colony mortality and bleaching, and has significantly altered large-scale features of reefs in locations like southern Florida (Saxby 2001). For instance, a cold water event in 1977 in the Dry Tortugas led to the sudden demise of prominent *A. cervicornis* thickets (Davis 1982). Walker and Ormond (1982) proposed that the growth rates and distribution of *Montastraea annularis* in the northern Florida Keys were in large part controlled by the periodic influx of cold water pushed out from Florida Bay during the passage of major cold fronts.

Most corals exist near their upper thermal limits. Heat stress associated with reduced tidal flushing, abnormally low tides, inter-annual climatic fluctuations (e.g., El Niño Southern Oscillation events), and the discharge of heated water from electrical and nuclear power plants has been demonstrated to affect rates of growth and calcification, metabolic functions, reproductive activity, and resistance to pathogens and disease (Neudecker 1981; Hung et al. 1992; Wilson et al. 2002). Warming of 1-2°C above the mean summer maximum temperatures for one to two weeks may also trigger the loss of zooxanthellae through bleaching (Figure 14). Localized coral bleaching was first reported at least 90 years ago (Vaughan 1914; Boschma 1924). Regional bleaching events were first observed in 1979-1980, with bleaching events of increasing extent and severity occurring in 1982-1983 and 1986-1988 (Williams and Bunkley-Williams 1990). Since the 1990s, regional scale bleaching has become a pervasive and frequent phenomenon, with the most intensive and extensive coral bleaching event on record occurring during the unusually strong El Niño/La Niña event of 1998-1999 (Wilkinson et al. 1999). Variation in temperature thresholds for bleaching and mortality may be related to the physiology of the coral or clade of zooxanthellae, the degree of adaptation of a species to a particular habitat or zone, as well as physical and environmental factors that may enhance susceptibility or resilience of the habitat (e.g., upwelling, turbidity, current patterns) to stressors (Williams and Bunkley-Williams 1990; Edmunds 1994; Fitt and Warner 1995; Kramer and Kramer 2000).

Sampling and Monitoring Methods

It is important to monitor water temperature fluctuations to help understand and characterize differences in coral growth, survival and recruitment, patterns of coral bleaching, and relationships between temperature and mortality or recovery.

Coral Reef Early Warning System (CREWS) stations - NOAA established CREWS stations (Figure 15) in a number of locations in the Caribbean and Pacific to record basic

Figure 14. Bleached coral in the Caribbean waters. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

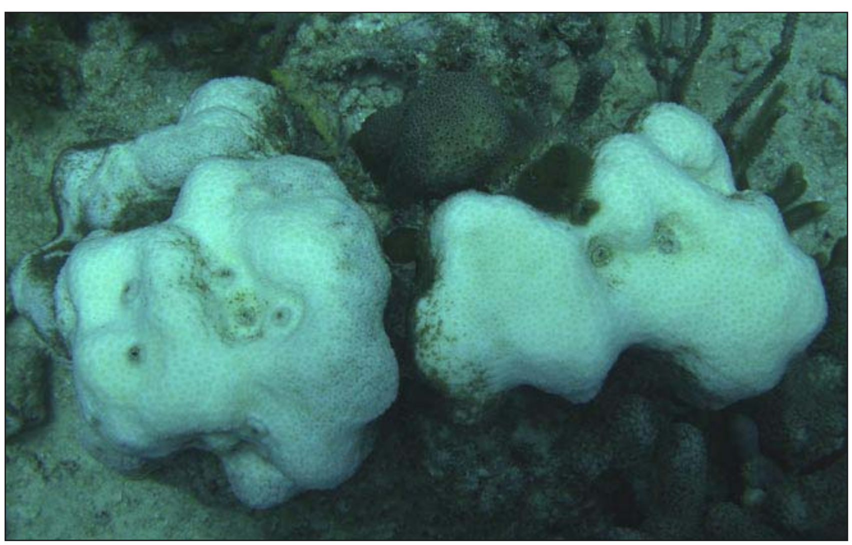

Figure 15. A CREWS station at Lee Stocking Island, Bahamas. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

meteorological and oceanographic parameters such as water temperature on an hourly basis. Data from CREWS stations assist in the prediction and interpretation of patterns and trajectories of coral bleaching, coral mortality, growth, and other parameters. While CREWS stations provide valuable comparative regional data, local water temperatures may vary, and should be monitored within study sites to obtain accurate information on temperature-related impacts. Temperature should be measured just below the water surface (approximately 30 cm) as often as possible using a mercury thermometer enclosed in a protective casing.

***In situ* Data loggers -** Data loggers (e.g., Hobos temperature meters) can be deployed on the reef to instantaneously record sea temperatures at intervals ranging from every few minutes to daily or weekly, and can provide average, minimum or maximum temperatures over a specific duration. Information from data loggers can be downloaded as frequently as necessary, and depending on the unit and the frequency of measurement, the instruments can be left in place for months to years. Data loggers should be calibrated against a certified reference thermometer after each deployment (Colin 2000; Fitt et al. 2000).

Water Sources

Upwelling[9]

Coral reefs thrive in waters that contain low levels of inorganic nutrients (i.e., oligotrophic waters). Nutrient concentrations are generally much lower than those of temperate coastal systems (e.g., 0.1-0.5 μM nitrate, 0.2-0.5 ammonium, and <0.3 phosphorus; Furnas 1991). At higher latitudes, as well as areas prone to intense upwelling, increased nutrient concentrations and high influxes of nutrients may limit reef development. In many locations, terrestrial discharges of nutrients and other pollutants to coastal waters have increased considerably from pre-industrial levels, reflecting increases in human activities in the surrounding watershed. Persistently high concentrations and fluxes of nutrients are major factors contributing to the decline of reefs. This has become especially problematic in coral reefs located close to shore, especially within embayments and lagoons and in reefs associated with large land masses and significant human populations.

Although excess nutrients are generally problematic, a continuous supply of inorganic nutrients is essential for the maintenance of metabolic processes, proper functioning of reef ecosystems, and persistence of coral and coralline algae-dominated communities. Many flourishing coral reefs occur in regions subjected to seasonal upwelling or other natural events such as volcanic eruptions that contribute temporary pulses of nutrients. Nutrient fluxes associated with upwelling events, currents, tides, and other sources can play an important role in the overall productivity of coral reefs. Furthermore, reefs will persist in areas affected by nutrient loading, provided that herbivores are sufficiently abundant and diverse and are able to control proliferation of macroalgae. Even under

[9] Transport of subsurface water to the surface.

low nutrient conditions, coral reefs are seldom subject to nutrient limitations due to the efficient recycling by the reef community and nitrogen fixation by cyanobacteria and other organisms.

Coral reef ecosystems can persist in areas affected by elevated nutrients and plankton productivity as long as water circulation removes excess production off the reefs and maintains water clarity. Once productivity increases to such an extent that water clarity and light penetration is reduced, normal functioning of the reef may be affected (Tomascik and Sander 1985). Chronic nutrient over-enrichment can introduce an inbalance in the exchange of nutrients between zooxanthellae and the host coral, and reefs may exhibit a progressive shift from high coral cover and low algal cover/biomass to high cover and biomass of fleshy algae. As algae decompose, dissolved oxygen concentrations may be greatly reduced, especially in coastal areas with limited flushing. Nutrients can also indirectly affect the reef structure through proliferation of fleshy and filamentous macroalgae that can rapidly overwhelm coral populations, and through an increased abundance of filter feeders such as boring sponges which are responsible for the bioerosion of reefs (Szmant 2002). The combined effects of reduced herbivory (resulting from overfishing and/or die-off of herbivorous sea urchins) and anthropogenic nutrient enrichment has been implicated in phase-shifts from coral-dominated systems to macroalgal-dominated communities throughout the Caribbean during the last two decades (Hughes et al. 1999; Stambler 1999; Szmant 2002).

Coral reefs prone to the effects of high nutrient concentrations are usually exposed to other anthropogenic stressors, such as:

- Increased sedimentation,
- Organic carbon enrichment, and
- Metals and organic pollutants originating from agriculture, industry, and stormwater runoff

Degraded water quality has direct physiological effects on corals, can affect growth and reproductive rates, may destabilize the functioning of the coral-zooxanthellae symbiosis, and may increase coral susceptibility to diseases or bleaching (Kim and Harvell 2002). By evaluating coral reef water sources, and the potential impacts resulting from them, restoration practitioners can design an effective restoration plan to include parameters to monitor water quality. Discussed below are examples of how upland and groundwater sources of water and freshwater inputs can affect coral reefs.

Upland source

The effects and degree of nutrient enrichment (i.e., eutrophication) vary greatly depending on the source (and type and extent of pre-disposal treatment), accompanying contaminants (e.g., organic matter, sediment loads, pesticides and herbicides, oil, heavy metals, and pharmaceuticals and/or pathogenic microorganisms), as well as interactions between gross production and total community composition. The most common causes of eutrophication of coral reefs are:

- Discharge of sewage and agricultural wastewater, with localized impacts from power-generating plants and other industrial discharge
- Forest clear-cutting
- Coastal development and dredging
- Oil drilling, production, and transport
- Beach renourishment, and
- Metal mining (Dubinsky and Stambler 1996)

Groundwater source

Because coral reefs are frequently surrounded by highly porous, limestone drainage areas, groundwater discharges from adjacent industrialized and urbanized terrestrial areas may be considerable, and in many cases have high nutrient content associated with sewage discharge and fertilizer runoff from agricultural areas, hotel gardens, and golf courses. The submarine groundwater discharge flux and associated input of nutrients, dissolved organic carbon, trace elements, and other contaminants could be quantified using naturally occurring radium (Ra) isotopes. Radium isotopes have been shown to be excellent tracers for groundwater inputs into estuaries and coastal areas (Moore 1996; Hussain et al. 1999; Krest et al. 2000). There are four radium isotopes (^{224}Ra, ^{223}Ra, ^{228}Ra, and ^{226}Ra) with a wide range of half-lives (3 days to 1600 years) that are produced by the decay of uranium and thorium in aquifer rocks. The presence of brackish or saline water along the coast causes the Ra to desorb, greatly increasing the concentration of dissolved Ra in saline coastal groundwater (Moore 1996). Through such analysis, the effect of groundwater sources on the delicate carbon and nutrient balance of coral reef ecosystems can be evaluated.

An understanding of the effects of nutrients on coral reef communities as well as how and when nutrient enrichment has contributed to coral reef decline or recovery requires consideration of all mechanisms involved in nutrient dynamics of coral reef ecosystems. These include:

- Patterns of upwelling versus coastal input of nutrients, sediments, and pollutants
- Degree of physical and biological transport and exchange of nutrients and other materials within reef zones and surrounding habitats
- Patterns of productivity and fates of primary production
- Composition, abundance, and biomass of fish and invertebrate grazers, and
- Grazing pressure and preferences, and effects of reduced herbivory on algal diversity and palatability

Freshwater inputs and salinity increase

The salinity of coastal and offshore environments is influenced by a number of environmental factors such as runoff, precipitation, evaporation, surface current patterns, and upwelling. Coral reefs are normally found in areas with salinities of 32 to 40 parts per thousand (ppt), with higher salinities (up to 45 ppt) reported for certain parts of the northern Red Sea and the Arabian Gulf. There is a general absence of corals reefs adjacent to major rivers (e.g., reefs do not occur adjacent to the Amazon and Orinoco River basins) primarily due to low salinity. As salinity declines, carbonate reefs are progressively dominated by vermetids, oysters, serpulids, and blue-green algae.

Salinity fluctuations are a key factor determining local zonation patterns of corals, with reefs in close proximity to major freshwater sources dominated by a few hardy species (e.g., certain species of *Porites, Montipora, Siderastrea,* and *Goniopora*). Certain species of corals found in tidepools, shallow nearshore lagoons, and near rivers are adapted to hypersaline and hyposaline waters, and can survive temporary salinity changes during periods of rainfall or drought. In a shallow lagoon within Biscayne Bay, Florida, which is periodically affected by reduced salinity levels during the rainy season, only a limited number of coral species, including *S. radians* (lesser starlet coral) and *P. furcata* (finger coral) can survive (Lirman et al. 2003). Rapid decreases in salinity after monsoon rains or flood events, as well as chronic stress due to flood rains or rates of evaporation that are outside the normal range experienced in a particular environment, can create conditions that fail to sustain corals. In addition to the effects of heavy rainfall, upwelling, natural fluctuations in salinity, and discharges from freshwater point sources and wastewater and power plants have caused coral mortality events (Jokiel and Coles 1974).

Experimental studies have found that most corals will not tolerate salinities at 110% of normal levels for more than two weeks, while salinities of 150% of normal levels will kill a coral within 24 hours (Borneman 2001). Four reef-building corals found in the Pacific - *Porites lutea*, *P. australiensis, Galaxea fascicularis*, and *Goniastrea pectinata* - died in less than 24 hours when exposed to 53 ppt, died in less than a week at 48 ppt, and experienced partial mortality when exposed to 44 ppt (Nakano et al. 1997). In addition to the potential for increased coral mortality associated with higher than normal salinities, a 20% reduction in salinity resulted in up to an 84% decrease in reproductive success (Richmond 1993). Since wide salinity fluctuations and factors that increase or decrease salinity levels can have detrimental impacts on benthic reef-building corals, salinity levels should be monitored within reef restoration sites to verify the role of salinity perturbations in the success of the project.

Sampling and Monitoring Methods

Water quality - A variety of methods are available to assess water quality parameters. Although inexpensive field kits exist, accurate estimates require sensitive detection methods due to the low nutrient fluxes observed in many oligotrophic reefs. It is recommended that nutrient sampling include analysis of both the water column and bottom sediments. Sampling should be undertaken at a minimum of four times per year, while weekly or bimonthly monitoring may be necessary to account for seasonal differences as well as sporadic major rainfall events. It may be difficult to detect nutrient influxes in areas affected by phytoplankton blooms because phytoplankton rapidly remove nutrients from the water. Thus, nutrient measures should be supplemented with measurements of chlorophyll under these conditions. Water samples are usually collected in acid-washed syringes or bottles, stored on ice, and frozen for later analysis in the lab. Water samples can be analyzed for dissolved inorganic and organic nutrients (nitrates, nitrites, ammonia, phosphates, and silicates) and sediment core samples analyzed for total carbon, nitrogen, and phosphorus. In addition, analysis of trace metals and other contaminants may be particularly useful for reefs adjacent to industrialized and urbanized watersheds.

Some methods to assess nutrients and related literature include:

- Seepage cylinder to estimate nutrient discharge in groundwater in nearshore areas (Corbett et al. 1999)
- Fluorometric analysis (e.g., ammonium and dissolved organic matter analysis, see Holmes et al. 1999)
- Persulfate method (total nitrogen and phosphorus in water samples, see D'Elia 1977)
- Cadmium reduction method (Parsons et al. 1984), and
- Flow autoanalyzer (Ryle et al. 1981)

There are numerous general water chemistry method manuals that provide detailed explanations on the necessary equipment and methods for conducting water quality analysis. These include: Strickland and Parsons (1972), USEPA (1983), Parsons et al. (1984), and APHA, AWWA, and WEF (1995). Additional resources can be found in the second appendix of this chapter.

Salinity

Salinity can be measured using a hydrometer, refractometer, or salinity meter. Water samples should be collected in small plastic vials from the surface and just above the substrate of the study site. For sites located near a freshwater discharge, a series of salinity measurements should be made to determine the extent of any gradient in salinity caused by the freshwater input.

Hydrometer - A hydrometer is placed into a tall flask with the sample water and salinity is determined by taking a reading of the position of the water surface at the bottom of the meniscus (Rogers et al. 2001). Hydrometers are typically calibrated for use at a specific temperature and a conversion chart must be consulted to estimate salinity of a sample taken at a different temperature (Rogers et al. 2001).

Refractometer - A refractometer is a hand-held instrument that measures the bending of light between dissolved salts as it passes through seawater (Strickland and Parsons 1972; Parsons et al. 1984; Rogers et al. 2001). To measure salinity, one or two drops of the sample are placed on the prism. The observer holds the cover down, faces the instrument toward the light, and looks at the scale through the eye piece to determine the salinity (Rogers et al. 2001). A refractometer must be frequently recalibrated with distilled water and may give incorrect readings in turbid waters.

Salinity meter - The most expensive and accurate measure of the salt content of water is an electronic salinity meter comprised of a probe connected by a cable to meter or a computer.

CHEMICAL

The chemical characteristics associated with coral reefs include nutrient concentrations from various water sources (discussed in the previous section, “Water Sources”) and, nutrients provided by epiphytes and algae that support corals. In the Functional Characteristics section of this chapter, under the segment titled “Supports Nutrient and Carbon Cycling,” is a discussion on the role epiphytes and algae play in supporting coral reefs.

FUNCTIONAL CHARACTERISTICS OF CORAL REEFS

Coral reefs and associated mangrove forests and seagrass beds perform important biological, ecological, and physical functions. Two of the main outputs of reefs are organic and inorganic carbon production. Carbon, available as bicarbonate ions dissolve in seawater, is fixed by reef organisms for the production of their skeletons at an annual rate of 1-10 kg per m^2 (Kinsey 1991). The resulting skeletal structure provides a substrate for the settlement and attachment of other sessile organisms, as well as topographical relief that serves as habitat for motile fishes and invertebrates. Coral and algal skeletal materials are also broken down into sediments that form beaches and soft bottom habitats, are incorporated into the reef structure, and form an important part of the inorganic carbon pathway.

Primary production of organic carbon by symbiotic zooxanthellae, turf algae, macroalgae, and coralline algae ranges from 3.5-32.2 kg per m^2 annually (Crossland et al. 1991). This production supports the diverse organisms and complex food webs found on coral reefs. In addition to sunlight as an energy source fueling photosynthesis and water motion for transporting resources and removing wastes, high rates of primary production are maintained through rapid removal of primary producers. Through grazing and dislodgement, turf algae and frondose algae are maintained in an early stage of ecological succession where rates of photosynthesis and growth are highest (Choat 1991). Secondary consumers (predators of herbivorous fishes and invertebrates) further enhance reef productivity by maintaining their prey in high growth phases and by supplying concentrated nutrients to their prey (Williams and Carpenter 1988). Furthermore, gradients of water temperature, light, nutrients, and organic matter affect the functions of coral reef ecosystems. Along gradients from offshore oligotrophic waters to nearshore eutrophic conditions, the symbioses between zooxanthellae and corals decrease, abundance of heterotrophic suspension feeders increases, and ratio of organic carbon to inorganic carbon production increases (McClanahan et al. 2002).

Of tremendous importance to the function of coral reefs is their proximity to other associated communities such as seagrass beds and mangroves. Mangroves (Figure 16) are highly productive habitats found on cays associated with leeward reefs and along the shoreline in areas protected from the full force of waves. They act as a buffer between the land and sea, trapping much of the soil and nutrients that runoff from land. Most of the production in mangroves is associated with the microbial community in the sediments, which is responsible for breaking down the organic matter from land and leaves that fall off trees, which is largely exported

Figure 16. Mangroves in Florida. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

to reef communities where it is utilized as a nutrient source.

Mangrove roots also act as nurseries and shelter for a number of coral reef species including juvenile fishes, mollusks, and lobsters. Seagrass beds provide food, shelter, and nurseries for reef-associated fishes and invertebrates, and also play an important role in trapping sediments and excess nutrients from reef communities and land.

Some of the functional roles of coral reefs and associated habitats include:

Biological

- Contributes to primary production
- Provides habitat and shelter/refuge for motile fish and invertebrates and cryptic fauna and flora
- Provides breeding, feeding, and nursery habitats for a wide range of marine species
- Provides hard substrate for settlement and growth of sessile organisms

Physical

- Protects shorelines from strong wave action and full impacts of storms

Chemical

- Supports nutrient and carbon cycling

BIOLOGICAL

Contributes to Primary Production

Coral reefs have high rates of gross production but generally little net excess production due to consumption of primary productivity by reef heterotrophs and highly efficient nutrient recycling between producers and consumers. Benthic and endolithic algae, cyanophytes, seagrasses, and zooxanthellate corals contribute significantly to primary production and enter the food web in varying ways. Algal turfs trap organic debris and provide sites for bacterial growth, and are a major accessible source of food for grazing benthic herbivores and detritivores. Reef-building corals gain much of their nutritional requirements from zooxanthellae. Corals also utilize other food sources to varying degrees, including zooplankton, suspended bacteria, detritus particles, and dissolved and particulate organic substances, and their waste products are translocated to the zooxanthellae. Algal mats, especially those within damselfish territories, often support blue-green algae populations that contribute significantly to reef nitrogen fixation.

Provides Habitat

Coral reefs show considerable structural diversity through a wide variety of ecological zones and numerous microhabitats. These habitats are created through both accretionary processes of reef-building organisms (e.g., corals and algae) and destructive forces that mechanically erode, dissolve, or bioerode their skeletons. Coral reefs are also often associated with other habitats such as mangroves and seagrass beds, many of which support unique sets of characteristic invertebrate and fish fauna or particular life stages of reef-dwelling species. Environmental conditions (e.g., wave exposure, currents, storm frequency, light levels, temperature) and biological factors (e.g., rates of bioerosion, type and amount of available food, competition, etc.) affect the distribution, abundance, and growth forms of the corals and other framework builders, as well as the occurrence of mangroves and seagrasses. Coral reefs vary enormously in size, shape, physical exposure, geological history, and vertical depth contours. Even within similar ecological zones, the spatial distribution of structure-forming organisms, algae, and sessile and mobile animals vary widely among reefs, partially due to differing morphologies of corals of different species and also the intermixing of coral assemblages with rubble, sand, and hard ground substrata.

The high diversity of species found on coral reefs is a direct reflection of the high number of niches afforded by this environment. In addition to macroinvertebrates and fishes found on the surface of the reef and in the water column, diverse species assemblages inhabit crevices and fissures in the reef. Many species occur in association with living and dead coral heads, and symbiotic relationships are plentiful. In addition, a specialized community of macroscopic and microscopic animals and plants live below the surface of the sand and rubble and within the skeletons of living and dead corals. Each species found on a coral reef has a specialized role in the ecosystem and contributes to the complex trophic food webs found there. Many species restrict their range to a particular section of the reef to suit particular needs such as refuge; substrate for attachment; or feeding, resting, nursery, and/or breeding grounds (*all of which are discussed in the following sections*). Other species may utilize multiple habitats during different stages of their life or different times of day. The organisms found among coral reefs can be grouped into the following categories:

- Ecologically, commercially, and recreationally important fish such as grouper *Epinephelus* spp., snapper *Lutjanus spp.,* grunts (Figure 17)
- Mobile macroinvertebrates (lobsters, crabs, mollusks, and echinoderms)
- Sessile and sedentary invertebrates (sponges, tunicates, gorgonians, and bryozoans)
- Infaunal organisms and meiofauna (diatoms, foraminifera, and microinvertebrates)
- Endolithic algae and cyanboacteria
- Epilithic and benthic algae (turf algae, macroalgae, crustose and erect coralline algae, and cyanobacteria) (Figure 18)
- Flowering plants (seagrasses and mangroves)
- Zooplankton and phytoplankton

Provides Shelter/Refuge from Predation

The structure of fish and invertebrate communities is influenced by the physical complexity of the substrate and amount of coral cover, with increases in substrate complexity providing a greater diversity of shelter and feeding sites. Coral reefs contain numerous crevices, fissures, and convolutions that increase spatial heterogeneity and microhabitat variety.

In general, small sessile invertebrates are most abundant on internal reef surfaces where they are protected from most predators, while

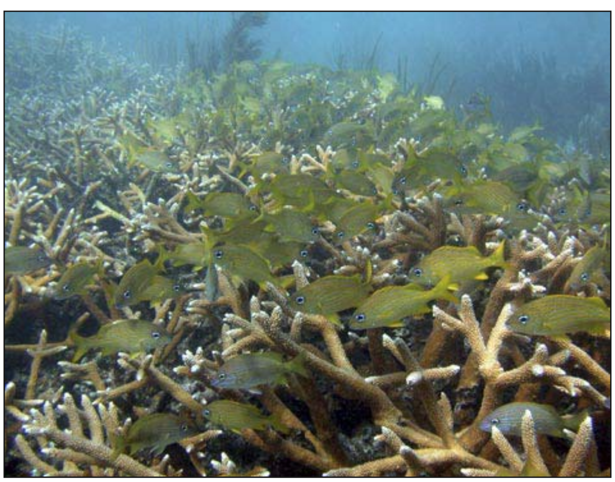

Figure 17. Grunts (Haemulidae) in staghorn coral (*A. cervicornis)*. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 18. Coral reef covered with brown algae (*Lobophora*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

algae, zooxanthellate corals, sponges, and other large sessile invertebrates are found on open reef surfaces, often in areas with high rates of herbivory. Certain corals that are extremely vulnerable to predation, especially those with a branching morphology (i.e., *Acropora*), often proliferate in turbulent reef zones and shallow reef-flat habitats where they escape predation by sea stars and other corallivores due to high wave exposure that limits the occurrence of these predators.

Interstices formed by coral skeletons trap plankton and provide shelter for small invertebrates. Some macroalgae and sessile animal taxa such as bryozoans, polychaetes, mollusks, barnacles, and tunicates occur in these crevices. Filamentous green algae, cyanobacteria, and crustose coralline algae are often abundant in cryptic habitats such as the underside of foliaceous corals. In both microhabitats, the intensity of feeding by other herbivores and carnivores is reduced. Many of the algal species found on coral reefs also have defensive strategies that protect them from grazing. A number of red coralline algae (e.g., *Porolithon* spp.) are hard and plate-like. Many brown algae are leathery and contain spines (e.g., *Turbinaria* spp.) and some green algae are calcified (e.g., *Halimeda*) or produce toxins (e.g., *Caulerpa)* to deter herbivory.

The potential risk of predation within exposed coral reef environments limits grazing activities of smaller reef fishes to areas with considerable structural relief. The distribution of herbivorous fish varies inversely with tidal exposure and wave action as well as with the availability of shelter for the herbivores from predatory fishes. Herbivorous fishes may be low in abundance in the very shallowest sites due to limited accessibility, abundant at intermediate depths due to high accessibility and shelter, and rare in deep reefs where the abundance of shelter declines (Hixon 1991). In areas where overfishing has reduced the abundance of piscivores, herbivorous fishes may be active over greater depths and algal standing stocks will be lower (Hay 1984). Furthermore, where large shelters are nearby, large herbivorous fishes will be locally abundant, while areas with few large shelters and numerous small shelters will have a dominance of small herbivores.

Diurnal[10] species such as most herbivorous fishes (e.g., surgeonfishes, damselfishes, and parrotfishes (Figure 19)) and small predatory fishes (e.g., goatfishes) rely on vision to feed. At night, most diurnal animals seek shelter within crevices in the reef (e.g., surgeonfish), bury themselves within the sand (e.g., wrasse), or construct mucus cocoons (e.g., some parrotfish) to block detection. If they are too large to shelter within protected spaces, many fishes go through a nightly color change, typically becoming darker. Many nocturnal predators (e.g., grunts, soldierfish) are highly gregarious during the day, and often shelter in dense, resting schools under coral heads in reef caves and crevices.

In addition to structural refuge offered by coral reefs, fish and invertebrate prey minimize the risk of predation through their morphology,

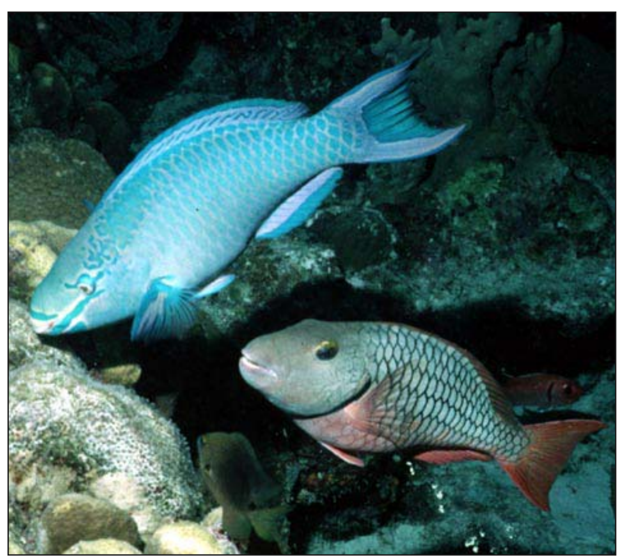

Figure 19. A terminal phase (male) princess parrotfish and an initial phase stoplight parrotfish. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

[10] Organisms active during the daytime.

color, toxins, and behavioral modifications such as schooling. Reef fishes exhibit a variety of body shapes and structures that discourage predation, such as tough skin, spines, ability to inflate, and deep bodies. Cryptic coloration, including mimicry[11], eyespots, and aposematic warning coloration is widespread among benthic reef fishes. Many nocturnal fish are red, which makes them invisible to predators.

Provides Breeding Grounds

Coral reef species have an extraordinary diversity of reproductive patterns defined by life history traits of the organism. The majority of coral reef species exhibit complex life cycles that include separate planktonic larval stages and bottom-dwelling juvenile and adult phases. Reproductively mature adults may spawn larvae (or gametes) into the water column, deposit eggs on the substrate, or incubate the eggs and release offspring in various stages of development, depending on the extent of parental care. To understand and predict changes in spatial and temporal distribution, abundance, population structure, and patterns of recovery following disturbance, it is necessary to understand the life history of the species of concern, environmental factors affecting the site, ecological interactions among associated species, and processes that affect survival of both planktonic and benthic phases of the organism.

Invertebrate reproductive patterns

Invertebrates exhibit both sexual and asexual reproduction and provide varying degrees of parental care to their offspring. Reproductive activities show annual, seasonal, monthly, lunar, and daily patterns. Environmental parameters such as seawater temperature, day length, salinity, food, moonlight, and tidal cycles regulate reproductive cycles through interactions with endogenous biorhythms.

The most common strategy for sessile invertebrates, including many of the coelenterates, sponges (Figure 20), bivalves, mollusks, tunicates, tube worms, and bryozoans, is to release eggs and sperm into the water column for external fertilization. Organisms using this strategy are referred to as broadcast spawners. Reproduction is usually seasonal and concentrated during brief annual periods. Most stony and soft corals, sponges, and several other sessile invertebrates participate in predictable mass spawning events, reproducing within several days of the full moon or new moon during summer. This strategy may maximize fertilization success and saturate planktonic predators such that a high proportion of the eggs survive.

A number of stony corals also brood their larvae. Eggs are fertilized internally by sperm picked up from the water column and well-developed planulae are released into the water. Some brooded planulae are produced asexually. Corals that brood larvae often reproduce on a lunar cycle for a number of months per year, and the large larvae that are released settle within hours to days after release, often recruiting close to the parental stock. About three quarters of all corals are simultaneous hermaphrodites and produce both male and female gametes, while the remainder has separate male and female individuals (Richmond and Hunter 1990).

In asexual reproduction, new clonal polyps are formed through budding of the "parent" polyp as

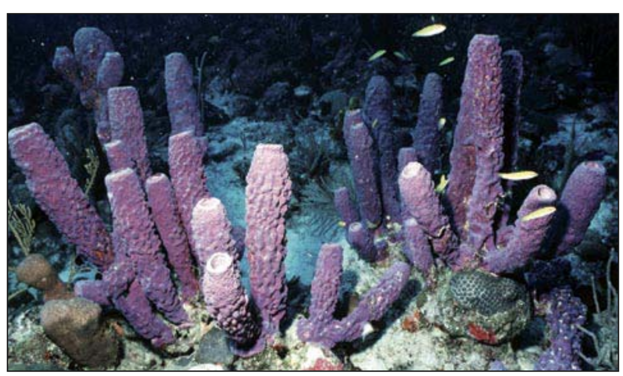

Figure 20. Sponges (Porifera). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

[11] Resembling another organism or structure to avoid being seen.

the colony continues to expand in size. Budding, fission, polyp bail-out, and fragmentation of adult colonies are also employed by corals and other anthozoans to form new colonies.

A number of motile invertebrates including most echinoderms, polychaetes, and certain mollusks (chitons and scaphopods) also release gametes into the water column for external fertilization. Most other motile invertebrates also have a planktonic larval phase, although reproduction may involve internal fertilization following copulation.

Gastropods and cephalopods may encase eggs in gelatinous strings or masses or in hardened capsules, and attach them to the substrate, although some gastropods brood their eggs. Most mollusks have separate sexes, with the exception of many limpets, the coral-eating snail *Coralliophila,* and other prosobranches that are protandrous hermaphrodites (i.e., change from male to female). Large numbers of reef squid come together to copulate and spawn at the same time, depositing a community pile of egg strings. Octopods care for the eggs after they are deposited and the females of some species die after the eggs hatch.

Almost all crustaceans have separate sexes, with the exception of a few shrimp that are protandrous hermaphrodites. Crustaceans typically copulate seasonally, shortly after the female molts. The female will brood eggs on her abdomen for several months before releasing larvae into the water column.

Reproductive patterns of fishes

Spawning patterns of reef fishes vary on daily, lunar, and seasonal time scales, with most fishes having long reproductive seasons characterized by one or more annual peaks. Species that spawn on a daily periodicity may have fixed, short spawning periods based on the timing of the tides or other factors, while others spawn throughout the day (e.g., parrotfishes and wrasses). For species that spawn on a lunar cycle, seasonally, or annually, reproduction of an entire local population may by synchronized or acyclic and unsynchronized. In addition to temporal variations, there is considerable variation in where and how species spawn, the types of eggs they produce, and the amount of parental care. Most fishes release a cloud of gametes into the water column for external fertilization, while others deposit their eggs on the benthos, either indiscriminately (e.g., chromis and sergeant major) or in discrete clutches that are intensively guarded (e.g., damselfishes). Some species spawn within a small home range or territory, either close to the reef (primarily small fishes) or in the water column. Several pelagic spawners migrate to traditional spawning grounds. Small grazers, planktivores, and mobile invertebrate feeders (bluehead wrasse, certain parrotfish, goatfish, and surgeonfish) typically travel short distances to local spawning areas, while large predatory groupers and snappers may migrate tens of kilometers to form transient spawning aggregations. Seahorses, jawfishes, and several species of cardinal fishes incubate eggs inside their mouths or within an abdominal pouch until hatching. Internal fertilization and live-bearing young is the least common reproductive strategy of reef fishes, but typical of sharks (Figure 21) and rays (Sale 1991).

Fishes that are characterized as broadcast spawners often exhibit polygamy (multiple mates), while many small site-attached pelagic spawners have small harems consisting of a single territorial male and multiple females (e.g., parrotfish and wrasses). In addition, a number of species, including most wrasse, parrotfish, and sea bass families are sequential hermaphrodites that change sex from female (initial phase) to terminal males (protgynous hermaphrodites). Less common are protandrous hermaphrodites (e.g., snook) and simultaneous hermaphrodites with both functioning ovaries and testes (small sea basses like hamlets - Figure 22). While most species will mate with multiple partners, several

Figure 21. Nurse shark (*Ginglymostoma cirratum*) among coral reefs. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 22. Hamlet (*Hypoplectrus* spp.) near Colpophyllia (brain coral). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

angelfish, butterfly fish, seahorses, pipefishes, jawfish, and other species establish stable relationships that last several breeding cycles.

The timing, location, and behavior of spawning in reef fishes are affected by risk of predation on adults and generally occur where and when the eggs and larvae have a high probability of drifting safely away from the reef (Sale 1991; Deloach 1999).

Provides Feeding Grounds

Coral reefs are characterized by complex trophic food webs consisting of diverse assemblage of primary producers, filter feeders, grazers, predators, and scavengers. The primary producers include symbionts associated with corals, giant clams, sponges, and other organisms, as well as algae, seagrasses, and cyanobacteria. Algae, cyanobacteria, and coelenterates dominate the community structure and production of new organic materials. Invertebrates and fishes transform this plant material into animal material and also utilize external sources of organic material, particulate organic carbon, and zooplankton. Herbivores include surgeonfish, parrotfish, and other fishes as well as a number of invertebrates (e.g., urchins and some mollusks and crustaceans) that feed primarily on benthic algae; a number of fishes and invertebrates also consume plankton. Herbivores are represented by browsers with cutting teeth that feed primarily on algae and grasses above the substrate and grazers that crop very close to the substrate, ingesting plant tissue and a portion of the associated substrate. They feed primarily on unicellular algae (e.g., diatoms), filamentous and fleshy algae on benthic substrates, and algae and seagrasses consumed incidentally with other prey items (e.g., epiphytes). A high diversity of secondary consumers are also found in the interstices of coral colonies and include filter and suspension feeders such as sponges, sipunculids, polychaetes, mollusks, and crustaceans. Macroinvertebrate feeding strategies are varied and include suspension or filter feeders that consume phytoplankton and zooplankton (e.g., sessile invertebrates), detritivores that ingest sediment and organic matter (e.g., sea cucumbers), corallivores that prey on reef-building corals, gorgonians and other cnidarians (certain gastropods, polychaetes, and echinoderms), invertebrate predators (certain polychaetes, gastropods, and crustaceans), and a few piscivores. The diets of reef fishes are quite varied and often change as they grow. Most reef fishes are planktivores during their larval stage, transforming into carnivores after settling into shallow-water habitats, and later switching to their adult diets.

Herbivores

Nearly all phyla of coral reef organisms contain one or more species that feed on plants to various degrees. While small mollusks (chitons and conch) and crustaceans may be locally important herbivores, larger, more abundant herbivores, such as sea urchins, surgeonfish, and parrotfish may alter the standing crop, productivity, and community structure of algae on coral reefs, and consequently affect the array of species with which sessile organisms must compete for space. Herbivory can increase community diversity by removing the dominant competitors and clearing substrate for new colonization, or decrease species richness by selectively removing preferred alga and altering rates of succession. For example, low intensities of parrotfish grazing lead to reef communities dominated by fleshy algae. At intermediate densities, a greater diversity of corals and algae occur, while high densities have low biomass of algae and low diversity of coral (Brock 1979). Intensive grazing by herbivores in some systems enhances local productivity by maintaining algal communities at an early successional stage.

The effects of herbivorous fishes on algae and seagrass community structure also depends on interactions between specific types of fishes and any morphological, structural, or chemical characteristics of the algae, as well as the degree of competition with invertebrate herbivores. For instance, long-spined sea urchin (*Diadema antillarum*) shows a strong preference for algal turf. When algal turf is plentiful, they avoid macroalgae and crustose algae. When algal turf is sparse, alternate food sources are consumed. The preference hierarchy among algal species is similar between *Diadema* (Figure 23) and herbivorous fishes (Hay 1984), although *Diadema* forages over a much smaller range in comparison with schooling herbivorous fishes. In addition, *Diadema* will occupy coral reefs, grassbeds, mangrove roots, and sand flats, and are able to survive on a wide variety of food sources, including circumstances under which herbivorous fishes cannot exist (Birkeland 1988). Territorial damselfishes also have strong local effects on shallow reef algae. The defensive and grazing activities of damselfish result in visually distinct mats of macroalgae that are of greater productivity than comparable areas outside of territories. Damselfish often maintain algal communities at a mid-successional stage that are a superior food source for the fishes and consist of a higher diversity.

Approximately 25% of all reef fishes eat algae. Many of these, such as parrotfishes, surgeonfishes, and rabbitfishes, occur in large

Figure 23. Sea urchins (*Diadema bonaire*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

Figure 24. Triggerfish (*Balistes* spp.) near Mountainous star coral (*Montastraea faveolata*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

schools with densities that may exceed 10,000 herbivorous fishes per ha, and secondary productivity that may approach 3 metric tons per km^2 per year (Hixon 1991). These fishes may substantially modify the standing crop of algae on reefs through intensive feeding, removing most of the algal biomass except for encrusting corallines, basal portions of filamentous algae, and chemically or structurally defended macroalgae. Herbivorous fishes are generally more selective than echinoids because they move over large areas and are visually discriminating. Several herbivores (e.g., parrotfish and large wrasse) often erode calcareous structures, producing sediment as a byproduct of feeding.

Corallivores

Adult fishes (e.g., certain butterflyfish, parrotfish, damselfish, blennies, and other species) and certain invertebrates (*Drupella* and *Coralliophila* gastropods, *Acanthaster* crown-of-thorns sea stars, *Hermodice* polychaetes, as well as some nudibranchs and crustaceans) are obligate or facultative corallivores that feed on coral tissues and associated symbionts or on coral mucus. These corallivores can affect the local distribution, abundance, and diversity of corals through selective predation on certain taxa, and have been observed to prevent recovery of coral populations after major disturbances such as hurricanes. Other carnivores (e.g., triggerfish (Figure 24), pufferfish, filefish) may affect abundances of reef-building corals indirectly by preying upon their corallivore predators or by controlling populations of sponges, ascidians, alcyoneans, and gorgonians that compete with corals for space.

Planktivores

Many species of soft corals, sponges, clams, feather-duster worms, and other filter feeders as well as small zooplankton utilize phytoplankton directly as a food source. In particular, coral reef communities with rich terrestrial nutrient input often support a rich phytoplankton-based food web characterized by an abundance of suspension feeding invertebrates and planktivorous fishes. Zooplankton is also an important food source for fishes and invertebrates, with planktonic eggs, larvae, and newly settled juveniles often subject to more intense predation than adults. Planktivorous fishes that feed in the day tend to occur in schools in the water column on reef slopes adjacent to deep water and in areas affected by currents. They feed primarily on transient zooplankton from open water, consuming primarily crustacean and fish eggs. Zooplankton increases in abundance and size after dark in many reef environments due to vertical migration upward within the water column, and include transient species as well as various polychaetes, ostracods, mysids, amphipods, and crustacean larvae that spend a relatively short period of time in the water column prior to settlement on benthic substrates. Nocturnal planktivores include fishes, echinoderms (e.g., brittle stars, crinoids, and basket stars) as well as a number of sessile invertebrates such as coelenterates that wait for passing food sources.

Some planktivorous fishes may affect recruitment success of invertebrate corallivores, herbivores, and other species of invertebrates and fishes by consuming early developmental stages of these organisms. For instance, a Red Sea damselfish is known to feed on larval urchins and sea stars *(Acanthaster)* (Figure 25). Intense predation by triggerfishes, pufferfishes, large wrasses, and porcupine fishes may also affect adult populations of urchins and sea stars. Intense predation is thought to limit population explosions of *Acanthaster* (Ormond et al. 1973) and prevent the formation of discrete barren zones due to overgrazing of algae by urchins (Hay 1984). Many of these planktivores dominate in abundance and biomass within mangrove forests, tidal channels, and outer edges of reef slopes, where they consume a variety

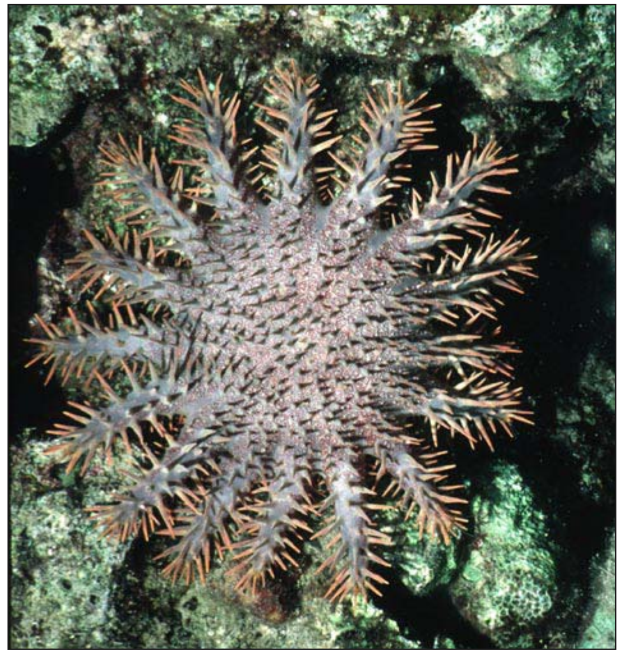

Figure 25. Sea stars (*Acanthaster*). Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

of organisms such as copepod, crab, mollusk, and echinoderm larval stages and post-larval fishes, depending on the season (Robertson et al. 1988).

Carnivores

Many of the large carnivores found on reefs are generalists and highly opportunistic in their feeding habitats. Predators have many different methods of food capture and ingestion, and predation pressure may influence prey populations and substrata composition. An increase in abundance of a species of prey often causes predators to switch their attention to the more abundant prey item. Several fishes are specialized feeders, but will alter their diet when their preferred prey becomes rare. Certain triggerfish and toadfish prefer *Diadema*, but began feeding on a broad range of mobile benthic invertebrates following the mass mortality of this urchin in the Caribbean. The population densities of the predators and prey, condition of the prey, its preference as a food source, and extent of defense by structural or chemical attributes and symbionts (e.g., crustacean guards) also affect predation pressure. Furthermore, changes in the physical or biotic environment can suddenly cause a prey species to become more vulnerable to predation.

Fishes that feed on mobile invertebrates are more common than those consuming corals and other sessile invertebrates. Crabs, shrimps, stomatopods, and amphipods are the major food source of many species, with selected predators targeting mollusks within reefs and in soft bottom communities. Some species of wrasse, angelfish, butterflyfish, filefish, and triggerfish feed to varying degrees on sessile invertebrates such as sponges, tunicates, and coelenterates, as well as large mobile epifauna. Most bottom-feeding fishes that consume small crustaceans, polychaetes, and other invertebrates within coral heads (e.g., trunkfish) and in the sediment (e.g., goatfish) are active in the day. Nocturnal fishes, such as squirrelfishes, bigeyes, and grunts, locate crabs and shrimps with their large eyes.

A number of motile invertebrates are also important predators. Errant polychaetes (e.g., *Hermodice*) feed on colonial cnidarians, sponges, and other sessile invertebrates. Certain mollusks (e.g., *Charonia*) prefer echinoderms, while the octopus will feed primarily on crustaceans and mollusks. Decapods (lobsters, crabs, and shrimp) couple predacious feeding with scavenging, although some are filter feeders (e.g., burrowing shrimp, pea crabs, mole crabs, and porcelin crabs).

Figure 26. A green moray (*Gymnothorax* spp.) among corals. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

A small number of invertebrates feed on fishes, including a few coral species, squid, and some crustaceans. Piscivorous fishes are represented by roving predators such as certain sea basses, sharks, jacks, morays (Figure 26), ambush predators such as frogfishes, lizardfishes, and scorpionfishes), and stalkers (e.g., trumpetfish and barracudas). Roving predators often have peak of feeding activity at dusk and dawn, concentrated during the time when diurnal schooling fish return to their nocturnal refuges and reduced light levels render anti-predator schooling mechanisms less effective.

Detritivores and scavengers

The dominant detritus feeders on coral reefs are sea cucumbers (Holothuridae and Stcihopodidae) that feed by shoveling sediments into their mouth and digesting the organic and inorganic detritus and associated microorganisms, protozoans, and other micro-fauna. Nearly all hermit crabs as well as many lobsters (Figure 27), crabs, and shrimp are also scavengers, feeding on almost any dead organic material. Bacteria and associated flora and fauna facilitate breakdown of detritus and waste products in sediments and the water column, providing nutrients that are channeled back to various primary producers.

Provides Nursery Grounds

Nearshore habitats associated with coral reefs, including the back reef, lagoonal seagrass and patch reef habitats, mangrove forests, algal flats, and rock, mud, and rubble habitats often contain high abundances of juvenile fishes and invertebrates. The habitats used by the juveniles

Figure 27. A lobster (Panuliridae) on a reef off Mona Island, Puerto Rico. Photo courtesy of Andrew Bruckner, NOAA National Marine Fisheries Service.

are often different from those used by adults. These juvenile habitats are often characterized by a high degree of structural complexity that supports production of juveniles to sub-adult or adult populations during a particularly vulnerable stage in their life cycle. The nursery value of different coral reef habitats is often species-specific, and will depend on their life history traits, environmental factors, seascape features and ecological processes affecting the distribution, abundance, and population dynamics of juveniles (Beck et al. 2001). Environmental factors that influence juvenile settlement and survival include water depth, salinity, temperature, turbidity, tidal regime, wave exposure, extent of disturbance, and other parameters. Seascape features such as size, shape, complexity, and quality of the habitats as well as the relative location of the habitat to sources of larvae, other juvenile habitats, and adult habitats also affect settlement patterns.

Most coral reef fishes and invertebrates have a two-phase life cycle characterized by planktonic larvae, demersal or benthic juveniles, and adults. Some site-attached benthic organisms such as territorial damselfishes use the same habitat as juveniles and adults, and settle, reproduce, and mature in a single location. As the juvenile fish grow and change their dietary requirements, they shift to intermediate habitats or their adult home range. Many parrotfish are adapted to a wide variety of habitats, but may remain in the same habitat from settlement through adult life stages. Economically important fishes such as snappers, groupers, grunts, and lobsters exhibit complex habitat, diet, and behavioral shifts during transition from settlement through late juvenile phases, with larvae settling in habitats that are distinct from adult habitats.

Seagrass communities harbor a wide range of benthic, demersal, and pelagic organisms. This includes permanent residents which spawn and spend most of their lives in seagrass beds and transient species. Transient species spend their lives in seagrass beds during their juvenile through adult life cycles but spawn outside the seagrass beds or move between habitats on a daily basis, using seagrass beds for food or shelter. Other transients seek food and shelter in seagrass beds during their juvenile stage, and move to other habitats as sub-adults or adults. Seagrass beds are considered the major nursery ground for commercial pink shrimp, spiny lobster, gray snapper, sea trout, barracuda, and grunts. See Chapter 9, “Restoration Monitoring of Submerged Aquatic Vegetation” for more details.

Mangrove forests offer habitats of different complexity and quality and are often vertically zoned in response to tidal changes, degree of inundation by seawater, and degree of association with other habitats. The prop roots provide a substrate for attachment of sessile organisms such as sponges, tunicates, bryozoans, bivalve mollusks, and coelenterates that settle as juveniles. A number of motile invertebrates including gastropods, echinoderms, and crustaceans use mangrove roots as nursery areas and/or adult habitats. In Florida, mangrove prop roots support juvenile populations of snook, gray snapper, spotted sea trout, red drum, barracuda, and mullets (Thayer and Sheridan 1999). In Curacao, 17 different fish species which inhabit coral reefs as adults were found to use mangroves, seagrass beds, and other shallow-water nearshore environments, including grunts, snappers, parrotfish, barracuda, butterfly, and goatfish (Nagelkerken et al. 2001). See Chapter 11, "Restoration Monitoring of Mangroves" for more details.

Research and monitoring efforts to assess the density, growth, survival, and movement patterns of ecologically and economically important species, and characterize linkages between juvenile and adult habitats may facilitate restoration decisions. A comparative sampling approach that examines habitat utilization patterns and production, and places these habitats within a spatial context of the overall habitat mosaic, will help determine how a species is affected by habitat loss or fragmentation and the likelihood of its recovery. This information may help identify the best suite of actions to restore function and connectivity among these habitats.

Provides Substrate Attachment

Most sessile invertebrates and algae require some form of hard substrate for attachment. This can include coral reef and hard ground substrates, mollusk shells, rubble, seagrass blades and calcified algae, mangrove prop roots, and various cryptic habitats such as the underside of plating corals and cavities within the reef framework. In many locations, suitable substrata becomes limiting and sessile organisms compete for available settlement sites. The structure and diversity of these communities is largely controlled by complex interactions between benthic inhabitants that compete for space, grazing activities of motile fishes and invertebrates, and physical and environmental factors. Local space limitations can create conditions involving contact between neighboring individuals that may ultimately result in overgrowth and death of a part or all of one organism by the superior competitor (Jackson 1979). Other biological factors such as herbivory and predation can also alter spatial relationships among species. At intermediate densities, urchin grazing may decrease competition between algae and corals and provide additional free space for settlement, while the absence of echinoids can result in massive coral mortality due to monopolization of space and overgrowth by fleshy macroalgae (Sammarco 1982). Physical disturbance also slows space monopolization, and can have a major influence on species diversity and zonation.

Sampling and Monitoring Methods

Macroinvertebrates

Many researchers monitor large mobile invertebrates that are fished for food or curios such as lobsters, conch, and sea cucumbers to determine the effect that fishing is having on the ecosystem. Another group of macroinvertebrates included in most monitoring programs are species that prey on corals such as crown-of-thorns sea stars (*Acanthaster*) and *Drupella* and *Coralliophila* gastropods and key herbivores (e.g., *Diadema* and other urchins). Non-invasive monitoring methods used to quantify populations of mobile macroinvertebrates include:

- Manta tows to identify populations of abundant, large species and assess the impacts of outbreaks of predators (e.g., *Acanthaster*) over large areas
- Roving diver (timed swim) surveys to estimate abundance of multiple species within relatively large uniform areas (conch within grassbeds), in topographically complex and cryptic habitats (e.g., lobsters within crevices, caves, or coral thickets) that may be missed by other methods, and for rare species that may be missed with other methods

- Belt transects to obtain information on abundance and size structure of larger target and keystone species (e.g., urchins) within specific zones or depths
- Point intercept methods for sessile invertebrates such as sponges and gorgonians
- Quadrats (or individual corals) to get precise estimates of smaller invertebrates such as *Drupella* and *Coralliophilla* and evaluate rates of coral tissue consumption, and
- Portable and stationary drop samplers and trap studies for lobsters and crabs, population surveys, and capture and release studies to quantify nocturnal invertebrates and assess mobile organisms in deeper or turbid environments where scuba diving is impractical (Negrete-Soto et al. 2002)

Fish

Fish monitoring methods include both fisheries monitoring (e.g., catch, effort, catch per unit effort, biological characteristics of key fisheries species) and biological monitoring of fish assemblages and/or target species. Biological monitoring approaches are discussed briefly below. The four most commonly used visual census techniques to quantify coral reef fish assemblages are broad-scale towed diver (manta tow) surveys, plotless methods (roving diver techniques), belt transects (Brock 1954), and stationary plots. In addition to visual censuses, sampling may be carried out using portable and stationary drop samplers, traps, block nets, trawls, and fish poisons (e.g., rotone or quinaldine). The most appropriate method depends on a number of factors including:

- Size of the survey area and desired scale of surveys
- Structural complexity of the survey area
- Species of interest (all species or target species such as food fishes, aquarium fishes, indicator species, or herbivores) and their behavior, and
- Life stage of interest (recruits, juveniles, adults, spawning aggregations)

Manta tow - Towed diver surveys involve towing one or two divers or snorkelers behind a boat at a constant speed. The diver maneuvers a towboard that can be outfitted with video and still cameras, slates, and other survey equipment. Compared to traditional dive surveys, which have limited spatial coverage, towed diver surveys provide rapid estimates of large areas and observers are able to differentiate fish assemblages within multiple habitats (e.g., patch reefs, rubble zones, algal flats, seagrass beds) in a single tow. This method allows for the detection of rare pelagic fishes that are infrequently encountered during traditional surveys, and is most effective at estimating abundance and density of large, mobile predators. It is not appropriate for estimating size or for use with cryptic species or small (<20 cm), bottom-dwelling animals.

Belt transect surveys - Belt transect surveys can be used to census the abundance and size of a defined list of reef fishes within specific habitats or zones. The approach involves deploying a transect of a predetermined length and then counting and recording the number of individuals (and other parameters as desired, such as size) within a fixed distance (e.g., a window of fixed width and height above the substrate) of the transect path. Divers may deploy the line prior to the assessment. However, it is preferable to release the line as you slowly swim in a straight line, as this minimizes disturbance to the fish prior to being counted. One example of a belt transect approach is the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol, for which divers extend a 30 m transect along depth gradients and census economically and ecologically fishes within a 2 m window (AGGRA 1998).

There are a number of factors that should be considered when conducting belt transect surveys:

- The precision and accuracy of transect surveys are affected by the length of the transect and size of area surveyed
- The width of the belt should be suitable to the type and behavior of fish that will be examined and the number of species to be counted
- It may be necessary to examine the reef within a 1 m belt for small, cryptic species and recruits, while 2-5 m belts can be used for larger, more mobile species
- Visibility also affects the width of belt
- Transects should cover a significant portion of the sampled habitat in order for the results to be representative of the fauna in the transect area, and
- A stratified design will provide greater information in sampling areas that have a high microhabitat diversity and high species diversity
- The optimal transect area is determined by the diversity and abundance of fishes; most researchers use 30-50 m long transects

Solitary species that are wary of a diver's presence may stay away from the transect line, while other species may be attracted to divers. Some of this can be avoided by laying the transect line behind the diver. Species present in relatively low numbers are less likely to be sampled by the transect method. To avoid bias, it is important to exclude species seen outside the transect area from the results. One of the major limitations of transect surveys is the absence or presence in large numbers of roving fishes that form large schools.

Roving Diver Technique (RDT) -The RDT assesses species presence, frequency of occurrence, and abundance of all fish species within a particular site or zone (Bohnsack 1995). Divers swim a compass direction, a depth contour, along some identifiable habitat feature, or in an area of a known size and record the number (and size) of each species observed during a predetermined period. The main advantage of the method is that it does not require the observer to deploy a transect line. This allows a diver to census a greater area, increasing the likelihood of observing inconspicuous fishes. The method does not provide a precise estimate of density per unit area, but rather the species observed per unit time.

Underwater visual surveys - The stationary underwater visual census method involves counting all target fishes within an imaginary cylinder of fixed diameter extending from the reef to the water's surface (Bohnsack and Bannerot 1986). The diver stands at the center point of the cylinder and makes several slow 360º turns, counting and identifying each observed species (and estimating their length) within a specific time. Using the size data, biomass estimates can be obtained using published mass-length relationships (Bohnsack and Harper 1988). This method works best for patch reefs and total fish counts, and avoids problems associated with moving divers and transect tapes.

Capture techniques - Under turbid conditions and when assessing juveniles, nocturnal, or cryptic species, block sampling, drop sampling, and trap sampling may be preferred over traditional visual census techniques. The fish poisons rotenone and quinaldine has been used to evaluate total fish composition within a defined area (e.g., small patch reefs) and may be particularly useful to evaluate early settlement juveniles in turbid locations. Poisons are not appropriate for large areas, deep habitats, or high flow environments and their use should be limited to avoid injuring other reef organisms. Traps may be an effective approach to characterize larval settlement patterns, and also are useful for assessing species composition within deeper areas. Traps may target certain species over others (depending on the bait and trap design) and it is difficult to quantify the area fished by a trap. Bottom trawls are most effective in shallow, soft-bottom habitats such as seagrass beds and algal flats, and can be used to quantify the diversity, abundance, life stage, and size of species within a certain area. Nets that are set in one location and allowed to stand for an extended period (e.g., overnight) can be used to survey movement patterns of species between habitats and in areas with high tidal flow or currents.

PHYSICAL

Protects Shorelines

Coral reefs form a physical barrier that protects coastal areas from the full force of waves, currents, and storms, thereby preventing erosion, property damage, and loss of life. Reefs also protect highly productive coastal wetlands such as mangroves and seagrass beds, as well as ports and harbors. In some cases, associated ecosystems are interdependent; mangroves may both protect coral reefs from silt and be protected by the coral reefs from strong wave action, thus protecting nurseries of commercially important reef fishes and invertebrates. During typhoons and hurricanes, damage from wave action to coastal communities is generally much less where there are reefs. In Guam, for example, losses to coastal communities during typhoons have been much less in areas protected by extensive reef flats, while villages located off narrow fringing reefs have suffered much greater damage (Birkeland 1997 a and b). Unlike human-constructed breakwaters which require considerable investment of resources to build and maintain, coral reefs are natural, self-repairing breakwaters. As coral reefs buffer the wave's energy, lagoons and other sedimentary environments that are suitable for mangroves and seagrasses develop over time (Ogden 1988).

CHEMICAL

Supports Nutrient and Carbon Cycling

Coral reefs are generally found in waters with lower dissolved nutrient concentrations than those of temperate coastal ecosystems. Despite this, coral reefs sustain a high gross primary productivity and biotic growth due to:

1) Tight nutrient cycling among individual organisms, and
2) Localized diurnal and seasonal nutrient inputs as water masses pass across reef communities

Dissolved nutrients on coral reefs can originate from a range of sources including *in situ* fixation by bacteria and cyanobacteria, fluxes out of reef matrices, terrestrial runoff, groundwater discharge and outflow of coastal water, onshore transport of oceanic water masses, and localized upwelling of nutrient-rich subsurface waters (D'Elia and Wiebe 1990). Nutrients are lost from reefs as salts, and as organic detritus which are fed upon by plankton, and larger pelagics (e.g., jacks) in coral reef areas. Nitrogen and other nutrients may also be advected out of coral reefs in dissolved or particulate form.

Inorganic and organic nutrients of oceanic waters are assimilated by phytoplankton and bacteria, and enter the reef food web through the activity of filter feeders, with a secondary mechanism of uptake involving direct assimilation of dissolved organic matter by corals and other benthic filter-feeding invertebrates (Sorokin 1993). Inorganic nutrients in the water column are also utilized by benthic algal communities, while seagrasses obtain nutrients primarily from the sediment through their roots. Nutrients contained in the biomass of zooplankton enter the nutrient pool of reef ecosystems through their consumption by planktonic and benthic predators. Fish and larvae of benthic invertebrates excrete feces containing the bulk of nutrients consumed, which are then mineralized by animals that feed on feces.

Nitrogen fixation is a key feature of the nitrogen cycle of most coral reefs. The assimilation of atmospheric nitrogen by nitrogen-fixing microbes and cyanobacteria occurs in sediments and reef substrates, epiphytes on macroalgae, endolithic organisms in coral skeletons, and cyanobacteria within sponges and corals (D'Elia and Wiebe 1990; Lesser et al. 2004). The fixed nitrogen is transferred to the rest of the trophic system through excretion of ammonium by nitrogen fixers, decomposition of nitrogen fixers, and grazing on nitrogen fixers by herbivores (Szmant-Froelich 1983). While microorganisms are responsible for many of the processes of nitrogen cycling, large organisms conserve and translocate significant quantities of fixed nitrogen and phosphorus, with much of the recycling and nutrient regeneration occurring within the sediments (Smith et al. 1981).

The symbiotic dinoflagellates of reef-building corals play an enormous role in the overall production of the reef, using sunlight, carbon dioxide (CO_2), water, and nutrients to produce sugars and cellular material and supply the coral with energy-rich products of photosynthesis, providing up to 95% of corals' carbon requirements, as well as essential compounds such as amino acids, complex carbohydrates, and small peptides (Hoegh-Guldberg 1989; Muscatine 1990). In addition to providing a protected microhabitat for zooxanthellae, the coral host supplies essential compounds such as ammonia and phosphate derived from the food caught by the coral (Trench 1979). Corals are able to consume inorganic nutrients (e.g., ammonia and inorganic phosphate); phosphate is accumulated in the zooxanthellae, where it is incorporated into adenosine triphosphate (ATP) and nucleotides, and translocated to the animal's cells. The phosphorous is mineralized by the coral, and again consumed by the zooxanthellae, drastically decreasing loss to the surrounding waters. A portion of the primary productivity is, however, indirectly cycled throughout the reef community via coral predators, coral mucus, and coral detritus. For instance, corals exude up to half of the carbon assimilated by their zooxanthellae as mucus. The released coral mucus efficiently traps organic matter from the water column and rapidly carries energy and nutrients to other reef zones, and may be deposited in associated sediments where it is consumed by the heterotrophic reef community (Sorokin 1993).

Understanding the complex interactions between biogeochemical and physical processes within reef ecosystems is important for determining the contribution of coral reefs to the global carbon cycle and the air-sea flux of CO_2. Coral reefs contribute to the ocean carbon cycle through the processes of photosynthesis, respiration, calcium carbonate ($CaCO_3$) production, and dissolution. One of the most significant benefits that reef-building corals derive from zooxanthellae is the enhancement of the calcification process, which is essential to coral skeletal growth (Muscatine et al. 1984). Photosynthesis by zooxanthellae increases $CaCO_3$ production by providing the energy needed by the host for the uptake of calcium from seawater and the transport to sites of calcification, and by creating an internal environment favoring calcification through the uptake of respiratory CO_2 (Porter 1976). The fate of CO_2 in coral reefs is dependent on many factors, including the ratio of organic carbon production to $CaCO_3$ production, irradiance levels, and the dominant type of calcifying organism (Buddemier 1996; Gattuso et al. 2000). Recent evidence suggests that reefs dominated by hard corals are sources of CO_2 to the atmosphere, whereas reefs dominated by macroalgae are oceanic sinks of CO_2. The precipitation of $CaCO_3$ by corals results in the release of CO_2 from seawater to the atmosphere, and respiration and calcification may increase acidification of water, which favors release of

CO_2 back into the water column (Ware et al. 1992).

Calcification, photosynthesis, and respiration are the three major metabolic processes dominating the community metabolism of coral reefs. By following changes in dissolved oxygen and total alkalinity of reef water, it is possible to evaluate these processes at a community level. Gross production is the rate of photosynthetic carbon and nutrient fixation into organic matter, resulting in oxygen evolution. Community respiration is the rate of aerobic decomposition of organic matter, which supplies energy to reef heterotrophs, causing inorganic carbon to increase and oxygen to decrease. Calcification is a measure of the rate of $CaCO_3$ deposition, which is higher in the day than at night for most organisms. Net fluxes of nutrients within reef environments have been estimated using a flowing water respirometry method and measurements of chemical changes (oxygen and pH) in the water as it flows over the reef; this involves taking samples of water flowing across reefs and estimating the elemental exchange between the reef and the water. Factors that affect nutrient fluxes and must be considered when using this method include the depth and velocity of the water, length of the transect, and oxygen concentration in the samples. Flow respirometry and other approaches used to estimate net fluxes of nutrients are described in more detail in D'Elia (1988). Investigations of the processes controlling seawater CO_2 and the air-sea exchange of CO_2 in coral reef ecosystems have generally been based on measurements of pH, total alkalinity (TA), and dissolved oxygen (Smith 1973; Suzuki et al. 1995; Kraines et al. 1997; Chisholm and Barnes 1999).

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS OF CORAL REEFS

The following matrices present parameters for restoration monitoring of the structural and functional characteristics of coral reefs. These matrices are not exhaustive, but represent those elements most commonly monitored. These parameters have been recommended by experts in coral reef restoration and are described in detail in the literature on coral reef restoration and ecological monitoring. The closed circle (●) denotes a parameter that should be considered in monitoring restoration performance. Parameters with an open circle (❍) are of secondary importance, depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Coral Reefs

Parameters to Monitor	Biological		Physical		Hydrological			Chemical	
		Habitat created by animals		Topography/Bathymetry		Currents/Wave energy	Water sources		Nutrient s
Geographical									
Acreage of habitat types		●							
Biological									
Plants									
Species, composition, and % cover of:									
Algae									❍
Epiphytes									●
Animals									
Vertical relief		●		●					
Hydrological									
Physical									
Shear force at sediment surface							❍		
Temperature						●			
Upstream land use						❍			
Chemical									
Nitrogen and phosphorus (N and P)									❍
Toxics						❍			
Soil/Sediment									
Physical									
Basin elevations				❍					
Geomorphology (slope, basin cross section)				●					
Sedimentation rate and quality				●					●

Parameters to Monitor the Functional Characteristics of Coral Reefs

Parameters to Monitor	Functional Characteristics: Biological — Exhibits symbiotic species interactions	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical — Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Chemical — Supports nutrient cycling
Geographical														
Acreage of habitat types	●	●	●	●	●	●	●	●	●			●	●	●
Biological														
Plants														
Species, composition, and % cover of:														
Algae	❍	❍	❍	❍	❍	❍	❍	❍	❍			❍	❍	❍
Epiphytes	●		●				●	●	●					●
Interspersion of habitat types		❍	❍	❍	❍		❍	❍	❍			❍	❍	❍
Nutrient levels in algal tissues (N and P)														❍
Biological														
Animals														
Species, composition, and abundance of:														
Fish		❍	❍	❍	❍		❍	❍	❍					
Invasive species			●	●	●			●	●					
Invertebrates		❍	❍	❍	❍		❍	❍	❍					
Coral growth rate	❍	❍	❍	❍	❍	❍	❍	❍	❍					
Coral recruitment and survivorship	❍	❍	❍	❍	❍	❍	❍							

Parameters to Monitor the Functional Characteristics of Coral Reefs (cont.)

Parameters to Monitor	Biological: Exhibits symbiotic species interactions	Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Chemical: Supports nutrient and carbon cycling
Grazer density				❍	❍									
Vertical relief of reef		●	●	●	●	●	●					●	●	
Trash			❍											
Upstream land use										❍	❍			
Water column current velocity												❍		
Chemical														
Toxics		❍	❍	❍										
Soil/Sediment														
Physical														
Basin elevations		❍	❍	❍	❍	❍			❍					
Geomorphology (slope, basin cross section)		●	●	●	●	●			●			●		
Sediment grain size (OM[12]/sand/silt/clay/gravel/cobble)						❍		❍				❍	❍	❍
Sedimentation rate and quality									❍			❍		

[12] Organic matter

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APPENDIX I: CORAL REEFS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

Arceo, H. O., M. C. Quibilan, P. M. Alino, G. Lim and W.Y. Licuanan. 2001. Coral bleaching in Philippine reefs: Coincident evidences with mesoscale thermal anomalies. Marine Science Institute, University of the Philippines, Diliman, Quezon City 1101 Philippines. *Bulletin of Marine Science* 69: 579-593.

Author Abstract. Massive bleaching was observed in various reefs throughout the Philippines (5-21^{o} N, 116-128^{o} E), beginning early June until late November 1998. Satellite-derived SST data from NOAA/NESDIS was used to examine thermal anomalies ('hotspots') observed in the country during this same period. Anecdotal reports from the Coral Reef Information Network of the Philippines partners revealed the extent of bleaching in other parts of the country. The observations coincided with the occurrence of a hotspot over the region. Coral community studies detected significant decrease in live coral cover (up to 46%) and increase in dead coral cover (up to 49%). The results support the hypothesis that elevated sea temperatures was the major cause of the bleaching event. Some patterns of susceptibility within and across reefs, possibly due to influences of factors such as wave energy, tidal fluctuations and reef morphology, were also observed. The extent and scale of the 1998 bleaching events in the Philippines could not be fully attributed to small-scale anthropogenic disturbances directly affecting reefs since severe bleaching was also observed in offshore reefs. Its coincidence with the El Nino-related temperature anomalies suggests that the interaction between human-induced and natural factors behind bleaching remains to be investigated further. This interaction is critical for reef recovery, and the discrimination between both impacts can be useful for policy and decision-making processes in management.

Bohnsack, J. A. 1995. Two visually based methods for monitoring coral reef fishes. In Crosby, M. P., G. R. Gibson and K.W. Potts (eds.), A Coral Reef Symposium on Practical, Reliable, Low-cost Monitoring Methods for Assessing the Biota and Habitat Conditions of Coral Reefs. Miami Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service, Miami, FL. EPA 904/R-95/016. Annapolis, Maryland. http://www.epa.gov/owow/oceans/coral/symposium/bohnsack.html

Author Abstract. Two visual methods are described to monitor coral reef fishes. The Roving Diver Technique (RDT) developed by the Reef Environmental Education Foundation

(REEF) uses volunteers to collect reef fish species presence, frequency of occurrence, and abundance data. The more quantitative Stationary Sampling Technique (SST) requires more highly trained divers to collect quantitative data on sizes, frequency of occurrence, and abundance for all visually observable species. From these data in index of biomass and importance value can be calculated. Both methods can be used to answer a wide variety of monitoring and scientific questions although each has advantages and disadvantages. Additional information methods used for monitoring reef fishes are described in this document.

Caribbean Coastal Marine Productivity Program (CARICOMP). 1997. CARICOMP Monitoring of Caribbean Coral Reefs. Proceedings of the 8th International Coral Reef Symposium 1: 651-656, Panama. Contact information: CARICOMP Data Management Center, Center for Marine Sciences, University of the West Indies, Mona, Kingston, Jamaica. Phone # (876) 927-1609 and Fax # (876) 977-1033. http://www.ccdc.org.jm/abstracts.html

CARICOMP Abstract. Permanent chain transects since 1993 at 15 sites around the Caribbean, using the CARICOMP Level One protocol, at 10 ± 3m depth, to assess benthic community composition and, later, productivity. Each of the sites differed in geographical situation and recent history. Though their locations were away from obvious point sources of pollution, some were known to have changed significantly previously to initiation of the survey. In 1995, studies showed that the main species present were algae (13-59% total cover, 16-74% live cover) and hard corals (6-42% total cover, 9-63% live cover). Minor components were soft corals (0.2-26% total cover, 0.5-50% live cover) and sponges (0-10% total cover, 0-16% live cover). *Diadema antillarum* was present at four sites located in the Bahamas, Barbados, Belize, Puerto Rico but were absent from the others. In 1993-94, researchers indicated that there were no major changes in coral cover based on observations, except in Jamaica (17.7% to 9.5%). Within the limitations of the method, the data will serve as a baseline reference for monitoring further change in benthic community composition.

Carriquiry, J. D., A. L. Cupul-Magana, F. Rodriguez-Zaragoza and P. Medina-Rosas. 2001. Coral bleaching and mortality in the Mexican Pacific during the 1997-98 El Niño and prediction from a remote sensing approach. *Bulletin of Marine Science* 69:237-249.

Author Abstract. A coral reef monitoring program was initiated at Bahia Banderas (21° N, 105° W), on the Pacific coast of Mexico, on January 1997, several months before the onset of the El Nino-Southern Oscillation (ENSO) event of 1997-98. Live coral cover, sea surface temperature (SST) and salinity were monitored during 1997-98, in conjunction with 'hot spot' satellite bleaching predictions of NOAA's NESDIS. Coral reef bleaching during the 1997-98 El Nino at Bahia Banderas coincided closely with satellite bleaching predictions and with experimental observations on coral tolerance to thermal stress. The initial bleaching event rapidly evolved into an unprecedented massive coral mortality (96%), equivalent to the catastrophic coral mortalities observed in the Galapagos Islands during the 1982-83 ENSO. The sudden mass bleaching and mortality of corals at Bahia Banderas was most likely caused by the marked accelerated warming rate (+3.5 degree C mo^{-1}), an order of magnitude higher than that observed during the 1982-83 El Nino in the Galapagos Islands (+0.35 degree C mo^{-1}). Also, the SST anomaly observed during the 1997-98 ENSO at Bahia Banderas (+6.1° C) was 30% higher than in 1982-83 in the Galapagos area (+4.5°C). The recovery of the Bahia Banderas coral reefs is uncertain since the dead coral substrate has already been covered with filamentous fleshy algae. In contrast to the long-lasting existence of corals and coral reefs in the region, reef frameworks are typically very thin. This situation may indicate the frequent recurrence of mortality events due to environmental extremes, such as ENSO, that have limited reef development in the northeastern tropical Pacific Ocean.

Chiappone, M., K.Sullivan-Sealey, G. Bustamante and J. Tschirky. 2001. A rapid assessment of coral reef community structure and diversity patterns at naval station Guantanamo Bay, Cuba. *Bulletin of Marine Science* 69:373-394.

Author Abstract. Ten shallow (<20 m) reefs at Naval Station Guantanamo Bay, southeastern Cuba, were surveyed during July-August 1996 to evaluate topographic complexity and community structure with respect to depth-related zonation and potential sedimentation impacts from the Guantanamo River. While the methods employed were not novel, coral reefs in the study area had not been previously studied and, because of low human population density, may provide useful comparisons to more disturbed reefs in the Caribbean. On leeward and windward sides of the Bay, four shallow (5 m) and four deeper (10 m) spur-and-groove reefs were surveyed, along with two reefs within the mouth of the Bay. On each reef, four 25-m transects were oriented perpendicular to shore on four haphazardly selected spurs and used to randomly select 1 m x 1 m quadrat locations. Benthic coverage using point-intercept counts and topographic complexity using the chain-length method were quantified within quadrats. All sampled reefs were dominated by algae, especially algal turfs, and stony corals. Mean percent algal cover among reefs ranged from 50 to 78%, while coral cover ranged from 11 to 49%. Analysis of variance showed that depth was more important than location in explaining the variability in mean coral cover. Cluster analysis using percent coverage of all bottom types and relative coral cover confirmed that reefs at the same depth were more similar in benthic composition. Several species considered to be less tolerant of sedimentation, however, were more abundant on windward reefs, suggesting that differences in sedimentation between windward and leeward areas may affect relative species abundance, but not total coral cover. Percent coral cover estimates from 9 of the surveyed reefs were well above recent values reported for other wider Caribbean reefs. The predominance of corals on these reefs is surprising, given the low abundance of herbivores (due to mass mortality and overfishing) and possible disease outbreaks affecting acroporid corals. These disturbances appear to have had less severe consequences than for other wider Caribbean reefs such as those in Jamaica and the Lesser Antilles, potentially due to the relative rarity of destructive storm events.

Cochran. S. 2000. Biologic Monitoring Sites Enhance Hawaii Coral Reef Studies. United States Department of Interior, United States Geographical Survey (USGS), Fieldwork Studies. Contact information: scochran@usgs.gov, Phone # (831) 459-3431. http://soundwaves.usgs.gov/2000/04/fieldwork.html

The USGS and scientists from the Hawaii Institute of Marine Biology, at the University of Hawaii, Manoa have collaborated to map coral reefs along the south shore of Moloka'i and to detect changes in reef health due to various environmental and anthropogenic factors. The coral reef mapping project includes the protocol established by the University's Coral Reef Assessment and Monitoring Program (CRAMP) which detects changes in coral cover over time with statistical confidence (P>0.8). The data obtained through this program are placed into a Hawaii-wide database for use by managers and reef scientists. Methods used for mapping reefs include permanent transects and photoquadrats located at 3-m and 10-m depths along the outer forereef and at a depth of 1 m in the inner reef flat. Algae, fish, coral, and other invertebrates were quantified at selected study sites. Re-sampling was performed at the sites over time. Digital video footage was collected along transects for percent coral cover analysis using twenty randomly selected video frames per transect with fifty randomly selected points per frame. Images taken from fixed photoquadrants allowed researchers to examine a single colony's recruitment, growth, and mortality trends. Ground-truthing of aerial photographs and LIDAR (Light Detection And Ranging) images were sampled using Digital video and photo recordings. Study sites were re-sampled once a year. Additional information on techniques used can be obtained from the source listed above.

English. S., C. Wilkinson and V. Baker. 1997. Survey Manual for Tropical Marine Resources, 2nd edition. Published by Australian Institute of Marine Science Townsville ISBN 333.952072013 or Protocols for Coral Reef Monitoring.

This publication discusses techniques used for coral reef monitoring. The first method described is broad scale monitoring such as Manta tow or time swim. This method allows researchers to observe a broad photo of the reef; observe changes in the physical structure of the reef (e.g., structural damage and diseases); and ensure that monitoring sites are descriptive of the whole reef. Researcher's record percent cover of live and dead corals, soft coral, and regional specific parameters (e.g., crown-of-thorns starfish, giant clams, and large patches of damage to corals). The tow method is used to select transect monitoring sites. Line intercept or other transect methods are used to assess coral health. Parameters are recorded as lifeforms or as species. Several lifeforms or species can be grouped into larger groups (e.g. branching and digitate *Acropora* and branching non-*Acropora* can be merged into branching coral). Transects are placed where coral density is highest and then used for fish census counts. Researchers advised that transects be marked from beginning to end with steel stakes. Live fish visual censusing can also be used and are based on line transects, but with the use of 3 X 50 m transects, allowing fish to be assessed in a column 5 m wide and 5 m high above the line. This method is designed particularly for counting fish, especially those targeted by fishers. The fish and lifeform transects can be performed on the same transect lines. Fish surveys must also be completed before benthos assessment, to circumvent fish deterrence. See publication for additional information on methods that can be used for coral reef monitoring.

Epstein, N., R. P. M. Bak and B. Rinkevich. Applying forest restoration principles to coral reef rehabilitation. 2003. Israel Oceanographic and Limnological Research, National Institute of Oceanography, Tel Shikmona, Israel. *Aquatic Conservation* 13:387-396.

Author Abstract. Forest restoration through silviculture (gardening) programs revives productivity, biodiversity, and stability. As in silviculture approaches, the coral 'gardening' strategy is based on a two-step protocol. The first step deals with the establishment of *in situ* and/or *ex situ* coral nurseries in which corals are farmed (originating from two types of source material: asexual [ramets, nubbins], and sexual [planula larvae, spat] recruits). The second is the reef rehabilitation step, where maricultured colonies are transplanted into degraded sites. We compare here the rationale of forest restoration to coral reef ecosystem restoration by evaluating major key criteria. As in silviculture programs, a sustainable mariculture operation that focuses on the prime structural component of the reef ('gardening' with corals) may promote the persistence of threatened coral populations, as well as that of other reef taxa, thus maintaining genetic diversity. In chronically degrading reef sites this may facilitate a halt in biodiversity depletion. Within the current theoretical framework of ecosystem restoration, the recovery of biodiversity indices is considered a core element since a rich species diversity provides higher ecosystem resilience to disturbances. The gardening measure may also be implemented worldwide, eliminating the need to extract existing colonies for transplantation operations. At degraded reef sites, the coral gardening strategy can assist in managing human and non-human stakeholders' requirements as is done in forest management.

Epstein, N., R. P. Bak and B. Rinkevich. 2001. Strategies for gardening denuded coral reef areas: The applicability of using different types of coral material for reef restoration. *Restoration Ecology* 9:432-442.

Author Abstract. Recreational and other human activities degrade coral reefs worldwide to a point where efficient restoration techniques are needed. Researchers tested several strategies for gardening denuded reefs. The gardening concept included *in situ* or *ex situ* mariculture of coral recruits, followed by transplantation into degraded reef sites. In situ nurseries were established in Eilat's (Northern Red Sea) shallow waters, sheltering three types of coral materials taken from the branching species *Stylophora pistillata* (small colonies, branch fragments, and spat) and monitored for two years. See publication for additional information on method used. Researchers stated that pruning more than 10% of donor colonies' branches increased mortality, and surviving colonies displayed reduced reproductive activity. However maricultured isolated branches surpassed donor colony life span and reproductive activity and added 0.5-45% skeletal mass per year. Results showed that forty-four percent of the small colonies survived after 1.5-year mariculture, revealing average yearly growth of 75 ± 32%. Three months ex situ maintenance of coral spat (sexual recruits) prior to the in situ nursery phase increased survivorship. Within the next 1.5 years, their colonies developed 3-4 cm diameter. Nursery periods of 2 years, 4-5 years, and more than> 5 years have been estimated for small colonies, spat, and isolated branches, respectively. Researchers suggest that reef gardening may be used as a key management tool in conservation and restoration of denuded reef areas.

Gleason. D. F., D. A. Brazeau and D. Munfus. 2001. Can self-fertilizing coral species be used to enhance restoration of Caribbean reefs? *Bulletin of Marine Science* 69:933-943.

Author Abstract. Reef restoration programs involving transplantation should be most successful when using coral species exhibiting high reproductive potential, local recruitment, and the ability to tolerate stresses induced by transplantation. One mode of enhancing reproduction, especially when population densities are low, is through self-fertilization. To determine if the high reproductive output observed in many hermaphroditic brooders is the product of self fertilization, randomly amplified polymorphic DNA was used to quantify selfing rates in three brooding, hermaphroditic Caribbean corals, *Favia fragum*, *Porites astreoides*, and *Agaricia agaricites.* See publication for additional information on methods used. Self-fertilization rates in the field were high (49% for *F. fragum*, 34% for *P. astreoides* and 38% for *A. agaricites*). Given these high selfing rates, we tested the resiliency of hermaphroditic brooders by transplanting intact and divided colonies of *P. astreoides* within and between 9 and 24 m depth. Survivorship was high in all transplant groups after 21 mo. Growth rates and larval production of transplanted colonies fell below those of colonies remaining at their depth of origin only at 24 m depth. Even so, colonies transplanted from 9 to 24 m depth appeared healthy throughout the experiment. These results suggest that hermaphroditic brooders meet at least two of the criteria needed for successful coral transplantation programs.

Hendee, J. C., E. Mueller, C. Humphrey and T. Moore. 2001. A data-driven expert system for producing coral bleaching alerts at Sombrero Reef in the Florida Keys, USA, pp. 139-147. In Pepper, D. W., C. A. Brebbia and P. Zannetti (eds.), Proceedings of the 7th International Conference on Development and Application of Computer Techniques to Environmental Studies. Computational Mechanics, Publications/WIT Press, Southampton.

Author Abstract. A computer expert system shell was employed to provide interpretations of near real-time acquired combinations of meteorological and oceanographic parameters from a SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape) station at Sombrero Reef. When environmental conditions were conducive to coral bleaching, according to different models, 'alerts' were automatically posted to the World-Wide Web and emailed to researchers so they could verify and study bleaching events as they might happen. The models were refined using feedback from field data on bleaching recorded after alerts from the expert system. The expert system was programmed to produce alerts when sea temperatures over 30˚C occurred, or when temperatures of 30˚C occurred concomitant with low winds. Alerts were produced in June 1998 when these conditions were met, but bleaching did not occur. Reconfiguration of the system, which included a point system for three models (high sea temperature only, high sea temperature plus low winds, high sea temperature plus low winds plus low tide), resulted in the transmittal of alerts which coincided with bleaching during early August, 1998. Bleaching occurred after sea temperature reached an average of 31.5˚C over a period of 3 d, with excursions over 31.8˚C occurring over fifteen times during those 3 d. High sea temperatures, low wind speeds and a very low tide occurred coincident to the time of bleaching, but it was not possible to tell if these were factors acting synergistically.

Jan, R-Q., J-P. Chen, C-Y. Lin and K-T. Shao. 2001. Long-term monitoring of the coral reef fish communities around a nuclear power plant. *Aquatic Ecology* 35:233-243.

Author Abstract. Over the past 21 years (1979-1999) we have observed temporal changes in the fish communities on a coral reef around a nuclear power plant in southern Taiwan. Data used for analyses were collected bimonthly by scuba-diving ichthyologists at four sub-tidal stations (Stations A, B, D, E). The commercial operation of the nuclear power plant was launched in the summer of 1984. During the study period the number of fish species varies, with the coefficient of variation (CV) ranging from 19.0% (Station A) to 25.2% (Station D). Nevertheless, the sequential data on number of species follow a random trend in terms of runs up and down at all four stations. This characteristic persists both before and after the initiation of power plant operation. Dendrograms drawn using UPGMA (unweighted pair-group method using arithmetic averages) on the dissimilarity coefficients between yearly fish occurrences show that the years 1980-1984 are more closely grouped than any other years. This phenomenon prevails at all stations, indicating that wide-scale change occurred between 1984 and 1985. After the power plant began operation, changes in water temperature were minute at these sub-tidal stations. Impacts from other sources such as chlorine release and fish impingement seem remote. We believe temporal variations in the studied fish communities can be better explained as arising from natural fluctuations of environmental factors as well as physical disturbance caused by typhoons. The latter factor is also thought to account for the major faunal change between 1984 and 1985.

Jordan, I. E. and M. J. Samways. 2001. Recent changes in coral assemblages of a South African coral reef, with recommendations for long-term monitoring. *Biodiversity and Conservation* 10:1027-1037.

Author Abstract. Two-mile reef, Sodwana, South Africa is an unusual coral reef, being situated on a submerged fossilized sand dune and being very southerly (27º 54'). It is a popular Scuba diving venue receiving about 100,000 dives year^{-1}. The line-intercept transect method, as recommended by the Global Coral Reef Monitoring Network (GCRMN), was used to determine soft coral, hard cora,l and other benthos percentage cover. Physical coral damage, disease, and bleaching were also recorded. Results were compared with those of B. Riegl (1993 - unpublished Ph.D. thesis) 5 to 7 years earlier. The reef appears to be ecologically and highly dynamic. In the interim, there has been an increase in living benthos cover of 22.3% but also an increase in coral bleaching from 0% in 1993 to 1% in 1998. Physical damage, despite the large number of dives on the reef, was minimal (1.52%), although it appears as if coral diseases may be increasing. The 20-m transects recommended by GCRMN are too long for this highly rugose reef with its distinct ridges and gullies. It is recommended that benthos cover, coral damage, bleaching and disease should be monitored annually using 40 5-m transects on the reef ridges and 40 5-m transects on the reef slopes

LeGore, S., D. S. Marszalek, L. J. Danek, M. S. Tomlinson, J. E. Hofmann and J. E. Cuddeback. 1989. Effect of chemically dispersed oil on Arabian Gulf corals: A field experiment, pp. 375-381. In Proceedings of the 1989 International Oil Spill Conference, API Publication Number 4479, American Petroleum Institute, Washington DC.

A large-scale experiment was conducted on Jurayd Island, off the coast of Saudia Arabia on coral responses to oil spills by setting realistic conditions. The corals were exposed to crude oil only at 24 hours and 120 hours. Coral reefs consisting primarily of *Acropora* with distributed colonies of *Porites sp., Platygyra* sp. and *Goniopora sp.* were studied. Plots were measured 2 X 2 m and situated over about a depth of 1-m at low tide and anchored in place. Oil was then added to the test plots using 14 liters within the 24-hour oil only treatment and, 5.63 liters within the 120-hour experiment. Hydrocarbons in the water concentration were measured using infrared. In oil only plots, visual inspections were done to assess corals that were exposed at the end of the 24-hour and 120-hour periods. Monitoring was conducted for one year with no changes occurring relative to the un-oiled plots. See publication for additional information on techniques used for monitoring. While the dispersed oil appeared to slow down coral reef recovery from seasonal bleaching, researchers did not observe this occurring in the oil-only plots. No correlation to treatment in the 24-hour exposure for the growth rates was observed. Authors concluded that healthy reef corals can tolerate short oil exposures without any noticeable effect but corals susceptibility to exposures may vary during winter season.

Lirman, D. and M. W. Miller. 2003. Modeling and monitoring tools to assess recovery status and convergence rates between restored and undisturbed coral reef habitats. *Restoration Ecology* 11:448-456.

Author Abstract. Boating activities are an increasing source of physical damage to coral reefs worldwide. The damage caused by ship groundings can be significant and may result in a shift in reef structure and function. In this study we evaluate the status of two restoration projects established in 1995, six years after two freighters, the M/V Maitland and the M/V Elpis, ran aground on reefs of the Florida Keys National Marine Sanctuary. Our approach includes field monitoring in support of simulation model development to assess the effectiveness of the restoration efforts. A population model was developed for the coral *Porites astreoides* to project the convergence rates of coral abundance and population size structure between the restored and surrounding reference habitats. Coral communities are developing rapidly on the restoration structures. Species richness and abundance of the dominant coral, *P. astreoides*, were nearly indistinguishable between the restoration structures and reference habitats after only 6 years. However, although abundance and size structure of *P. astreoides* populations are rapidly approaching those of the reference habitats (a convergence in size structure within 10 years was simulated), maximum coral size will take twice as long to converge for this species. The sensitivity of the model to maximum recruitment rates highlights the importance of recruitment on the recovery rates of restored habitats, suggesting that special attention should be afforded to provide coral recruits with appropriate recruitment substrate at the time of restoration. Finally, the rates of convergence and, hence, the level of success of a restoration effort were shown to be influenced not only by the recruitment and survivorship rates of corals on the restoration structures but by the characteristics of the reference population as well. Accordingly, reference populations ought to be considered a "moving target" against which restoration success has to be measured dynamically. The simple, cost-effective, monitoring-modeling approach presented here can provide the necessary tools to assess the current status of a restoration effort and to project the time required for coral populations to resemble those found on undamaged reference habitats.

Motta, H., M-A. Rodrigues and M. H. Schleyer. 2001. Coral reef monitoring and management in Mozambique, pp. 43-48. In Souter, D., D. Obura and O. Linden, (eds.), Coral Reef Degradation in the Indian Ocean: Status Reports and Project Presentations 2000. CORDIO, Stockholm, Sweden.

A survey was conducted at the end of summer 1999 on coral bleaching in relation to ENSO on Mozambican coastline. Bleaching was observed on seventeen reefs. Visual assessments were made of reef type, faunal cover, and the extent of reef damage that may have resulted from bleaching and crown-of-thorns starfish (COTS). Based on the results, the effects of El Niño bleaching in Mozambique were most widespread on exposed reefs in the north and declined south except at Inhaca Island where detrimental bleaching was recently observed. Widespreade COTS damage was seen at Bazaruto and Inhambane. Monitoring was conducted between August and September. During the first year of monitoring, 9 "core" reefs were selected for annual survey. See publication for additional information on methods used. The reefs condition varied between healthy to severely impacted due to natural and anthropogenic stresses. However, the main factors responsible for reef deterioration were bleaching and the crown-of-thorns starfish infestation. On the reefs of northern Mozambique and in marine protected areas coral cover was greatest. Recovery was observed on few reefs with soft corals as the primary colonizers.

National Oceanic and Atmospheric Administration. 2002. A National Coral Reef Action Strategy, Report to Congress. NOAA Coral Reef Conservation Program, Office of Response and Restoration, National Ocean Services, Silver Spring, MD. Contact information: Phone # (301) 713-2989, roger.b.griffis@noaa.gov. http://coris.noaa.gov/activities/actionstrategy/01_exec_summ.pdf.

The National Coral Reef Action Strategy document was developed to comply with the requirements of the Coral Reef Conservation Act of 2000 (CRCA) and aid in tracking implementation of the National Action Plan to conserve coral reefs. Information provided in this document was obtained from government and non-government organizations, scientists, resource managers, stakeholders, and the public. The major goals of the National Coral Reef Action Strategy are to increase the understanding of coral reef structure and functions, identify threats to coral reef habitats, establish effective monitoring and assessment techniques used, conduct surveys that track changes in reef habitats, enhance the understanding of social and economic factors of conserving coral reefs, improve education and outreach, and reduce coastal pollution and physical impacts to the reef. To ensure that these goals are accomplished, NOAA and the U.S. Coral Reef Task Force encourage (1) working with partners and stakeholders, developing and implementing a long term program that will inventory, assess and monitor U.S. coral reef habitats; (2) developing a web-enabled data management and information system for U.S. reef monitoring and mapping data that will provide user-friendly GIS based mapping; and (3) developing and creating a biennial report on the status of U.S. coral reef habitats.

Nemeth, R. S. and J. S. Nowlis. 2001. Monitoring the effects of land development on the near-shore reef environment of St. Thomas, USVI. *Bulletin of Marine Science* 69:759-775.

Author Abstract. This study evaluated the impacts of shoreline development on the coral reef at Caret Bay, St. Thomas, USVI. Studies in rates of sedimentation, changes in water quality and changes in the abundance and diversity of corals and other reef organisms were conducted along five permanent transects from July 1997 and March 1999. Monitoring was conducted monthly. See publication for additional information on methods used. The results from monthly monitoring before, during and after construction indicated that sedimentation and total suspended solids increased during large rainfall events, and that sediment load onto Caret Bay reef was greatest directly below ravine outlets and in locations where the shoreline was sheltered. Sedimentation rates decreased relative to average monthly rainfall after buildings, landscaping and road paving were completed Based on visual assessment of coral condition researchers indicated that coral pigment loss was associated with both influx of terrigenous sediments and with natural seasonal phenomena. Bleaching of coral colonies showed a positive relationship with sedimentation ($r^2 = 0.92$). Reef sites exposed to sedimentation rates between 10 to 14 mg cm^{-2} d^{-1} showed a 38% increase in the number of coral colonies experiencing pigment loss than reef sites exposed to sedimentation rates between 4 to 8 mg cm^{-2} d^{-1}. Coral cover along the entire reef tract declined about 14% (range: -3.92% to -31.34%). This decline in coral cover from pre- to post-construction surveys showed weak negative associations with sedimentation ($r^2 = 0.52$) and bleaching ($r^2 = 0.48$). Patterns of abundance of macro algae, sponges and encrusting gorgonians were mainly to natural seasonal changes rather than to rates of sedimentation. Overall monthly monitoring was good at detecting and differentiating changes in the reef environment that were associated with human activity and natural causes.

Petersen, D. and R. Tollrian. 2001. Methods to enhance sexual recruitment for restoration of damaged reefs. *Bulletin of Marine Science* 69:989-1000.

Author Abstract. Natural recruitment of scleractinian corals is highly influenced by various environmental effects. Predation, sedimentation, algal growth and grazing may cause high mortality rates in larvae and settlers. In the past, methods have been developed to produce large quantities of planulae. Under laboratory conditions the survival of *ex situ* produced propagules can be optimized to obtain large amounts of sexual recruits. Sexual recruitment plays an important role in conservation management, especially for the preservation of genetic diversity in natural and *ex situ* populations. We carried out pilot studies which indicate the possibility to transport, settle and recruit scleractinian corals, here *Acropora florida* Dana 1846, in closed-system aquaria using artificial seawater. After further development, this method promises to be an economical and effective way to mariculture corals for restoration of damaged reefs. To fulfill this aim, collaboration with commercial coral farms and public aquaria should be envisaged. Coral farms that provide work for coastal populations can play an important role in mariculturing sexual settlers. Such farms could produce thousands of propagules for reef conservation and even more for the aquarium trade thus reducing natural collection of corals and providing financial support by resulting incomes. Public aquaria may help to optimize this method.

Riegl, Bernhard. 2001. Degradation of reef structure, coral and fish communities in the Red Sea by ship groundings and dynamite fisheries. *Bulletin of Marine Science* 69:595-611.

Reef degradation was investigated on 66 Egyptian Red Sea reefs--60 reefs for dynamite damage (using line transects) and six ship grounding sites (using 1 m sample squares). Ship groundings and dynamite fishing caused similar damage, reduction of the reef to rubble (65% of reefs were dynamited mostly leeward, 58%). Changes in coral (line transect study) and fish communities (point count study) in impacted sites were documented. On impacted reefs, coral cover decreased, bare substratum and rubble increased, and fish dominance shifted away from Pomacentridae. Oceanographic conditions result in a stable pattern of coral communities (windward Acropora, leeward Porites). Most dynamite damage was on leeward, near-climax Porites reef slopes or Porites carpets. Most ship groundings were on windward Acropora reefs with regeneration periods calculated to be between 100 and 160 yrs. Regeneration time of dynamite damage is expected to be similar because of similar damage. Rehabilitation could speed up recovery but has to be consistent with natural community patterns. Coral transplants should mimic previously existing community structure in order to avoid space preemption by introduced superior competitors. Particularly if Acropora were introduced on a large scale into normally Porites dominated reef areas, re-establishment of the original community within the desired time-frame could be delayed.

Riegl, B., J. L. Korrubel and C. Martin. 2001. Mapping and monitoring of coral communities and their spatial patterns using a surface-based video method from a vessel. *Bulletin of Marine Science* 69:869-880.

Author Abstract. Maps are useful tools for understanding spatial dynamics and the general distribution of ecosystems, which is of high value to resource managers and scientists, and many management plans rely heavily on maps. Restoration ecologists are aided by maps to be able to assess the severity of impacts and to be able to produce restoration strategies. A variety of approaches exist to mapping the spatial distribution of benthic biota and bedforms, like remote sensing from satellites or planes, or geophysical methods like side-scan sonar surveys. Most of these methods were developed for specific reasons other than coral reef research and coral-specific applications have only fairly recently been developed. The method described in this paper is an application that was specifically designed for coral research. In order to establish the value and spatial distribution of coral areas that were almost accidentally discovered during a dredging pre-survey in the southern Arabian Gulf (Dubai, United Arab Emirates), a concise method was called for that not only allowed the description of the coral covered area, but also allowed coral species to be differentiated as well as the healthy coral distinguished from the diseased. This called for a visual survey, since other frequently used methods, like airborne imagery or side-scan sonar, allow delineation of coral covered area but give no information on species or health status. Due to the large area involved (37.7 km^2), the time-frame available and the desired level of accuracy (100% visual cover of the area), a diver-based mapping approach was not possible. Therefore, rather than have divers undertake large numbers of video transects, we decided to make 'mega-video transects' from a boat that covered the entire coral area. This had the advantage of significantly reducing diver time, speeding up overall survey time, and increasing accuracy by providing 100% recorded visual cover of the coral area. The desired output was a map that specified spatial patterns of coral communities that could be used for management planning. Furthermore, over 1996 a thermal anomaly led to widespread coral mortality in the study area and it was of interest to map the spatial extent of coral growth lost in this event. This paper describes (1) the technical details of the vessel-based video survey, (2) shows the product (the maps), and (3) discusses management and monitoring implications of the product.

Rinkevich, B. 1994. Restoration strategies for coral reefs damaged by recreational activities: The use of sexual and asexual recruits. *Restoration Ecology* 3:241-251.

Author Abstract. The unique marine ecosystems of coral reefs express varying levels of degradation as a result of increasing anthropogenic pressures. This is the main reason why more than 200 coral reef localities were proclaimed as natural reserves or marine parks under varying legislation, rules, and monitoring and management programs. Ironically, the conventional management plans increased accessibility to many reef localities and enhanced dramatically the impact of tourism on reef habitats. Recreational activities including SCUBA and skin diving, fishing, human trampling, sediment resuspension, and other damage caused by "innocent" visitors are causing a rapid deterioration of many reefs. Their destruction requires years and decades for full recovery. Rinkevich proposed to rehabilitate such damaged habitats by the alternate strategy of "gardening coral reefs" with asexual and sexual recruits. Coral branches, colony fragments, and whole small colonies (asexual recruits) and laboratory or *in situ* settled planula-larvae (sexual recruits) are designed to be transplanted into denuded reefs for restoration. This approach is further improved when the sexual and asexual recruits are maricultured *in situ* within special protected areas, before being transplanted. The use of sexual recruits ensures an increase in genetic diversity. Rinkevich discussed several methodologies and results already accumulated showing the applicability of this gardening strategy for rehabilitation of denuded coral reefs. This restoration strategy should be integrated with proper management similar to that of already established reforestation in terrestrial habitats. The best candidates for employing this strategy are the fast-growing coral species, usually branching forms and species that brood their planulae larvae.

Rinkevich, B. 2000. Steps towards the evaluation of coral reef restoration by using small branch fragments. *Marine Biology* 136:807-812.

Author Abstract. Gardening of denuded coral reef habitats is a novel restoration approach in which sexual and asexual recruits are used. The present study aimed at the evaluation of the potentiality for restoration use of different types of small fragments subcloned from the Red Sea coral species *Stylophora pistillata*. *In situ* short-term (24 h, ^{45}Ca method) and long-term (1 year, alizarin Red S vital staining) experiments revealed high variation (up to 70%) in growth rates between up-growing branches of a specific genet, and that tip ratios in dichotomous branches (n = 880) differ significantly between newly formed and older branches, further emphasizing the within-colony genetic background for spatial configuration. Small, isolated branches (<4 cm) revealed high survivorship (up to 90%, 1 year) and up to 20-30% (1 year, single- vs. dichotomous-tip branches, respectively) growth, showing that small-sized branches are suitable for restoration purposes. Results differed significantly between genets. Total length added for dichotomous-tip branches was in general at least twice that recorded for single tips of a specific genet. Restoration protocols may be applied either by sacrificing whole large colonies via pruning high numbers of small fragments or, by pruning only a few small branches from each one of many genets. An *in situ* "nursery period" of approximately 8 years is predicted for *S. pistillata* small fragments.

Risk, M. J., J. M. Heikoop, E. N. Edinger and M. V. Erdmann. 2001. The assessment 'toolbox': Community-based reef evaluation methods coupled with geochemical techniques to identify sources of stress. *Bulletin of Marine Science* 69:443-458.

Author Abstract. There have been few seminal advances in techniques of health evaluation of coral reefs since line transects and visual fish counting were first proposed in 1972, yet the rate of resource destruction increases rapidly. Especially in Third World settings, coastal communities need access to simple techniques that have been shown to identify stress on reefs: (1) Coral mortality indices, (2) Benthic bioindicators (stomatopods, forams, amphipods), (3) Coral associate counts, and (4) Bioerosion amounts in coral rubble. Coral growth rates are an undependable measure of reef health: corals on dying reefs with low coral cover often exhibit higher than normal growth rates. Transect data may be cast into other forms, such as triangular diagrams, to be more effective in reef management. All of these rapid assessment techniques have been shown to be effective in the hands of persons with limited technical training. Each is rapid and cost-effective. Once one of the 'tools' in the assessment 'toolbox' has detected stress, the precise nature of the source can be identified via geochemical techniques: (1) Sewage: stable isotope ratios of nitrogen (delta ^{15}N) in a number of organisms (stomatopods, corals) are enriched at sites subject to sewage discharge. (2) Siltation: in areas subject to siliciclastic input, insoluble residues in coral skeletons are a measure of exogenous sediment input. (3) Thermal/Light stress: as has been shown in studies of El Niño events and the Indonesian 'haze' of 1997, the delta ^{13}C signal in coral skeletons is a measure of metabolic stress caused by changes in light and temperature.

Rogers, C. S. and V. H. Garrison. 2001. Ten years after the crime: Lasting effects of damage from a cruise ship anchor on a coral reef in St. John, United States Virgin Islands. *Bulletin of Marine Science* 69:793-803.

Author Abstract. In October 1988, a cruise ship dropped its anchor on a coral reef in Virgin Islands National Park, St. John, creating a distinct scar roughly 128 m long and 3 m wide from a depth of 22 m to a depth of 6 m. The anchor pulverized coral colonies and smashed part of the reef framework. In April 1991, nine permanent quadrats (1 m^2) were established inside the scar over a depth range of 9 m to 12.5 m. At that time, average coral cover inside the scar was less than 1%. These quadrats were surveyed again in 1992, 1993, 1994, 1995 and 1998. Recruits of nineteen coral species have been observed, with *Agaricia agaricites* and *Porites* spp. the most abundant. Quadrats surveyed outside the scar in June 1994 over the same depth range had a higher percent coral cover (mean = 7.4%, SD = 4.5) and greater average size (maximum length) of coral colonies than in quadrats inside the damaged area. Although coral recruits settle into the scar in high densities, live coral cover has not increased significantly in the last 10 yrs, reflecting poor survival and growth of newly settled corals. The relatively planar aspect of the scar may increase the vulnerability of the recruits to abrasion and mortality from shifting sediments. Ten years after the anchor damage occurred, live coral cover in the still-visible scar (mean = 2.6%, SD = 2.7) remains well below the cover found in the adjacent, undamaged reef.

Rogers, C. S. and J. Miller. 2001. Coral bleaching, hurricane damage, and benthic cover on coral reefs in St. John, U.S. Virgin Islands: A comparison of surveys with the chain transect method and videography. *Bulletin of Marine Science* 69:459-470.

Author Abstract. The linear chain transect method and videography were used to quantify the percent cover by corals, macroalgae, gorgonians, other living organisms, and substrate along permanent transects on two fringing reefs off St. John. Both methods were used simultaneously on Lameshur Reef in November 1998 and on Newfound Reef in March and October 1998. Hurricane Georges passed over St. John in September 1998 and a severe coral bleaching episode began the same month. Both methods gave remarkably similar values for coral cover, while the video method gave consistently higher values for gorgonians and macroalgae. The most dramatic difference was in the quantification of bleaching. At Newfound, the chain method indicated 13.4% (SD = 14.1) of the coral tissues were bleached and the video method, 43.4% (SD = 13.0). Corresponding values at Lameshur were 18.1% (SD = 22.3) and 46.5% (SD = 13.3). Although hurricane damage was conspicuous at Newfound Reef, neither method showed significant changes in coral cover or other categories as a result of the storm.

Syms, C. and G. P. Jones. 2001. Soft corals exert no direct effects on coral reef fish assemblages. *Oecologia* 127:560-571.

Author Abstract. Correlations between abundance of organisms and their habitat have often been used as a measure of the importance of particular habitat features. However, experimental manipulation of the habitat provides a more unequivocal estimate of its importance. In this study we quantified how fish communities on small patch reefs covaried with changes in benthic cover habitat features. A random sample of small patch reefs was selected and both fish abundance and habitat measures recorded. Naturally occurring patch reefs could be classed into three habitat types based on their benthic cover. Reefs dominated by massive soft corals were the most abundant (50%), followed by those dominated by rock and soft corals in equal proportions (36%), then reefs dominated by branching corals (14%). Fish assemblages differed between the reef types. Communities on soft-coral-dominated and rock/soft-coral-dominated patch reefs formed a continuum of species responses correlated with degree of soft coral cover. In contrast, branching-coral-dominated reefs were occupied by a more discrete set of species. We tested the role of soft corals in contributing to this pattern by experimentally reducing soft coral cover on patch reefs from a baseline level of ~67% to ~33% and ~6%, and monitoring the experiment over two years. Contrary to expectations derived from the correlative data, and in contrast with previous manipulations of hard corals, soft-coral disturbance did not generate any corresponding changes in the fish assemblage. This negative result indicated that the quality and heterogeneity of habitat generated by soft corals on patch reefs was indistinguishable from equivalent-sized habitat patches formed by bare rock alone. Nevertheless, because soft corals are living organisms they have the potential to generate indirect effects by interacting with other organisms such as hard corals. In the long-term, we hypothesize that biotic interactions between habitat forming organisms might affect composition of fish assemblages on patch reefs.

Torres, J. L. 2001. Impacts of sedimentation on the growth rates of *Montastraea annularis* in southwest Puerto Rico. *Bulletin of Marine Science* 69:631-637.

Author Abstract. Growth rates of the massive reef-builder coral *Montastraea annularis* (morphotype II) were obtained at three heavily disturbed reefs near the Guanica, Guayanilla, and Ponce Bays on the south coast of Puerto Rico. These were compared with growth rates from a virtually undisturbed reef located at La Parguera reef platform on the southwest coast. Sediment plumes have affected the disturbed sites for more than 10 yrs. Resuspended sediment rates (g cm^{-2} d^{-1}) were measured for a year period, and correlated with growth rates. Sediment composition from the samples was also taken into consideration. Average growth rates of *M. annularis* were in the order of 5.4 ± 0.98 mm yr^{-1} at Guanica, 6.68 ± 1.35 mm yr^{-1} at Guayanilla and 7.01 ± 0.63 mm yr^{-1}) at Ponce. These were significantly lower ($P < .05$) than those obtained at Parguera (10.76 ± 1.43 mm yr^{-1}), and negatively related with sediment rates and percentages of terrigenous sediments reaching the sites. Calcium carbonate percentages were significantly higher ($P < .001$) at Parguera and were related positively with coral growth rates suggesting that sediment produced within the reef did not affect the corals as sediments coming from external sources (i.e., inland). The species *M. annularis* had suffered a decline in its growth rates across the reefs of the southwest coast of Puerto Rico. It was determined that linear extension rates of this species correlate negatively with increased sedimentation rates and percent of terrigenous sediments. Carbonate percentages correlate positively with linear extension rates of *M. annularis* and, hence, do not interfere in the growth rates of this species, instead they may be incorporated into the skeleton and used as an alternative source.

United States Coral Reef Task Force Working Group on Ecosystem Science and Conservation. 2000. Coral Reef Protected Areas: A Guide for Management. 17 pp. NPS publication D-1449. U.S. Coral Reef Task Force, Department of the Interior, Washington, D.C. http://www.coralreef.gov/blueprnt.pdf

This report presents information that managers of coral reef protected areas should be familiar with before monitoring. This includes (1) location of the reefs using aerial photography and other remote techniques. Photography may also be use to record baseline reef conditions and provide permanent record of reef exterior at a specific time; (2) the condition of the reefs (whether diseased or healthy); (3) whether the reefs have changed and the cause. For example, changes that occur in reef condition and species abundance due to pollution, storms, or direct impact from boats; (4) whether the present measures are sufficient to prevent coral reef deterioration and in some cases reef recovery.

The monitoring methods and parameters selected will depend on the objectives, threats predicted, and management course of action. Authors also state that measuring coral abundance variations over time and other species that reside on healthy reefs can provide foundation for evaluating changes on nearby reefs that may be stressed by anthropogenic sources. Therefore when monitoring is performed, one should record the number of persons using the reef areas, concentrated zones, and types of activities occurring around or nearby the reef. See publication for additional information that should be taken into consideration for monitoring of reefs.

United States Environmental Protection Agency (EPA) Science Advisory Panel. 2000. Coastal Reef Monitoring Executive Summary, EPA Advisory Panel, Key Colony Beach, December 5-6, 2000. Contact information: Reef Relief Environmental Center, Phone # (305) 294-3100 and Fax # (305) 293-9515. http://www.reefrelief.org/coral_reef_monitoring_project1.html

Coral reef monitoring was conducted at forty reef sites located within five of the nine EPA Water Quality Segments in the Florida Keys National Marine Sanctuary during 1994. Permanent station markers were installed at these sites in 1995. Sampling began in 1996. There were 160 stations among forty sites sampled up to 2000. Three additional sites were installed and sampled in the Dry Tortugas in1999. Sampling was performed using a Sony CCD-VX3 with full automatic settings and artificial lights (two 50 watt) at 40 cm above the benthos. In 2000, sampling was performed using digital video filming all sites with a Sony TRV 900. Video frames were used to predict percent cover analysis with minimal overlap between images. A custom software application Point-Count was used to analyze coral reefs images. Using this method, the analyst opens each image and the software adds ten random points over the image. Selected benthic taxa (stony coral, octocoral, zooanthid, sponge, seagrass, and macroalgae) and substrate would then be identified under each point. After images are analyzed, the data is converted to an ASCII file for Quality Assurance. In addition, hypothesis testing was also used to analyze the percent cover, species richness, and disease/condition data.

Wagner, G. M., Y. D. Mgaya, F. D. Akwilapo, R. G. Ngowo, B. C. Sekadende, A. Allen, N. Price, E. A. Zollet and N. Mackentley. 2001. Restoration of coral reef and mangrove ecosystems at Kunduchi and Mbweni, Dar es Salaam, with community participation, pp. 467-488. In Richmond, M. D. and J. Francis (eds.), Marine Science Development in Tanzania and Eastern Africa 1. WIOMSA Book Series.

Author Abstract. A baseline study was conducted on the fringing coral reef around Mbudya Island. The snorkeling visual census technique was used to estimate percentage of bio-cover. There were substantial areas of no bio-cover (15-40%), which was attributed to dynamite fishing and wave action. Of the hard coral cover, which was 47% on the landward side of Mbudya and 12% on the seaward side, 40-60% was dead, probably largely due to coral bleaching. The live coral included twenty-nine genera representing eleven families. Fish were generally more abundant on the landward side. Preliminary trials were conducted on ecosystem restoration with community involvement. Fishermen were involved in transplanting corals on the fringing reef at Mbudya Island. Approximately, 500 fragments of *Galaxea*, *Acropora, Porites* species, and *Montipora* species were transplanted in seven dynamited sites, using cement filled, and disposable plastic plates. Monitoring was subsequently carried out in the restored sites. Approximately 3 months after transplanting the corals, *Galaxea* species showed very significantly greater survival (100% complete survival) than *Porites* species (55.7%) complete survival, 13.9% partial survival), but there was no significant difference between *Acropora* species and *Montipora* species survival. Over a period of 5 months, increase in height was significant for *Galaxea* species and *Porites* species, but not for *Acropora* species. Likewise, a baseline study was conducted in Mbweni Mangrove Forest using the transect line plots method. One site near the village, which had formerly been dominated by *Rhizophora mucronata*, has been severely cut for firewood and building poles in recent years. It now consists mostly of saplings, dominated by *Ceriops tagal* (0.20 individuals/m super(2)), followed by *R. mucronata* (0.10 individuals/ m^2). In another site, which was clear-cut about two years ago, *C. tagal, Avicennia marina* and *R. mucronata* (mostly seedlings) are now found at densities of 0.23, 0.10 and 0.01 individuals/ m^2, respectively. Women at Mbweni village assisted with the transplanting of more than 3000 seedlings of *Rhizophora mucronata* in Mbweni Mangrove Forest. This mangrove replanting activity resulted in the spontaneous formation of a new community-based organization (CBO) known as Mbweni Environment and Women's Group. The monitoring of mangrove seedlings showed that after 8 months, 35-38% were in perfect condition. The site that had been clear-cut showed very poor seedling survival.

Walter, D. J., D. N. Lambert and D. C. Young. 2001. Sediment facies determination using acoustic techniques in a shallow-water carbonate environment, Dry Tortugas. *Marine Geology* 182:161-177.

Author Abstract. Two high-frequency acoustic seafloor classification systems (12- and 15-kHz) were used in conjunction with sediment core analysis to characterize sediment facies at a study site near Garden Key in Dry Tortugas, Florida. The acoustic system uses echo return amplitude to compute acoustic impedance that is then correlated with sampled sediment impedance values calculated from wet bulk density and compressional wave velocity. Several bottom provinces were identified using the 15-kHz data to construct a real-time map of ship tracks in colors that represent the surficial sediment facies type. Sediment facies over the entire study site (36 km^2) range from sandy silts to exposed limestone rock and coral reef structures. Color contour maps using the 12-kHz data, created after correlating acoustic impedance predictions with core measured sediment properties, validates the initial facies pattern predictions made in real-time. The sediment facies patterns indicate a long-term pattern of deposition of fine-grained, silt-sized, surficial sediments in an area adjacent to the emergent carbonate embankment. Two-dimensional acoustic profiles along survey tracklines also provide cross-sectional views of seafloor and subbottom stratigraphy that confirm the buildup of these fine sediments in the northwest corner of the study site. A generous supply of sediment resulting from an abundance of benthic green algae (*Halimeda* spp.) on adjacent shallow platforms form a thick sequence of fine sandy silt at the base of the southeastern edge of the embankment and fringing reef. Sediment cover over the limestone bedrock thins and becomes coarse southeast of Garden and Bush Keys, suggesting the likely existence of a dominant flow around the shallow carbonate embankment that restricts export of fine sediments out of the area.

Wulff, J. 2001. Assessing and monitoring coral reef sponges: Why and how. *Bulletin of Marine Science* 69:831-846.

Author Abstract. Functional roles of sponges in coral reef ecosystems include: increasing coral survival by binding live corals to the reef frame and preventing access to their skeletons by excavating organisms; mediating regeneration of physically damaged reefs by temporary stabilization of carbonate rubble; reworking of solid carbonate through bio-erosion; recycling nutrients and adding to primary production through microbial symbionts with special biochemical capabilities; clearing the water column of procaryotic plankton; serving as food for a variety of megafauna; and attracting support for responsible human stewardship of coral reefs with aesthetically appealing colors and morphologies. Nevertheless, sponges tend to be avoided in assessment and monitoring of coral reefs because they are not easy to quantify or identify, and because we have only recently begun to understand the importance of their many functional roles. As we gain more understanding of these roles of sponges in coral reefs, the need to carefully assess and monitor changes in sponges is becoming clearer. Focus on functional roles dictates choice of methods for assessing and monitoring sponges, as follows: (1) volume will generally be the most useful way to quantify sponge populations; (2) accurate identification to genus, family, or even order, combined with a brief description and reference to voucher specimens, is preferable to guesses on species names, in cases for which identification can't be verified by specialists; (3) permanently marked sites must be monitored over time in order to be able to detect community changes and to distinguish beneficial from detrimental effects of sponges on corals.

Yamano, H., M. Tamura, Y. Kunii and M. Hidaka. 2002. Hyperspectral remote sensing and radiative transfer simulation as a tool for monitoring coral reef health. *Marine Technology Society Journal* 36:4-13.

Author Abstract. Recent advances in the remote sensing of coral reefs include hyperspectral remote sensing and radiative transfer modeling. Hyperspectral data can be regarded as continuous and the derivative spectroscopy is effective for extracting coral reef components, including sand, macroalgae, and healthy, bleached, recently dead, and old dead coral. Radiative transfer models are effective for feasibility studies of satellite or airborne remote sensing. Using these techniques, we simulate and analyze the apparent reflectance of coral reef benthic features associated with bleaching events, obtained by hyperspectral sensors on various platforms (ROV, boat, airplane, and satellite), and suggest that the coral reef health on reef flats can be discriminated precisely. Remote sensing using hyperspectral sensors should significantly contribute to mapping and monitoring coral reef health.

APPENDIX II: CORAL REEFS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Caribbean Coastal Marine Productivity Program (CARICOMP). 2001. CARICOMP Methods Manual: Manual of Methods for Mapping and Monitoring Physical and Biological Parameters in the Coastal Zone of the Caribbean. 93 pp. CARICOMP Data Management Center, Centre for Marine Sciences, University of the West Indies. Mona, Kingston, Jamaica. Florida Institute of Oceanography, University of South Florida, St. Petersburg, FL, USA. http://www.ccdc.org.jm/caricomp_manual_2001.pdf.

The CARICOMP program focuses on understanding productivity, structure, and function of coral reefs, mangroves, and seagrass ecosystems. Members of this program designed a methods manual that provides standards for monitoring and assessing the condition of these marine habitats. Some physical measurements that should be taken when monitoring the habitats condition include a detailed site description and selection, site mapping, and time series measurements. A description of coral reefs physical characteristics, parameters that are to be measured, and methods used to monitor and assess the habitat's condition are also provided. Methods and procedures that are commonly used on coral reefs and described in this document include: line transects, recording timing and frequency, sample strategy and collection, data management, survey of habitat structures and grazers. Additional information on methods and procedures used to assess and evaluate the health of each of the habitats mentioned in this abstract are described in this manual.

This Manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed.

Crosby, M. P. and E. S. Reese. 1996. A Manual for Monitoring Coral Reefs with Indicator Species: Butterfly Fishes as Indicators on Indo Pacific Reefs. 45 pp. Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration.

This manual discusses the use of an indicator species, coral feeding butterfly fishes (family Chaetodontidae) to assess the health of corals reefs in the Indo Pacific regions. Researchers determined the correlations of fish feeding preference, abundance, and behavior with coral abundance and health. Butterfly fishes are monitored along 1 to 30m transects near areas with high coral cover. The number of each species of butterfly fish on either side of the transect line is counted. Also evaluated were the fishes feeding behavior on the coral. Coral cover is also assessed under the transect for 0.5 m or 1.0 m intervals. Line transect methods are also used to determine coral diversity and abundance. The coral species type is identified along the transect line as well as at a specific point in the study area and then recorded. Coral percent cover is established by dividing the number of observations of a specific coral species by the number of data points along the transect. The methods mentioned is this manual for assessing coral health are relatively simple, less expensive and yet effective compared to some other monitoring methods used.

English, S., C. Wilkinson and V. Baker. 1997. Survey Manual for Tropical Marine Resources, 2nd edition. Australian Institute of Marine Science Townsville ISBN 333.952072013 or Protocols for Coral Reef Monitoring. http://www.coral.noaa.gov/gcrmn/protocol.html

This publication discusses techniques used for coral reef monitoring. One method used is Manta tow or time swim. This provides a broad scope of the reef; observes any change in reef structure (like blast damage, plagues); and ensure that more detailed monitoring sites are representative of the whole reef. The Manta tow consists of two minute snorkel tows (minimum of nine) behind a boat at slow speed with stops to record percent cover of live and dead corals, soft coral, and regional specific parameters, e.g., crown-of-thorns starfish, giant clams, large patches of damage to corals. These tows are used to select transect monitoring sites to ensure adequate representation of the entire reef.

Another method used to assess coral reef health is Line Intercept or Transect. Five line transects each 20 m long are commonly used with the parameters recorded as lifeforms, or as species. Lifeforms or species can be grouped into larger groups; however, larger groups cannot be sub-divided back into more detailed groups after data have been collected. Belt and video transects can be inter-calibrated with the lifeform transects. Transects are placed where coral density is highest. Researchers advised that transects be marked from start and finish with steel stakes. Live fish visual censusing can also be used and are based on line transects. The primary focus for this method is counting all fish, especially those targeted by fishers and some indicator species like the Chaetodonts. The fish and lifeform transects can be conducted on the same transect lines, with fish surveys completed before benthos assessment, to avoid deterring fish. See publication for additional information on methods used for coral reef monitoring.

Environmental Protection Agency (EPA) Science Advisory Panel. 2000. Coastal Reef Monitoring Executive Summary, EPA Advisory Panel, Key Colony Beach, December 5-6, 2000. Contact information: Reef Relief Environmental Center, Phone # (305) 294-3100 and Fax # (305) 293-9515. http://www.reefrelief.org/coral_reef_monitoring_project1.html

EPA, Florida Keys National Marine Sanctuary (FKNMS) and National Oceanic and Atmospheric Administration (NOAA) have addressed the importance of monitoring. The sampling site locations were chosen using stratified random procedures. The study was performed at forty reef sites located within five of the nine EPA Water Quality Segments in the Florida Keys National Marine Sanctuary during 1994. Permanent station markers were installed at these sites in 1995. From 1996 to 2000, 160 stations among 40 sites were sampled. Three additional sites were installed and sampled in the Dry Tortugas beginning in 1999. The project's 43 sampling sites include: 7 hard bottom, 11 patch, 12 offshore shallow, and 13 offshore deep reef sites. Sampling performed through 1999 was conducted using a Sony CCD-VX3 with full automatic settings and artificial lights (two 50 watt) at 40 cm above the benthos. By 2000, digital video filming was used at all sites with a Sony TRV 900. The videographer films a clapperboard prior to beginning each transect. The date and location of each film segment is recorded. Percent cover analysis was predicted on selecting video frames that abut, with minimal overlap between images. Image analyses were conducted using a custom software application Point-Count for coral reefs. Selected benthic taxa (stony coral, octocoral, zoanthid, sponge, seagrass, and macroalgae) and substrate are identified under each point. After images are analyzed, the data is converted to an ASCII file for Quality Assurance and entry into the master ACCESS data set. Additional information techniques used are described in this report.

Jaap, W. C. 1995. Monitoring methods for assessing coral reef biota and habitat condition. 80 pp. In Crosby, M. P., G. R. Gibson and K.W. Potts (eds.), A Coral Reef Symposium on Practical, Reliable, Low-cost Monitoring Methods for Assessing the Biota and Habitat Conditions of Coral Reefs. EPA 904/R-95/016.

Researchers used various techniques to evaluate and assess injured or damage to reef resources. Aerial photogrammetry, ground truth surveys, and Global Information System (GIS) mapping were used for larger scale assessments. Techniques commonly used for *in situ* evaluations include: transect, quadrat, 35 mm photography, and video. Sediment and organism samples are collected to assess pollutants (e.g., trace metals) that may be present in the sediment. Disease and bleaching of the reef organisms were evaluated using histopathology and electron microscope analysis. Coral reefs were monitored in the Florida Keys in 1978. Methods used for monitoring include quadrats, line transects, and photography. Quadrat sampling methods involved counting and identifying the organisms under an X, Y coordinate grid (planar point intercept), estimating the cover using a grid of squares, and mapping the distribution of the taxa of interest within the quadrat (*in situ* mapping). Line transects are used in data collection by estimating species abundance. Photography was used to capture spatial patterns and changes occurring over time of a habitat. Additional information on methods used for assessing coral reef conditions is described in this document.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems, 94 pp. United States Geological Survey Open-File Report 02-497. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Motta, H., M-A. Rodrigues and M. H. Schleyer. 2001. Coral reef monitoring and management in Mozambique, pp. 43-48. In Souter, D., D. Obura and O. Linden, (eds.), Coral reef degradation in the Indian Ocean: Status reports and project presentations 2000. CORDIO, Stockholm, Sweden.

Author Abstract. Mozambique is situated on the eastern coast of Southern Africa, between 10° 27'S and 26° 52'S latitude and 30° 12'E and 40° 51'E longitude. The Mozambican coastline, about 2,770 km long, is the third longest in Africa and is characterized by wide diversity of habitats including sandy beaches, sand dunes, coral reefs, estuarine systems, bays, mangroves and seagrass beds. A survey on coral bleaching was undertaken in 1999, at the end of summer, to look at effects of the ENSO event in the region. Evidence of bleaching was sought on a total of 17 reefs and a visual assessment was made of reef type, faunistic cover and the extent of reef damage attributable to bleaching and crown-of-thorns starfish (COTS). The results show that the effects of El Nino bleaching in Mozambique were most extensive on exposed reefs in the north and this diminished further south except at Inhaca Island where serious recent bleaching was encountered. Extensive COTS damage was also found at Bazaruto and Inhambane. As part of a broader program, monitoring started in the same year with the installation and first visits to stations. Sites were selected for a preliminary survey, according to a number of criteria. The field work was carried out between August and September during 22 days. For the first year of monitoring, 9 "core" reefs were selected for annual survey. These reefs were widely distributed throughout the coast and represent different reef types. Before video transect was done, an observer would conduct a general survey and start a species list. This list was helpful on data analysis of video-transect. The condition of reefs surveyed varied between healthy to heavily impacted by natural and anthropogenic factors. Many reefs are degraded from bleaching and the ravages of crown-of-thorns starfish. Coral cover was highest on the reefs of northern Mozambique and in marine protected areas. The high cover of rock and algal surfaces reflects mortality that was reported at these sites in earlier surveys. There is evidence of recovery on some reefs on which soft corals are the primary colonizers. Carnivores dominated fish populations in the north and in protected areas, following a similar pattern to that of coral cover. High fishing pressure on the other reefs was shown by the small size classes of fish and the dominance of herbivores, which are least, preferred by fishermen. Before the initiation of the monitoring programme, however, participants went through a process of preparation. A training course was held in August 1999, attended by a number of participants from MICOA itself, the Institute of Fisheries Research and the University. Some of the participants were later integrated in the team that started the monitoring programme.

Morelock, J. 2000. Measuring Present Condition of Coral Reefs. University of Puerto Rico, Department of Marine Sciences, Mayagüez, Puerto Rico. Contact information: Phone # (787) 265-3838 or (787) 832-4040 ext. 3443, 3447, Fax # (787) 265-5408. http://geology.uprm.edu/Morelock/GEOLOCN_/corsurv.htm

This article discusses ways to measure the present health condition of coral reefs. Methods used include: linear transect, the quadrat, and the photoquadrat. Linear transects can be used as a reference (i.e., coral cover is estimated or measured in some way along either side of the line) or cover can be point-counted at regular intervals beneath it. A popular method used includes draping a 10 m chain so that it follows the topography of the reef surface. Each individual links in the chain found at the top of each substrate type is counted.

Quadrats however are randomly tossed at each position or arranged along a pre-determined transect. Coral cover can then be estimated within each sub-square or point-counted at the intersections of a grid within the quadrat frame. Photo transects may include the use of a Nikonos with strobes at a fixed distance above the bottom to photograph the coral cover within a quadrat. The image can be point counted using any quadrat-based or the area can be measured based on photo quadrat. However if permanent reference points (i.e., rigid pins in the reef) are instituted, then the photographic series can be repeated accurately at another time. Additional information on methods used to monitor and measure coral health can be obtained from the source mentioned above.

Pernetta, J. C. 1993. Monitoring Coral Reefs for Global Change, a Review of Interagency Efforts. 102 pp. IUCN Publications Unit, Cambridge, England.

This paper discusses basic biological and physical parameters for monitoring coral reefs as well as methods used for monitoring. Biologic parameters that are used for monitoring coral reefs include: percent cover of corals (scleractinian and non-scleractinian), algae (calcacerous rods, macroalgae and turf algae) and sponges (ascidians, sand, rubble and bare dead coral). Parameters are assessed using the Line Intercept Transect and Manta-tow methods on the Great Barrier Reef and in Asian countries. The Line Intercept Transect (LIT) methods estimates percent cover of corals, algal cover and other organisms. Transect are also used to assess fish abundance, species diversity and approximate biomass. Physical parameters that are recommended to be monitored include water temperature (temperatures taken from water representative of the shallow transects), salinity, sedimentation, sea level using a high quality local datum (Global Positioning System) to measure/interpret water level, and storms using visual. Methods used to monitor each parameter are described in this document. See publication for additional information needed on parameters and methods.

Rogers, S. C., G. Garrison, R. Grober, A-M. Hillis and M. A. Franke. 2001. Coral Reef Monitoring Manual for the Caribbean and the Western Atlantic. Virgin Islands National Park, St. John, USVI, Phone # (340) 693-8950.

This manual presents the physical, chemical and biological parameters that are to be considered when monitoring coral reefs. The physical and chemical parameters that are recommended to be monitored include: temperature (increase in temperature results in bleaching of the corals); dissolved oxygen (important for the survival of marine animals); salinity (reefs may experience some fresh water influx); pH changes (which may indicate the reef has a new or additional sources of pollution); light transmission (the amount of light available for photosynthesis of algae influence coral growth); sedimentation (sediments may reduce light availability reducing photosynthetic rates and cause depletion of dissolved oxygen); nutrient availability (species abundance may be reduced if nutrients are depleted); and current speed and direction (currents transport nutrients, sediments and pollutants).

Biological monitoring of coral reefs should include monitoring the condition of corals, its growth, whether bleached or not, diseases, and algal overgrowth; using quadrats to measure the percent cover, species diversity, relative abundance, density and size, and monitor coral, octocorals, sponges, seagrasses, and algae; using linear transect for measuring percent cover, species diversity, and relative abundance; and estimating the spatial index.

Researchers recommend that monthly observations be conducted when monitoring individual coral colonies; quadrat and transect surveys be performed within six-week intervals to provide sufficient data for percent cover and species diversity changes to be assessed. Monthly observations may also aid in reducing threats that may damage reef organisms while conducting surveys. Researchers further advised that short-term data be used for data analysis instead of large amounts of raw data. See publication for additional information on techniques used for coral reef monitoring.

Samways, M. J. and M. J. Hatton. 1999. An appraisal of two coral reef rapid monitoring manuals for gathering baseline data. *Bulletin of Marine Science* 69:471-485.

Author Abstract. There is concern worldwide that many coral reefs are suffering degradation and loss of biodiversity. In response, some rapid coral reef health monitoring manuals have been developed that purport to have wide biogeographical applicability and user friendliness. These manuals however, have been little tested in areas beyond their centers of origin. This study uses two of the manuals (involving line-intercept transects; English et al., 1997) and corallivorous chaetodont behavior to do a first, expeditionary assessment on a relatively inaccessible coral reef in the Seychelles, Western Indian Ocean. Future revisions of the manuals should perhaps consider the following points as extra guidance for newcomers to the methodologies. At any one time and site, at least ten, rather than five, transects should be done. Sensitivity of many fishes to line-transect diver activities suggests that the Stationary Visual Census Method is much preferred to line-intercept counts. Line-intercept coral data are well-illustrated by simple rank-abundance curves, flagged with species identifications. Such curves also apply well to specific fish taxa, but not to the general fish assemblage. Statistical correlations between fishes and benthos cannot be done from line-intercept data within transects as they are not independent variables, and this should be made explicit in the manuals. Stationary visual censuses would overcome this problem. Data gathered according to the practical manuals are amenable to multivariate analysis. Clarke and Warwick's (1994) manual and associated software are strongly recommended for follow-up analysis. Obligate corallivorous butterfly fishes clearly have potential for monitoring coral reef health but that the metric requires calibration and cross-referencing with other metrics. Further recommendations on coral reef health monitoring relative to the manuals are given, with emphasis on the importance of clearly defining the biodiversity and conservation questions before monitoring is started.

Shafer, D. J., B. Herczeg, D. W. Moulton, A. Sipocz, K. Jaynes, L. P. Rozas, C. P. Onuf and W. Miller. 2002. Regional Guidebook for Applying the Hydrogeomorphic Approach to Assessing Wetland Functions of Northwest Gulf of Mexico Tidal Fringe Wetlands, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. Technical Report ERDC/EL TR-02-5.

This manual is designed to provide practitioners with guidelines for monitoring and assessing wetland functions. The manual outlines protocols used for collecting and analyzing data needed to assess wetland functions in the context of a 404 permit review or comparable assessment setting. When assessing tidal fringe wetlands in the northwestern Gulf of Mexico the researcher must define the assessment objectives by stating the purpose (for e.g., assessment determines how the project impacts wetland functions); characterize the project area by providing a description of the structural characteristics of the project area (for e.g., tidal flooding regime, soil type, vegetation and geomorphic setting);

use screen for redflags; define the wetland assessment area; collect field data using a 30-m measuring tape, quadrats and color infrared aerial photography; analyze field data; and apply assessment results. This document provides additional detail information on criteria selection and methods used for assessing tidal fringe wetlands.

Steyer, G. D., C. E. Sasser, J. M. Visser, E. M. Swenson, J. A. Nyman and R. C. Raynie. 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories. *Journal of Environmental Monitoring and Assessment* 81:107-117.

Author Abstract. Wetland restoration efforts conducted in Louisiana under the Coastal Wetlands Planning, Protection and Restoration Act require monitoring the effectiveness of individual projects as well as monitoring the cumulative effects of all projects in restoring, creating, enhancing, and protecting the coastal landscape. The effectiveness of the traditional paired-reference monitoring approach in Louisiana has been limited because of difficulty in finding comparable reference sites. A multiple reference approach is proposed that uses aspects of hydrogeomorphic functional assessments and probabilistic sampling. This approach include: a suite of sites that encompass the range of ecological condition for each stratum, with projects placed on a continuum of conditions found for that stratum. Trajectories in reference sites through time are then compared with project trajectories through time. Plant community zonation complicated selection of indicators, strata, and sample size. The approach proposed could serve as a model for evaluating wetland ecosystems.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

United States Environmental Protection Agency (USEPA). 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington DC. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

United States Environmental Protection Agency (USEPA). 1993. Volunteer Estuary Monitoring. A Methods Manual. 176 pp. U.S. Environmental Protection Agency, Washington, DC, Office of Water. EPA Report- 842-B-93-004. http://www.epa.gov/owow/estuaries/monitor/

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include: understanding estuaries and what makes them unique, impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary are physical (e.g., substrate texture), chemical (e.g., dissolved oxygen) and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

APPENDIX III: LIST OF CORAL REEF EXPERTS

The expert listed below has provided his contact information so practitioners may contact him with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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