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Stressors and Disturbance Regimes on Back Reef Systems: Scale and Scope from Natural and Anthropogenic Sources

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Abstract

Back reef environments present a particular challenge in terms of characterization and management. Shallow near shore and lagoonal habitats associated with reef systems are the first areas to be impacted by land-based sources of pollutants and disturbances, defined as "stressors". Stressors are a link in the chain of events that lead to environmental change or "phase shifts" in natural systems. Stressors as "damaging stimuli" need to be defined in terms of thresholds for both populations of organisms, and ecological communities. Stressors alter the abundance and dynamics of individual populations of organisms, and thus impact the community structure and function. Microbial communities are key to processing nutrients and pollutants from land-based sources, but poorly characterized. The effects of changes in microbial communities usually go unnoticed until visual signs of change occur in macro-organisms (death, disease or a shift in predominate species). Because microbial communities have a major influence on the transformation of nutrients as well as a protective influence, short-term stressors often can result in latent changes in larger back reef communities. The most notable changes in back reef environments from stressors include: 1) Changes in coastal species abundance and diversity (including local extirpation), 2) Changes in natural community structure, 3) Changes in coastal water quality (or the dynamic" habitat), and 4) Changes associated with exotic species invasion. Advances in technologies and research have facilitated the detection of stressors and stress responses. Recent researches in stable isotopes signatures as indicators of nutrient flux across the land-sea interface have helped identify eutrophication sources. Detection of pathogens, advances in microbial ecology (genetic probes), and disease ecology, bleaching and pollutant studies (e.g. pesticides, fungicides, pharmaceuticals) have helped identify chronic stressors to back reef systems. Historical ecology and studies of long-term environmental change remain key to understanding the nature of change and chronic degradation of complex coastal systems. Although we understand the basic ecology of tropical marine systems in a general sense, researchers need to initiate programs to look at integrated processes across the shoreline, particularly in terms of ecosystem function in back reef environments.

Keywords: Lagoonal habitats; Ecological; Stressors; Pathogens; Fungicides; Isotopes

Introduction

Back reef environments present a particular challenge in terms of characterization and management. Shallow near shore and lagoonal habitats associated with reef systems are the first areas to be impacted by land-based sources of pollutants and disturbances. Stressors can be described as a component of the chain of events that lead to environmental change or "phase shifts" in natural systems [1,2]. Stressors are defined as stimuli that produce damage, and can be abiotic and biotic in nature. It is relatively easy to identify stressors that are catastrophic in nature, regardless of the source (a human-induced oil spill or natural hurricane event). However, it is often the chronic and long-term stressors that are more relevant to management to understand both the nature of variability in back reef systems, and to understand how stress can undermine the resistance and recovery of both individual species as well as natural communities.

Researchers have focused on the importance of a holistic approach to coral reef and fisheries management, with a call for "ecosystem management" to quantify and project "system services" from back reef and coastal environments [3]. This management philosophy seeks to place economic value on reefs for their roles in coast line stability, fisheries production and pollutant processing. The health of human communities is to a large part dependent on the health and services provided by natural ecological systems [4]. Ultimately, the impact of pollutants and physical alteration on any coastal systems will be the loss of production and diversity of large reef systems, but these changes are not easily prevented by current management paradigms. There are few real and measurable ecological criteria for judging "sustainability" or "compatibility" of land-based activities with adjacent marine environments [5]. At issue is the determination of threshold levels of disturbance or stress that impact a population of organisms in a given system for a given region.

"Stressors" have both long-term and short-term impacts on communities, but degraded or compromised natural systems can change irreversibly; thus, "how much of what type of stressors can natural systems take?" When does the natural variability of an abiotic or biotic factor move beyond a normal range, and constitute a "stress"? Stressors are produced by both natural and anthropogenic sources. Intact ecological systems are thought to have resistance and resilience to withstand natural stressors such as hurricanes and severe weather events. Communities such as coral reefs and rain forests are thought to benefit from intermediate levels of disturbance, and thus the

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community overall benefits from the stress on some populations [6]. Human-produced stressors range in scale from local alterations to the coastal environment to over-fishing to global climate change.

This paper will provide an overall characterization of human-produced stressors, with an overview of documented impacts on populations as well as on natural communities. There are new techniques and research innovations that may help elucidate the processes and causal links for coastal degradation. The applicability of these methods to future monitoring and management paradigms are a critical need for future funding.

Characterization of Stressors

The literature is rife with descriptions of coral reef systems that are ecological degraded. It is obvious to define a highly degraded reef with loss of trophic complexity and degraded water quality [1]. The difficulty arises in the characterization of critical levels or thresholds of stressors that initiate or begin this “slippery slope to slime” scenario. Stressors, in the physiological sense, are stimuli that produce damage in some real and measurable manner. Stressors, regardless of source, can produce both short-term responses and long-term adaptations in natural systems (Table 1). To clarify terminology, it is important to understand “stressors” as damaging stimuli to individual species. The net impact of stressors seen across a community includes damage across species from many taxa, across life history stages, and even damage by location or proximity to the stimuli. Fragmentation of back reef habitats is a serious ecological concern for nursery value and fisheries production, but fragmentation is the result of catastrophic stressors (e.g. dredge and fill of mangrove creek systems, marina construction, channels and waterways) that ultimately transform the seascape [7].

Stressors as “damaging stimuli” need to be defined in terms of thresholds linked to specific anthropogenic inputs. Stressors such as toxins are well defined physiologically by characteristics such as “LD-50”, or a dosage or exposure level at which 50% of the population is killed. Stressors in ecological systems can more appropriately be characterized as damage to individuals in the basic processes of growth, reproduction, and recruitment processes. Natural systems are compromised in their resilience and resistance to change when fragmented and reduced in spatial extent by human alterations of coastal areas. The full scope of coastal habitat complexity is necessary to support diversity and production through island connectivity [8]. Herein lays the problems in theoretical and empirical application. A “stressful” level of temperature is that pattern of temperature change (rate and severity) that significantly damages the physiological function of the organism. How is this threshold of damage distinguished from natural variability? The key is defining stressor thresholds, and how that threshold is compromised by overall system-wide alterations by humans.

There are several specific case studies in the coral reef research literature that help elucidate these threshold levels of stressors on back reef systems. For example, the increase or decrease of nutrient input into back reef habitats can affect the quantitative (productivity, abundance) and qualitative (community structure) characteristics of coastal marine communities [9]. Sewage input in Kaneohe Bay, Oahu, Hawaii, provides a documentation of threshold levels of nutrient runoff on a back reef ecosystem. Sewage discharge directly into the bay over a 25-year period caused a change in the benthic community at the south end of the bay from a system dominated by corals to one dominated by suspension feeders, deposit feeders, and the “green bubble alga” *Dictyosphaeria cavernosa* [10]. Sewage from two large treatment plants was diverted from the bay to a deep ocean outfall in 1977-1978, and the system began to change back to its original structure. Nutrients, turbidity and chlorophyll a concentrations declined rapidly in the year after sewage diversion, and phytoplankton and *D. cavernosa* abundance

Abiotic and Biotic variables that can become stressors	Short-term response	Long-term adaptation or acclimation
Temperature		
Extreme heat or cold temperatures experienced over a period of time or over a cycle (diurnal, tidal) that is not typical of normal variability.	Increased metabolic costs Reduced deposition of energy reserves Higher food or nutrient demand Bleaching of corals, soft corals, sponges	Selection of more heat tolerant individuals and species and their symbionts Reduction in growth rate and reproductive output Increased susceptibility to disease, lower energy reserves
Oxygen		
Reduce oxygen availability to animals from reduced photosynthesis or restricted amounts of oxygen in the water (e.g. increased BOD)	Death or partial mortality in some individuals and species from hypoxia stress or localized anoxia	Appearance of “dead zones” of acute anoxia Selection towards more hypoxia tolerant species
Energetics–Food and Nutrients		
Stressors that reduce the amount or quality of food energy available to animals or alter the nutrient regime normally experienced by plants	Reduced growth or depletion of food stores Death or partial mortality in some individuals and species from food or nutrient stress Change in diet for some predators or herbivores Increased marine plant growth rate depending on the nutrient regime	Lower coverage of clonal species (but some clonal species might increase) Lower reproductive output Lower recruitment success Dominance of more resistant or “weedy” species
Pathogens		
Increase in the number and severity of disease-causing agents, impacts both plants and animals	Death or partial mortality in some individuals and species from disease	Change in community structure both with types of species present and abundance of species
Toxins and Pollutants		
Toxins that accumulate in sub-lethal levels that can impact selected species and selected life-history stages of species	Change in mortality rates for species or life-history stages of some species Change in abundance of some species Increased susceptibility to diseases or other stress stimuli	Change in community structure both with types of species present and abundance of species

Table 1: Description and definition of the abiotic and biotic variables that human actions can alter to stressful levels on back reef systems. Responses of species are particularly critical for benthos (corals, macroalgae, sponges and soft corals) that cannot move to avoid the stressful stimuli. Change in community structure both with the abundance of individuals (population-level changes) and the number of species present (community-level change) will occur with long-term exposure to stressors.

and numbers of filter feeders decreased [11]. However, Kaneohe Bay has not completely returned to "pre-sewage conditions", and initial trends of recovery have slowed or even reversed at some locations in the bay [10], probably due to continued anthropogenic impacts resulting from the growing human population living near the bay. Stresses resulting from long-term impacts of dredging, sedimentation, stream channelization, non-point sources of nutrients, and the introduction of potential toxicants have not been remediated [10].

The complexity of land-based sources of pollutants, especially nitrogen (N), to near shore waters is now approached through a combination of spatial datasets and radioisotopes. Human population growth in coastal watersheds and the resulting run off of nutrients and contaminants to the coastal waters have been documented by spatial models [12]. Rarely have these models been directly related to stressor thresholds for coral reef benthos populations with the end objective to develop ecologically meaningful coastal development limits or carrying capacities.

The Florida Keys presents another case study of the complexity of stressors related to human activities. Changes in land use and land-based sources of pollution (particularly agriculture) have occurred on a dramatic scale throughout the tropical south Florida ecological system for the past 100 years [13]. The unique coastal geomorphology of the Florida Keys combined with the relatively recent sea level rise with the formation of Florida Bay 4000 ybp combined to create a very spatially complex and heterogeneous reef tract. This naturally-variable system contained lagoon, near shore and reef tract environments. Researchers found it difficult to establish a causal link between obvious pollution stressors and degradation of back reef habitats [14,15]. The challenges in identifying stressors come from several factors: 1) Little baseline information existed on processes critical to sustaining back reef and reef communities of the Florida Keys despite over 100 years of land-use change in the Keys and Everglades watershed, 2) The large spatial scale of the back reef systems including Florida Bay was poorly characterized in terms of the natural variability of key abiotic and biotic parameters (e.g. the presence of natural cross-shelf and latitudinal gradients along the reef system), and 3) The role of episodic storm events on water quality and sediment deposition was not understood or characterized on meaningful ecological scales. Hurricanes and large tropical storms provide an important disturbance regime for meso-scale sediment or detritus transport on and off of islands in particular (Figure 1). At any given point in time, there is likely a mosaic of varying states of disturbance and recovery across an island archipelago essential for the functioning of the wider ecological system. In the Florida Keys, management and research continue to struggle with the understanding of relatedness in Upper, Middle and Lower Keys systems.

The characterization of stressors has hinged on a fundamental characterization of tropical coastal environments [16,17] and will require the combination of system-wide and organism-level approach. The characterization of stressors most likely to impact the long term viability of back reef systems requires then a two-step process of first identification of the coastal system by benthic assemblages and processes, and then, the quantification of anthropogenic impacts (threats) that translate to stressful levels of abiotic and biotic variables (Table 1). The first review paper in this series on back reef environments presented the role of natural variability in back reef environments. Natural variability is a component of initial system characterization, as habitats function ecologically as a mosaic from the coastal zone to the outer shelf.

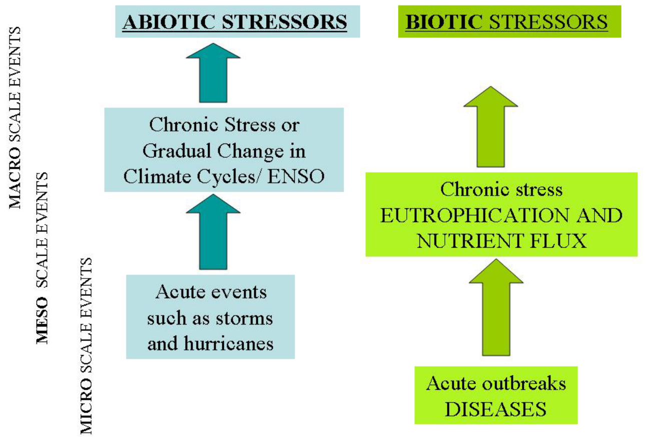

Figure 1: Summary of important stressors to the back reef environment by scale (both temporal and spatial). Some stressors can occur across multiple scales.

Population-Level Changes from Stressors

Population-level changes in back reef system are defined as changes in the basic population structure and processes by a disturbance to recruitment, growth, fecundity or mortality rates. Population-level studies of lethal and sub-lethal toxicity of heavy metals, petroleum, herbicides, pesticides, synthetic hormones, PCBs, and pharmaceuticals on tropical marine organisms have a long and prolific record in the literature [18-20]. Are these really population-level studies, or just studies of individual species? Also, is the literature really that prolific given there is an awful lot we don't know about these fundamental questions? The earliest studies in aquatic toxicology focused on understanding the effects of chemical pollutants on tropical marine organisms. Chemical contaminants are thought to have chronic, acute, direct and indirect impacts on tropical marine organisms and associated habitats, such as coral reefs, mangroves and seagrasses [21]. However, there remains a significant challenge in understanding the chemical changes and transport mechanisms that get these molecules into the near shore marine environment [12]. Understanding the mode of transport depends on detailed knowledge of the physical environment. For example, the rate of discharge in a coastal region is based on its hydrogeology [22].

A handful of studies have examined the effects of agricultural pesticides on marine organisms. Pesticides, such as organochlorides, organophosphates, and carbamates, can have long-lasting and toxic effects on living organisms due to their slow rate of decomposition and the toxicity of their intermediate breakdown products [22]. Although DDT was banned in the United States in 1973, Singh and Ward [23] found elevated concentrations in the coastal waters of St. Lucia. Since chemical compounds strongly adsorb to soil particles [24], high concentrations have also been detected in sediments. Bioaccumulation of these compounds has been found in animal tissues [19,25,26]. Arukwe [27] found that anthropogenic chemicals disturb reproduction in fish by disturbing the endocrine system.

Pesticides have also been shown to decrease photosynthetic and respiration rates in benthic organisms, such as *Halodule* sp., a common seagrass in the Caribbean [28,29] and corals [30]. Corals have a thin, lipid-rich layer of tissue that rapidly takes up chemical compounds [21] and a symbiotic relationship with an algal host that is maintained through chemical communication. Therefore, coral colonies may be particularly susceptible to pesticides [22] and heavy metals [31]. Chemical pollutants may have negative impacts at the population level since coral reproduction and recruitment are chemically mediated processes sensitive to coastal pollution and changes in water quality [32].

Methods for evaluating pollutants on tropical marine organisms have slowly been developing. Evaluation of chemical stressors includes exposure tests, bioassays, and ecological response analyses at the individual, population, and community levels [21]. Exposure analyses include determining sources, pathways, and concentrations of toxic chemicals in an ecosystem. For example, the form and bioavailability of toxic chemicals in seawater, and the rate of bioaccumulation in an organism's tissues are unknown for many chemical contaminants. More recently, molecular biomarkers have been developed to examine the direct effects of such stressors on coral reef organisms, however results are not yet conclusive and more work is needed to tease out variability and confounding environmental factors [31,33]. Furthermore, the effect of chemical pollutants on processes such as reproduction and recruitment has yet to be determined. Understanding toxic effects at the species-level as well as at the ecosystem-level is critical. Ultimately, linking biomarkers of exposure within an organism to the population or community level will provide the most useful information to managers [21].

While exposure concentrations and fate and transport processes of chemical pollutants have been determined in temperate regions, parallel research in tropical marine systems is in its infancy. Pollution studies in the future need to incorporate three essential components: 1) Understanding of the fate and transport mechanisms for the chemical in the environment, including bioaccumulation, 2) Elucidating the impact on organisms throughout their life cycle with both acute and chronic exposure levels, and 3) Documenting the long-term scale and scope of these impacts on in situ populations of organisms. Population-level changes in more or less-susceptible species will ultimately change the structure of back reef communities.

Community-Level Changes from Stressors

The detection of community-level change in highly variable systems is difficult, especially in complex systems [2]. The burden of proof has been placed on the scientific community to not only document the change, but also to establish the chain of events leading to that change (sources-stressors-symptoms as pictured in Figure 2. Established protocols exist for differentiating disturbance-induced changes from natural community changes and variability due to succession, seasonality, and other natural biological events. These protocols are well represented in the environmental impact assessment literature, and only recently are tied to better understanding the overall system ecology and "system outcome" from anthropogenic disturbance. A quick review of established "disturbance detection" protocols for natural communities follows.

A modified BACI (Before/After and Control/Impact) approach has been used to evaluate catastrophic disturbance events or stressors (e.g. grounding events). The BACI approach relies on the assumption that the impact (disturbance event) will cause a pattern of change in the affected area that varies from the natural pattern of change in an unaffected control location. The original BACI design includes two sampling dates (before and after the disturbance event) at two sites (control and impact). There are some inherent flaws in this original design, including the fact that many BACI studies lack replication of sample sites, often due to the impact of natural and even more so anthropogenic impacts being localized and spatially limited. Furthermore, if the control and impact study sites are arbitrarily chosen, it is possible that inherent differences in the sites will make the two sites naturally differ over time, regardless of whether there was a true disturbance effect. Since the BACI approach was first developed, many modifications have

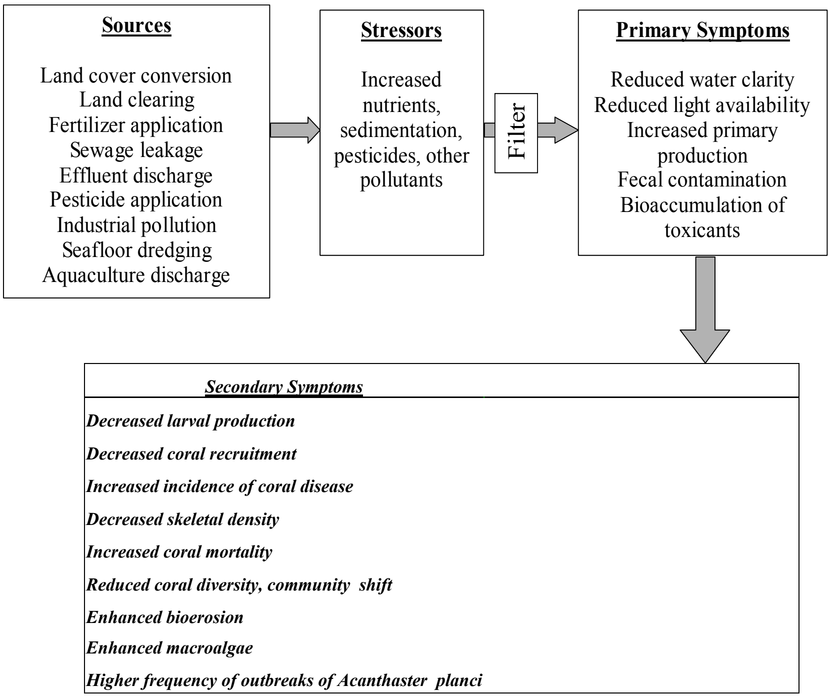

Figure 2: Schema of potential sources, stressors, primary symptoms, and secondary symptoms directly affecting stony corals and coral reef benthos. The "filter" represents local conditions that determine the resistance and resilience of a reef to being affected by terrestrial runoff (from ISRS Briefing Paper #2, 2004).

been suggested in order to correct for interpretational, logistic, and/or statistical problems associated with the original approach. A "model study" of the effects of disturbances on near shore marine communities should contain spatial replication, selection of control sites, temporal replication, and simultaneous sampling of control and impacted sites. The rigors of documenting low-level disturbances or chronic pollution impacts are rarely met in tropical reef systems, with impacts most easily understood in hindsight.

New methods in multivariate analysis of a wide suite of abiotic and biotic factors have been most successful is detecting initial community-level changes from stressors. Thus, the inclusion of multivariate techniques can better elucidate patterns of change, since changes in even one target species will likely affect other components. Some multivariate techniques, such as non-dimensional MDS plots can illustrate patterns (directions) of change among chronological samples. Thus, if there were three pre-disturbance sampling times (labeled A, B, C) and three post-disturbance sampling times (labeled D, E, F) at each sample site, comparing the patterns in the paths of the samples over time may highlight similarities and differences following disturbance impacts. Figure 3 illustrates a hypothetical situation in which an MDS plot shows differences between control and impact sites, indicating a disturbance effect.

Stressors produce community changes first recognized by visual "symptoms" including syndromes in benthic invertebrates, most notably corals and sponges. Syndromes can result in dramatic changes in abundances of dominant species. Detection or documentation of community-level change is accompanied by a presumption of change in ecological function or production of that system. Chronic stress to reef (and back reef) environments can lead to a series of system-altering changes that include: 1) Changes in coastal species abundance and diversity (including local extirpation), 2) Changes in natural community structure, 3) Changes in coastal water quality (or the "dynamic" habitat), and 4) Changes associated with exotic species invasion. Coastal development and alteration by humans are likely the key activity giving rise to stressors in back reef environments. Starting from the removal of native coastal vegetation "buffer zones" to the construction of marinas and finger canals has been linked to the demise of corals throughout the tropical oceans [34-36]. Much of the decline in the growth, recruitment and reproduction of corals is attributed to degradation of water quality or fishing impacts. The synergistic effects of pollution and overfishing can dramatically shift the threshold of stressors, and thus amplify the damage to both populations and communities.

Underlying the conspicuous community of benthos in the back reef environment are the complex and poorly characterized microbial communities. Microbial communities play a pivotal role in transformation of nutrients in a largely oligotrophic system. Microbial assemblages can exert a protective influence on benthic organisms, such as corals. However, short term stressors often shift dominance of microbes, and initiate disease, nutrient limitations or abiotic changes in the environment (e.g. dissolved oxygen depletion). The mechanisms by which stressors affect microbial communities are complex; research has elucidated the diversity of responses from stimulation of population growth, initiation of metabolic changes, or induction of prophage (viruses integrated into the host DNA) or changes in behavior of specific microbial populations within the community [37-39].

Specific microbial communities have evolved in association with macro organisms since their appearance on earth. These relationships have become obligate and complex, particularly with aquatic organisms. Studies by Ritchie and Smith [39] have shown that the microbial communities are coral species specific. In addition, they change when exposed to stressors. The net result of this microbial community change is a loss of the specific protective matrix that had evolved with the coral species, thereby, rendering the coral susceptible to disease. Stressors affecting these symbiotic microbial communities change community structure in one of three ways: 1) The differential stimulation of specific populations; 2) The differential inhibition of specific populations and 3) The introduction of new populations (perhaps pathogens) into the community from the water mass. The net effect is destabilization of the overall community as well as the functional relationship with the host.

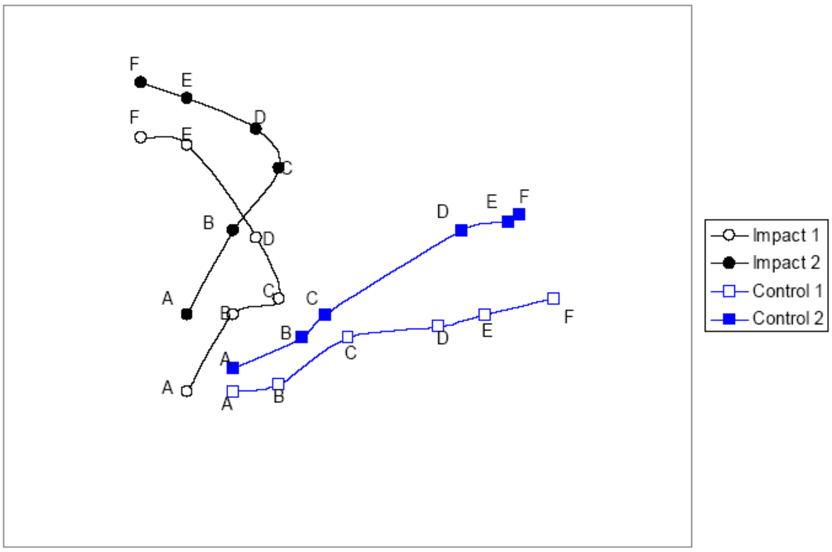

Figure 3: Hypothetical MDS plot showing directionality of chronological temporal replicates (A-F) at two control sites (squares) and two impact sites (circles) before (sample times A-C) and after (sample times D-F) a disturbance event. A line connects the chronological replicates for each unique study site. The MDS shows that prior to disturbance, the four communities had similar patterns and directions of change/ succession over time, while after the disturbance, the impact sites and the control sites varied in their patterns of change.

Recent studies on the function of microbial communities only reinforces the underlying ecological processes, particularly nutrient and energy flux, as critical to community stability, resilience and resistance. The relationship between biological production (ecosystem function) and diversity has become a central focus of environmental science, and must be fundamentally linked to nutrient cycles. Coastal environments represent a model system for examining the impact of anthropogenic disturbance on this balance of species diversity, habitat complexity and ecological function. Central to the ecological function of the back reef is the quality of the medium.

Water quality is fundamental to both species and natural community distribution in nearshore marine environments, and the impact of water quality degradation is complex. Changes in water quality parameters stem from human alterations of coastal hydrology and runoff patterns. Because water quality parameters such as temperature, salinity and turbidity vary naturally with tidal, diurnal and seasonal cycles, changes in natural variability are difficult to document. Documenting changes in coastal water quality would require some knowledge and monitoring of pre-development conditions, but detection still requires the collection of both abiotic and biotic data to document change [2]. Sewage and wastewater discharge are notorious for long-term changes in tropical marine environments [10,11]. Human activities on land inevitably increase nutrient inputs to coastal waters from deforestation, wastewater, fertilizer, and other sources [40,41].

In fact, water quality studies in Montagu Bay and Nassau Harbour, adjacent to New Providence, do not show elevated nutrient concentrations compared to waters adjacent to undeveloped islands [42]. Despite alteration to 100% of the shoreline, with loss of reef and seagrass habitats, the patterns of water quality variability with tides and seasons are not statistically different when compared to lightly-developed islands in a national park. The ability to detect and document changes in inorganic nutrients in tropical nearshore waters is limited to point sampling on tidal, diurnal or seasonal cycles and only extreme values for parameters such as total nitrogen appear higher in boxplots constructed to capture water quality variability. Most studies have documented the ecological changes to coral reefs rather than establishing pollution sources, quantities and pathways for non-point, land-based pollution [43,44]. The water-quality monitoring program in the Florida Keys National Marine Sanctuary involves a massive sampling effort of over 1400 stations throughout the Florida Keys. This program is only beginning to characterize water quality parameters for Florida Bay, the nearshore Keys waters, and the Keys reef tract, with the only obvious water quality degradation near, and in, dredged residential and commercial canals systems. Detailed water quality monitoring is essential for remediation of problems associated with coastal development, but not necessary for the identification or prediction of ecological impacts. The most significant water quality impacts of coastal development that can be documented are likely to be manifested after severe storms and hurricanes. Anthropogenic alteration of the coastal zone will exacerbate natural disturbances, primarily in the scope and severity of nutrient and sediment transport from land to sea.

Advances and Future Challenges in Stressor Characterization and Detection

New research initiatives are helping to move beyond the basic characterization of back reef environment to understanding the "rates and fates" of key nutrients and microbial complexes. Stable nitrogen isotope analysis is employed to identify this near shore response to anthropogenic nutrient loading. Nitrogen isotope ratios ($^{15}N/^{14}N$ usually expressed as $\delta^{15}N$) can be used to discriminate between marine- and terrestrial-based organic matters and, therefore, to detect terrestrially formed organic matter from sewage effluent in the marine environment.

New methods in detection of pathogens are critical in limiting chronic stressor impacts to wide spread changes in the health of benthos (G. Smith, pers. comm.). These new methodologies that examine the details of nutrient and pathogen flux to back reef environments are still critically dependent on understanding the historical ecology and long-term environmental changes that have already occurred in tropical island systems.

A central research gap is our understanding of variability and fluctuations in benthos and fish under "normal" conditions, particularly the role of the "normal" micro biota in the function of the back reef ecosystem. Threshold levels of certain stressors (e.g., temperature, nutrients, salinity, etc.) that lead to significant change in populations need to be determined. Researchers have begun to look at new ways of modeling the complex interactions of several stressors co-occurring, and how this synergy changes thresholds of mortality and disease in populations. Management demands will require better approaches to understanding restoration needs and the significance of large reductions of species from the back reef environment (e.g., conch, *Diadema*, any commercially exploited species). Advances in research will utilize a multi-disciplinary approach across the scale of single organism's response to regional systems response.

Conflicts and Management Challenges

For the countries around the world with coral reef resources, sustainable tourism is often part of a national vision for natural resource management. Many of the decisions for locating development are based on a relatively narrow view of the coastal landscape. Although there has been much policy discussion of "sustainable development" of island systems, there remain no real ecological criteria to judge sustainability on islands as isolated and highly variable landscapes. The coastal environment is already fragmented by historical or unplanned alterations. The discussion of the role of marine protected areas has led scientists to look at a network of areas to be set aside as "ecologically intact", meaning no fishing. These "intact" areas can be key control sites for long-term monitoring and disturbance detection. However, this "intactness" and ecological functionality of even protected back reef environments may be, in the long-term, challenged by scales of stressors beyond local sites, regions or even single oceans.

Although we understand the basic ecology of tropical marine systems in a general sense, researchers have rarely looked at integrated processes across the shoreline, particularly in terms of ecosystem function. Protected areas and fisheries reserves adjacent to developed coasts and cities will have an important role in both education and remediation. Restoration of coastal areas that have been altered by development, dredging or loss of wetlands can be expensive, and demonstration projects that are practical outside the funding environment of the US need to be established in conjunction with coral reef research efforts. Restoration and remediation of many coastal environments is inevitable with population growth and the growing need for ecological services. The conservation of coastal fisheries resources as well as the protection of human life and property will motivate the political will to tackle restoration projects. Scientists may need to present information in a more integrated package not dependent on "change-no change" hypothesis to motivate the stakeholders.

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