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Ocean &
Coastal
Management

Ocean & Coastal Management 46 (2003) 261–276

www.elsevier.com/locate/ocecoaman

Biological indicators in the Caribbean coastal zone and their role in integrated coastal management

Dulcie M. Linton*, George F. Warner

Centre for Marine Sciences, University of the West Indies, Mona, Kingston 7, Jamaica

Abstract

Caribbean coastal ecosystems are increasingly being threatened by natural and anthropogenic factors. The scale of these factors is at local, national, regional and global levels. Threats include the effects of fisheries and extraction, eutrophication, siltation, and pollution as well as global climate events such as El Niño and global climate change. Integrated coastal management (ICM) should clearly demonstrate the adverse effects of environmental impacts, thus justifying the need for mitigation and should evaluate the success of management efforts. ICM requires robust indicators that gauge the ‘health’ of the coast in relation to environmental, social and economic activities. Biological indicators (bioindicators) offer a signal of the biological condition in an ecosystem. Using bioindicators as an early warning of pollution or degradation in an ecosystem can help sustain critical resources. Biological indicators in the Caribbean are focused around particular ecosystems, especially coral reefs, seagrass beds and mangrove forests and include a range of biological parameters relating to particular species, groups of species and biological processes. The use of these indicators is critically reviewed and the presence or absence of a relevant framework for their use in Caribbean ICM programs is discussed.

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1. Introduction

Integrated coastal management (ICM) brings together all those involved in the development, management and use of coastal resources, and those whose activities affect these resources, within a framework that facilitates the cohesion of their

*Corresponding author. Fax: +1-876-977-1033.

E-mail address: dmlinton@uwimona.edu.jm (D.M. Linton).

interests and responsibilities and encourages sustainable management [1]. In a geographical sense, ICM embraces the shoreline, nearshore and coastal waters and also the inland watersheds because of the potential impacts on coastal systems from land-based activities.

ICM requires robust indicators that gauge the 'health' of the coast in relation to environmental, social and economic activity allowing for the management of the impacts on resources so that any adverse effects are minimized. An indicator is a sign or signal that relays a complex message in a simplified and useful manner providing insights about a trend or event that cannot be directly observed. Indicators are essential tools for monitoring the state of the coastal environment. They can inform managers and policy makers of the effectiveness of strategies in achieving sustainability and need to be based on rigorous scientific, social and economic research.

Coastal indicators can be used in two overlapping ways: as a means of communication and as a means of measuring. They can be used to monitor conditions of the coastal environment on an ongoing basis to assess impacts and requirements for management and to monitor the effectiveness of an ICM process. Thus, indicators can increase understanding of important issues, assess conditions and trends, project trends, compare conditions in different geographical areas, measure performance and results of policies or actions, inform decision-making, and show the connections between environmental, social and economic concerns.

One subset of environmental indicators is that in which the living component of the environment is used to reflect the state of the environment in response to human-induced stresses and the efforts of the ICM program to reduce or reverse these. This group of indicators is called biological indicators or bioindicators and includes the plants and animals found in the ecosystem. By displaying changes in their presence/absence, condition, behavior and numbers they can provide information about the health of a specific ecosystem. Where definite patterns exist in the responses of the biological community to stress, finding these patterns can show what types of stress are present, and sometimes the source(s) of those problems.

Stress is generally thought to induce both quantitative and qualitative changes in the structure and functioning of communities. Structural changes are usually assessed by analyzing species diversity and/or composition. Functional changes include measures such as photosynthetic activity, growth rate and fecundity, and are not monitored as frequently as structural changes.

Stress in aquatic systems, such as that caused by a change of pH in the environment, is thought to alter the biochemical processes of the organisms that make up communities, thereby altering the way the organisms function. By measuring the rates of various activities within organisms (e.g. growth rates, enzyme activity), the effects of stress on the functioning of communities can be highlighted. Stress can modify the structure of communities by altering the species complement, relative abundance of individual taxa, diversity and evenness of the community. Generally, stress is believed to cause a reduction in diversity and to increase dominance by one or a few tolerant species.

Biological assessment of an aquatic community depends on the ability to define, measure, and compare the relative biological integrity (the condition of a community relative to one inhabiting a pristine or minimally impacted habitat) between similar systems or within the same system over time. Measures such as community structure and function, including species richness, species abundance and indicator species are used [2]. Typically, the biological integrity of a natural community is described by expressions or numerical values called biocriteria. The process of biocriteria assessment [3] includes the conversion of monitoring data to biological indices for comparison with a minimally impaired reference site. The findings can then be fed into the ICM process.

Bioindicators are thought to be useful to the ICM process for a number of reasons. They may provide early warning of pollution or degradation of an ecosystem, alerting managers to halt or mitigate the impact before critical resources are lost. They only assess pollutants that are bioavailable and have adverse effects on biota, and therefore those thought to be important [4]. Unlike physical measures, which may only be useful during an impact, biological responses are cumulative and observable after the event that caused them. Thus episodic impacts become apparent through their lasting effects on the biota. Similarly, low intensity, chronic impacts (e.g. low-level pollution) may be undetectable by physical or chemical measures but the cumulative biological effects may be easily detectable. Bioindicators can help to assess synergistic or additive relationships among impacts, which is an important consideration in light of the typical combination of impacts impinging on most coastal systems in the developing world [5].

Bioindicator species should normally be abundant throughout the study area and should be easy to sample in an objective and quantitative manner. Ideally, they should indicate gradations in the response relative to the amount of stress. Optimally, they should show response specificity, so that a particular impact on the ecosystem can be identified. Typically, the causes of change in an ecosystem cannot be specifically linked to any one factor. For example, bleaching events in corals are thought to be as a result of any one or a combination of high temperature, fluctuating salinity, insolation and sedimentation.

To facilitate the participation of the widest cross-section of individuals, bioindicators should have a stable taxonomy that can easily be taught to non-specialists. Ideally they should not be species exploited by humans, as this would confound any trends in monitoring their abundance [6–8]. Exceptions include measures of the capacity of an ecosystem to sustain exploitation of a biological resource, such as a fish stock.

There are some potential problems with the use of bioindicators in ICM. Natural fluctuations are inherent in complex systems such as coral reefs and so monitoring abundance of a particular species may be inconclusive or even misleading [9]. Monitoring multi-species assemblages may alleviate this problem, as similar population responses of several species should reduce noise associated with natural fluctuations in numbers of a given species [10]. Monitoring community structural changes through abundance and diversity measures can be insensitive, so functional measures such as growth rate, fecundity measures (e.g. size at first reproduction,

mean number of eggs/female, recruitment), and size frequency distribution can reveal changes that abundance and diversity may miss.

The selection of the most appropriate bioindicators for a particular assessment or monitoring program depends on the objectives of that program. Management objectives and methods vary greatly between islands, countries and regions, depending on the status of the ecosystems, the management structure in place and socioeconomic and political conditions. There is no one bioindicator species that will suit all programs. Biomonitoring programs should be cost-effective in achieving desired goals, employ scientifically sound, easily learnt and adaptable methodologies and require relatively inexpensive equipment. These features will increase the likelihood of biomonitoring being adopted in ICM programs, particularly in developing countries.

2. Bioindicators for monitoring Caribbean coastal marine ecosystems

Caribbean mangroves, seagrasses, and coral reefs are closely associated. They exist in a dynamic equilibrium influenced by contact with land [11]. Sediments and nutrients, carried by freshwater runoff, are first filtered by coastal forests, then by mangrove wetlands, and finally by seagrass beds. The existence of coral reefs is directly dependent upon the buffering capacity of the shoreward coastal ecosystems which help to create the oligotrophic conditions under which coral reefs flourish. Coral reefs, in turn, buffer the influence of the open ocean on the land.

Within the wider Caribbean region, there is general agreement that coastal marine systems are changing for the worse. The ultimate causes are population growth and human-induced changes both in the coastal zone and in the upstream watersheds. Mangroves are removed for lumber, charcoal, aquaculture, and land reclamation. Seagrasses are being dredged for harbors or for beaches in hotel development and deforestation inland is leading to increased runoff and sedimentation. Nutrients from sewage and agricultural runoff increase eutrophication, and coastal fish stocks are being depleted [12,13].

ICM is required to arrest the multiple impacts on the Caribbean marine environment. Scientists have for a long time recognized the importance of bioindicators in ICM in the Caribbean. While their use has not been formalized, the requisite research and results have indicated the suitability of a number of organisms as early warning signals of ecosystem degradation. Some of these will be examined here and their ability to indicate changes in the status of tropical marine environments discussed. Because of the overlapping nature of the stresses to coastal systems, this review is organized into two very broad habitat divisions: those sheltered, nearshore systems mainly with particulate or soft substrata, and the coral reef systems, mainly with hard substrata. Recommendations are then made for further development and inclusion in ICM programs.

2.1. Embayments, harbors and mangroves

Impacts on nearshore environments include eutrophication (enrichment with dissolved forms of nitrogen and phosphorus and other plant nutrients) and other pollution from a range of sources including sewage, shipping, industry and agriculture.

2.1.1. Water column

Planktonic algae have been used as bioindicators of water quality for a long time. Phytoplankton chlorophyll-*a* has been used as an estimate of trophic status in aquatic systems and is a good indicator of nutrient loading by nitrogen and phosphorus. A better understanding of the mechanisms and trends of phytoplankton successions or “blooms” and their interactions with human activities may play an important role in the monitoring of coastal eutrophication.

Phytoplankton population dynamics and chlorophyll-*a* have been used as indicators of deteriorating water quality, specifically nutrient loading (nitrogen and phosphorus), in Kingston Harbour, Jamaica, for more than 30 years [14–16]. Some of the possible effects of eutrophication on phytoplankton populations are successions in the species composition and changes in abundance or production. The use of the planktonic community and traditional water quality indices to establish a new baseline of eutrophication in Kingston Harbour, Jamaica, 20 years after initial ecological assessments was evaluated [17]. The conclusion was that the planktonic community provided the most reliable index of increased eutrophication and changes in water quality. Physical and chemical variables were less reliable, indicating no change and significant but erratic change, respectively. Plankton biomass in 1992–3 was 5–10 times greater than in 1971, while zooplankton abundances were 4 times greater. Community composition in both cases was altered recording fewer taxa than previously found.

In another study, Hoilett and Webber [18] showed that phytoplankton biomass and the abundance of a particular type of zooplankton copepod were related to the level of eutrophication in mangrove lagoons in Kingston Harbour. The phytoplankton community was again a stable, sensitive, reliable and efficient indicator of water quality in mangrove lagoons, with an eight-fold increase in biomass in more eutrophic conditions.

2.1.2. Benthic macrofauna

The clearly defined response of the European intertidal gastropod mollusc *Nucella lapillus* (dogwhelk) to tributyltin (TBT) pollution from anti-fouling paints on ships is an extremely sensitive indicator of exposure to this chemical. Responses are at the individual level and include imposex, the imposition of male sexual characteristics on females, leading to effective sterility, or at the population level with reduction in juveniles, few females and eventual population disappearance in badly contaminated areas [19,20]. Close relatives of *N. lapillus* occur in the Caribbean and can be expected to respond similarly.

2.1.3. Mangrove forests

Productivity measures (leaf litter g/m²/day) and percentage cover were useful in distinguishing mangrove forests impacted by eutrophication [21]. Productivity decreased with increasing levels of eutrophication, while percentage cover increased. Mangrove forest species composition differed with eutrophication levels, tending towards monospecific stands of *Rhizophora mangle* in less eutrophic conditions and a mixed species composition, dominated by *Laguncularia racemosa* at the heavily impacted site.

In Trinidad, local populations of red mangrove (*Rhizophora mangle*) displayed a high incidence of mutations (evidenced by chlorophyll-deficient or albino plants) due to elevated levels of mercury in the underlying sediments [22]. The mercury contamination was restricted to an area near a roost of scarlet ibises and was caused by the birds feeding elsewhere in mercury contaminated sediments. It was suggested that the red mangrove has life cycle characteristics (vivipary and self-pollination) which make it a useful in situ mutagen bioassay for tropical coastal environments.

2.1.4. Mangrove root sessile community

Studies of bryozoan communities at various locations in and around Kingston Harbour indicated that species composition and diversity may be affected by environmental stress signified by poor water circulation, eutrophic water, widely fluctuating salinity, suspended solids, high temperatures and widely varying dissolved oxygen [23]. Sites that were more impacted had fewer species of bryozoans, all of which had a creeping growth habit. Salinity appeared to have been the most important factor influencing the abundance and distribution of bryozoans. One bryozoan species of the genus *Bowerbankia* was found only at highly impacted sites, where the salinity values fluctuated widely due to fresh water inputs, indicating that this species may be adapted to surviving conditions of varying salinities.

Oysters are sessile filter feeders found in the mangrove root community. The temperate European flat oyster (*Ostrea edulis*) and the tropical mangrove oyster (*Crassostrea rhizophorae*) have been shown to be sensitive to hydrocarbon pollution [24].

2.1.5. Seagrass beds

Seagrass populations in and around Kingston Harbour exhibited an increase in leaf productivity rates and leaf area but a reduction in shoot density and total biomass with increasing eutrophication levels [25]. Comparison with a study conducted 10 years earlier indicated an overall decline in shoot biomass and density parameters suggesting that eutrophication levels in the Harbor have increased with time. It was concluded that because seagrass populations are stationary, they respond cumulatively to continued eutrophication, such that they can be used as a signature of long-term water quality. Excessive nutrient inputs to tropical seagrass meadows have been found to increase macroalgal epiphyte loads on seagrass blades [26] by decreasing irradiance, lowering seagrass productivity [27] and ultimately causing seagrass die-off [28].

2.2. Coral reef habitats

Coral reefs flourish in clean, oligotrophic waters and so can be stressed by relatively low levels of eutrophication, which might be normal for a mangrove forest. Other sources of stress include sediments, organic loading, elevated water temperature and direct physical damage. The indirect effects of human exploitation of other reef resources (e.g. fish) may also be deleterious to corals.

2.2.1. Macroalgae

The relative dominance of sessile primary producers in tropical marine ecosystems is controlled by complex biological interactions between competition and grazing [29] and affected by abiotic factors such as nutrient availability [30]. Nutrient inputs from human activities, particularly in the form of N and P, have shifted the balance on coral reefs in favor of the more opportunistic species of macroalgae, causing overgrowth and eventual mortality of corals. Sustained eutrophication causes long-term decline in biotic diversity and fisheries production of coral reefs [31]. Researchers such as Goreau [32] and Lapointe [33] have reported macroalgae blooms or overgrowth on Jamaican fringing reefs due to a combination of reduced herbivory and to increased fertilization by nutrients derived from inappropriate land and sewage management practices. Blooms of the macroalgae *Chaetomorpha linum* and *Lyngbya* sp., overgrowing the fore reef communities on fringing reefs in the Negril Marine Park, Jamaica in August 1998, followed the onset of the summer wet season and were probably due to nutrient inputs from sewage or agricultural runoff. Discovery Bay, Jamaica, suffers from seasonal *Chaetomorpha linum* blooms in the warmer summer months, indicative of ground-water NO_3^- enrichment of the fore reef [33]. Dominance of reefs by fleshy benthic algae rather than by corals indicates either nutrient loading [33] or lack of grazing organisms [34].

Cyanobacterial blooms, thought to be in response to low water quality, have been observed to completely cover large areas of reefs in the Florida Keys, leading to the eventual death of the original benthic cover, especially the soft corals and gorgonians. Richardson [35] and Thacker and Paul [36] were unable to find any significant relationship between phosphorus or nitrogen availability and cyanobacterial abundance in Guam but indicated that they may have missed pulses of nutrient input from streams and shore runoffs after rainfall, since measurements were not done very frequently.

2.2.2. Corals

Percent hard coral cover is a widely used reef monitoring parameter, calculated from data using transects. Reductions in percent cover are thought to signal stressful environmental conditions for corals. This is a major parameter used by the Caribbean Coastal Marine Productivity Program (CARICOMP) and other monitoring programs such as Atlantic and Gulf Rapid Reef Assessment (AGRRA), Caribbean Planning for Adaptation to Climate Change Program (CPACC), and Reef Check. Measures of percent cover do not provide the early warning signals

necessary to mitigate impacts. By the time benthic census methods have detected differences in coral cover on reefs, corals have already died and efforts must now be aimed at preventing further damage and death. Even the best census methods cannot identify the reason why the reef community has changed, they can only detect differences. Similarly, coral mortality indices, which measure the proportion or ratio of live and dead hard coral colonies and the proportion of dead surface on individual live colonies, can only be used as indicators of past and/or continuing stress, but do not provide early warning signals.

Several coral-related measures have been used as indicators of water quality. These include coral growth rates, productivity, calcification, fecundity and recruitment. Research results for growth rates have been conflicting with some researchers suggesting a decline in growth with environmental stress [37,38] while others suggested the opposite [39]. Productivity and calcification can be measured from changes in the oxygen concentration and pH of seawater flowing across a reef flat and may be used as indicators of water quality [40]. Carricart-Ganivet and Merino [41], from work done with *Montastraea annularis* in the Southern Gulf of Mexico, suggested that as corals experience harsher environments of higher turbidity and sediment load, they respond by extending their skeleton more with the same or less calcium carbonate, with a concomitant reduction in skeletal density. Corals are thought to be good indicators of the metal content in the marine environment. An important fraction of the metals in the marine environment is associated with particulate organic matter [42]. Corals incorporate organic material in the pores of their skeleton [39,43]. In so doing they incorporate seawater contaminants such as trace metals and phosphorus into their skeleton during normal growth [44–46], making them faithful long-term recorders of environmental water quality.

Tomascik and Sander [47] suggested that coral fertility is decreased on reefs subject to increased eutrophication. Runoff and sedimentation may prevent successful reproduction and recruitment in corals and other reef organisms [48]. Recruitment intensity itself may be a useful measure to inform managers whether physically damaged reefs may require coral transplantation or whether they can be left to recover naturally [49]. Physical damage to corals, in the form of broken coral rubble, is used as an indicator of diving over-capacity in the Red Sea [50].

The frequency and severity of occurrences of coral diseases may indicate environmental stress, since stress may cause a decline in natural immunity. However, some coral diseases appear to be novel so may indicate the introduction of exotic micro-organisms. White band disease, in particular, is thought to be new and has played an important role in Caribbean reef degradation [51]. A widespread disease of sea fans, observed throughout the Caribbean, was associated with the fungus *Aspergillus* sp., a genus typically inhabiting terrestrial soils. Infection by *Aspergillus* was thought to occur by hyphae associated with sediment particles, suggesting that the disease may be linked to increased turbidity from runoffs [52].

In the case of bleaching, the appearance measures the extent of physical stressors such as water temperature, salinity and insolation [53]. Surface temperature in excess of 30°C is most commonly indicated. Bleaching occurs through loss of zooxanthellae but considerable loss may occur before the coral tissue becomes noticeably pale, thus

reducing the accuracy of the indicator. However, widespread and severe bleaching is an obvious, if crude, indicator of stressful conditions.

2.2.3. Sessile reef community

Data from transects of hard corals, sponges, gorgonians and benthic algae are used to describe the reef community. Diversity indices can be calculated and comparison of their relative values allows a classification of environmental conditions on the reef. Foraminifera have proven to be a very useful group of paleoenvironmental indicators. Their shells are important sediment constituents, they are small and widely abundant, different taxa have evolved to exploit most environments, substrates and nutritional modes in marine systems and their shells morphologically and geochemically record environmental conditions. They show strong predictable responses to eutrophication stresses shifting from dominance by large algal-symbiotic species in more oligotrophic conditions to assemblages characterized by small heterotrophic species [54]. The marked response of foraminifera to nutrient enrichment makes them highly suitable for use as bioindicators of eutrophication. A user manual for Foraminifera in coral reef assessment has been developed by Crevison and Hallock [55]. Called the “FORAM” (Foraminifers in Reef Assessment and Monitoring) Index, it is based on 30 years of research and utilizes foraminiferal assemblages from surface sediments of reef-associated environments. The index can provide resource managers with a simple metric for determining the suitability of benthic environments for communities dominated by algal symbiotic organisms, such as reef corals.

Sessile invertebrates, associated with corals, have been suggested for use as bioindicators. These include zoanthids, hydroids and tunicates. Almost all coral associates are filter-feeding heterotrophs and would therefore be expected to increase in water with elevated nutrient concentrations. Birkeland [56] reported increased numbers of heterotrophic suspension feeding organisms on reefs in high productivity waters. Maragos et al. [57] reported shifts in benthic communities from autotrophic to heterotrophic under sewage stress. Similarly, the density of coral associates on massive corals increases with organic loading. Stressed corals will be less able to protect themselves against settlement and overgrowth by these organisms [58].

Increasing densities of coelobites (reef cavity dwellers), especially those boring in coral skeleton such as bivalve molluscs and sponges, have been correlated with the productivity and sometimes the eutrophication of tropical coastal waters [59]. Most bioeroding organisms are heterotrophic suspension feeders and may therefore respond positively to increasing levels of eutrophication. Work done by Holmes [60], in Barbados fringing reefs revealed an increase in the rate of bioerosion of *Porites porites* rubble by clionid sponges along an eutrophication gradient. The abundance of branching corals was also positively related to the frequency of boring sponge invasion. Hunte and Allard [61] found that the abundance of *P. porites* on Barbados fringing reefs was higher at increased eutrophication levels. Branching corals such as *P. porites* rely on fragmentation as their principal mode of propagation. It is thought that fragmentation occurs more easily under eutrophic conditions. They suggested that increased bioerosion may be partly responsible for community shifts towards

branching corals in polluted waters. Rose and Risk [62] found similar results with *Cliona* infestations of live *Montastrea cavernosa* heads in Grand Cayman. Risk et al. [63] suggested that distinctive cross-continental shelf patterns of bioerosion (by sponges and bivalves) in *Porites* and *Acropora* on the Great Barrier Reef were explained primarily by increasing organic input with proximity to the mainland.

Choi [64] showed that coelobites in rubble, such as foraminifers, bryozoans, tunicates, molluscs, sponges and serpulid worms, decreased in abundance with proximity to an off-shore oil drilling well head. A numerical index was developed with points assigned for presence/absence and abundance of various coelobites in each piece of rubble.

2.2.4. Macroinvertebrates

A generalized ecosystem shift on pollution-stressed reefs from coral dominated symbiotic organisms towards those dominated by heterotrophic macroinvertebrates, may be an indication of increased water column productivity and eutrophication. Scavengers and filter feeders including barnacles and crabs may become common. Abundance measures are included in several current monitoring schemes [65,66].

In the Caribbean, densities of sea urchins are often measured since these animals are known to be important grazers, removing algae that would otherwise compete for space with corals [67]. Increased urchin density, especially of the long spined sea urchin *Diadema antillarum*, is taken as an indicator of potential coral recovery [68].

Stomatopod crustaceans are benthic reef dwellers that inhabit shallow reef flats and seagrass communities and live in cavities in hard substrata such as coral rubble. They are particularly suited as bioindicators of reef health due to their abundance and ubiquity in the Caribbean and Indo-Pacific, their sensitivity to pollution and the ease of sampling their populations [69]. Indonesian stomatopods showed consistent, graded responses to increasing levels of pollution, including decreases in overall abundance, probably due to recruitment failure through toxicity or behavioral changes of larvae. Stomatopods were used as bioindicators in a 5-year study in Panama after the Galeta oil spill in 1986 [70]. Results indicated that they responded to heavy oiling by an initial decrease in abundance and increasing growth rate, followed by reduced recruitment that continued for more than 2 years.

Amphipods show acute and chronic sensitivities to pollutants and toxicants as well as altered behavioral responses to sublethal levels of a variety of compounds. The use of amphipods in environmental monitoring has been limited to the few temperate regions where long-term taxonomic and natural history investigations have been undertaken. In California, amphipods are currently used as primary biological monitors at sewage outfalls. Monitoring programs incorporating amphipods have been used to assess the environmental effects of oil spills in the Persian Gulf, Alaska, and Panama. California and the Environmental Monitoring and Assessment Program (EMAP) of the EPA have designated several species of amphipods as bioassay organisms for sediment toxicity tests in soft-bottom environments [71]. Amphipods are so useful as bioindicators that US Government agencies now require their identification to the species level in permitting operations such as oil leases and outfalls. Their incorporation into bioassessment programs on coral reefs is

dependent upon completion of comprehensive coastal resource inventories and taxonomic surveys [72].

2.2.5. *Commercially valuable fish species*

Some monitoring programs (e.g. Reef Check) include censusing abundance of commercially valuable fish species to measure fishing pressure. Target groups include food fishes (e.g. Serranidae, Haemulidae) as well as aquarium fishes (e.g. Chaetodontidae) [66].

Indicators of overfishing are well known to scientists in the industry. In mixed fisheries such as those on coral reefs, these indicators include small size of target species and a reduction in the proportion of preferred to less preferred species in the catch. Another measure of the health of fish stocks and of overfishing is a decrease in overall catch per unit effort [73]. Data from the Fisheries Division of Jamaica indicate that yields from the north coast fisheries are 5–10 kg/boat day compared to 20–50 kg/boat day on the south coast [74].

2.2.6. *Chaetodontid fish*

Chaetodontids or butterfly fish are thought to provide effective early warning signals of deterioration of coral reefs. The simple hypothesis behind their use as coral reef bioindicators is that they feed on corals and so if corals decline then butterfly fish populations should also decline or change their behavior in response. Results have not been conclusive in linking changes in chaetodontid populations with declines in corals, possibly because butterfly fish may be exploited for the marine aquarium trade. Nevertheless, they have been incorporated into reef monitoring programs in SE Asia [75,76] and a manual for their use in reef monitoring has been developed by Crosby and Reese [77].

3. Conclusions and recommendations

The research reviewed above shows the tremendous potential that exists for the use of bioindicators in ICM in the Caribbean. Clearly, the usefulness of any particular indicator depends on the determination of an appropriate baseline to allow comparison. Marine bioindicators, at best, respond predictably to a specific stress, however, most give a more generalized indication. Graded response curves are rarely available and await further research. For developing countries, bioindicators that require minimal scientific training and equipment may be more successful, and these are likely to show generalized responses.

The following bioindicators have already been developed to some degree. As indicated below, they do not all give unambiguous signals, but they appear to be useful and suitable for wide application. They require adapting to local conditions, and training for those gathering and analyzing the data:

- Phytoplankton biomass: as an indicator of eutrophication, particularly in sheltered lagoons and harbors.

- Foraminifera species composition: a user manual for Foraminifera in Reef Assessment and Monitoring (FORAM) Index has been developed and is available for use.
- Seagrass productivity measures and algal epiphyte loads on seagrasses: as indicators of eutrophication.
- Gastropod imposex: as a very sensitive and well-developed indicator of exposure to tributyltin (TBT), and thus of commercial shipping activity.
- Percent cover by hard corals: as a general indicator of stress—foundational to all coral reef assessment programs and critical for establishing baseline data.
- Coral bioeroders, especially sponges: as indicators of increasing eutrophication and/or organic loading on reefs.
- Bleaching of corals: as an indicator of stress, but not accurate or specific.
- Contaminant uptake by coral skeletons: provides a past history, but not necessarily a present signal.
- Coral mortality and broken coral: indicators of past stress, but do not necessarily identify the cause.
- Stomatopod biomonitoring: for pollution detection.
- Chaetodontids: a manual for reef monitoring has been developed.
- Fisheries or fish survey data: for detecting over-exploitation.

Other potential bioindicators of generalized environmental stress require further research to determine whether they are effective and likely to provide unambiguous signals of particular stresses. These include:

- Composition and structure of the sessile community on mangrove roots.
- Coral disease frequency and intensity.
- Growth rates of corals and other reef biota.
- Productivity and calcification of reefs.
- Measurements of reproductive and recruitment success of corals.
- Various organisms, such as amphipods.

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