FORAMINIFERA AS BIOINDICATORS IN CORAL REEF ASSESSMENT AND MONITORING: THE FORAM INDEX

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Abstract. Coral reef communities are threatened worldwide. Resource managers urgently need indicators of the biological condition of reef environments that can relate data acquired through remote-sensing, water-quality and benthic-community monitoring to stress responses in reef organisms. The "FORAM" (Foraminifera in Reef Assessment and Monitoring) Index (FI) is based on 30 years of research on reef sediments and reef-dwelling larger foraminifers. These shelled protists are ideal indicator organisms because:

- Foraminifers are widely used as environmental and paleoenvironmental indicators in many contexts;
- Reef-building, zooxanthellate corals and foraminifers with algal symbionts have similar water-quality requirements;
- The relatively short life spans of foraminifers as compared with long-lived colonial corals facilitate differentiation between long-term water-quality decline and episodic stress events;
- Foraminifers are relatively small and abundant, permitting statistically significant sample sizes to be collected quickly and relatively inexpensively, ideally as a component of comprehensive monitoring programs; and
- Collection of foraminifers has minimal impact on reef resources.

USEPA guidelines for ecological indicators are used to evaluate the FI. Data required are foraminiferal assemblages from surface sediments of reef-associated environments. The FI provides resource managers with a simple procedure for determining the suitability of benthic environments for communities dominated by algal symbiotic organisms. The FI can be applied independently, or incorporated into existing or planned monitoring efforts. The simple calculations require limited computer capabilities and therefore can be applied readily to reef-associated environments worldwide. In addition, the foraminiferal shells collected can be subjected to morphometric and geochemical analyses in areas of suspected heavy-metal pollution, and the data sets for the index can be used with other monitoring data in detailed multidimensional assessments.

Keywords: bioindicators, coral reefs, Foraminifera, zooxanthellae, algal symbiosis

1. Introduction

Human activities are changing environmental conditions on a global scale. Roughly half the Earth's land area has been transformed or degraded (Vitousek *et al*., 1997). Human activities have effectively doubled the annual transfer of nitrogen from the atmospheric pool of N_2 to biologically available fixed nitrogen (Schnoor *et al*., 1995). Much of this fixed nitrogen, along with nitrous oxide gases from burning of fossil fuels (Prinn *et al*., 1990), is washed into aquatic systems by rain. As a result of strato-

Environmental Monitoring and Assessment **81**: 221–238, 2003.

spheric ozone depletion, the intensity of biologically damaging ultraviolet radiation (UV_b) at 20° N latitude between April and August now exceeds the June 1969 (summer solstice) maximum (Shick *et al*., 1996). Carbon dioxide concentration in the atmosphere has increased by nearly 30% since the beginning of the Industrial Revolution (Shimel *et al*., 1995), with impacts ranging from global climate change to changes in ocean chemistry that inhibit calcification.

The U.S. Environmental Protection Agency's (EPA) Environmental Monitoring and Assessment Program (EMAP) was created to develop and monitor indicators of pollution exposure and habitat condition. Objectives are to determine the magnitude and geographic distribution of resources that are adversely impacted by pollution and other environmental stresses (Messer *et al*., 1991). Coral reefs are among the ecosystems most threatened by human activities. Bryant *et al*. (1998) estimated that nearly 60% of the Earth's coral reefs are threatened by relatively local impacts including nutrients and other chemical pollutants, sedimentation, destructive fishing practices, and shipping. An assessment of the status of the world's coral reefs in 2000 concluded that more than one quarter have been lost (Wilkinson, 2000), about 15% to mortality following 1997–98 mass bleaching events. Risk (1999) noted that resource managers have monitored water quality and reef conditions for decades but they lack bioindicators that can link those measures to meaningful efforts to preserve remaining reef resources. Attempts to interpret water-quality data continue to be confounded by the reef community's ability to sequester nutrients, making them unavailable to monitoring yet readily effective in inducing community change, an enigma recognized by Laws and Redalje (1979) but widely misunderstood (Risk, 1999).

This paper utilizes EPA "Evaluation Guidelines for Ecological Indicators" (Jackson *et al*., 2000) to present a simple index, the FORAM (Foraminifera in Reef Assessment and Monitoring) Index (FI), based on foraminiferal assemblages from surface sediments. The FI is intended to provide resource managers with a measure, which is independent of coral populations, to determine whether water quality in the environment is sufficient to support reef growth or recovery. A major advantage of foraminifers in reef assessment is their short life span, as compared with long-lived reef-building corals. Foraminiferal assemblages can potentially facilitate differentiation between long-term reef decline associated with declining water quality and temporary reef decline associated with episodic mortality events (Cockey *et al*., 1996).

2. Conceptual Relevance

2.1 RELEVANCE TO ASSESSMENT

The FI applies historic observations that healthy coral reefs had abundant mixotrophic larger foraminifers (e.g., McKee *et al*., 1956; Hallock 1981a, 1988), which were important sediment constituents. On coral reefs that are subject to

significant nutrification (i.e., increase in nutrient flux that results in change in biological community structure), with or without increased terrigenous sedimentation, populations of smaller heterotrophic foraminifers proliferate and their shell numbers overwhelm those of declining larger foraminifers (Hirshfield *et al*., 1968; Cockey *et al*., 1996).

Unfortunately, over the past 25 years, reef-building corals have declined nearly worldwide in response to a variety of factors unrelated to nutrification, including new diseases, bleaching in response to temperature stress, and physical impacts such as hurricanes and ship groundings. Coral reef communities are subject to a myriad of stresses and are declining from most of them. Thus, it is critical to have an indicator of water-quality conditions that will support reef development, even in the absence of healthy coral populations following mass mortality events. Cockey *et al*. (1996) argued that larger foraminiferal populations, which are immune to coral-specific diseases and recover much more quickly from physical impacts than long-lived coral populations, are sensitive indicators of water-quality conditions that support reef development.

According to Engle (2000, p. 3-1), "An ideal indicator of the response of benthic organisms to perturbations in the environment would not only quantify their present condition in ecosystems but would also integrate the effects of anthropogenic and natural stressors on the organisms over time (Boesch and Rosenberg 1981; Messer *et al*. 1991)." This information is precisely what foraminiferal tests in the sediments provide.

2.2 RELEVANCE TO ECOLOGICAL FUNCTION

Environmental perturbations of critical concern to coral reefs fall into three major categories (e.g., Hallock 2000; 2001): local impacts, new diseases of regional extent, and global change. The FORAM Index can be used to address local impacts and to assist in differentiating between local impacts that affect water quality and impacts that result from regional- to global-change issues.

The principal physiological analogy between reef-building corals and larger foraminifers is the dependence of both groups on algal symbionts to enhance growth and calcification (e.g., Lee and Anderson, 1991). This analogy and examples from both groups were used to develop a model to predict the energetic benefits of algal symbiosis (Hallock, 1981b), with the conclusion that this mode of life was energetically most advantageous when dissolved nutrients (i.e., NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}) and particulate food resources were scarce. Physiological studies of corals (e.g., Falkowski *et al*., 1993; Steven and Broadbent, 1997) and of larger foraminifers (Lee, 1998) have since demonstrated that fixed nitrogen limitation is crucial to maintenance of the host-symbiont relation.

Birkeland (1977; 1988) recognized that nutrient availability on the local or regional scale is a major control on benthic-community structure, especially in sub-

tropical and tropical seas (see also Hallock and Schlager, 1986; Hallock *et al*., 1993). Coral reefs thrive in the most nutrient-depleted oceanic waters where mixotrophic nutrition, i.e., the recycling of nutrients between host and algal symbionts, is most advantageous. As the nutrient supply increases, reef-building coral domination of the benthos gradually gives way to macroalgal domination as algal symbiosis becomes less advantageous. Slightly higher nutrient flux promotes phytoplankton blooms in the water column, limiting light penetration to the benthos. Light attenuation promotes the dominance of the benthos by non-symbiotic filter-feeding animals such as sponges and ascidians and of detritus-feeding echinoderms and crustaceans that do not directly require sunlight for survival (as observed, e.g., in Kaneohe Bay, Hawaii by Smith *et al*., 1981).

Benthic foraminiferal assemblages respond similarly to nutrient flux (Hallock, 1987, 1988). In very low-nutrient marine environments, such as those found around most Pacific atolls, larger foraminifers that host algal endosymbionts (Table 1) completely dominate sand-size sediments in reef systems (e.g., McKee *et al*., 1956; Hallock, 1981a). As nutrient supplies increase, bioeroded coral fragments, calcareous algae, molluscan debris, and smaller herbivorous and detritivorous foraminifers (Table 1) become more common as sediment constituents (Hirschfield *et al*., 1968; Hallock, 1988; Cockey *et al*., 1996).

As the environment becomes unsuitable for the survival of foraminifers with algal symbionts, their dead tests become rare in the sediments, and remnants become increasingly corroded (e.g., Cottey and Hallock, 1988). These changes occur with nutrification, which does not result in a measurable increase in dissolved nutrients in the water column because the planktic and benthic communities are able to incorporate and utilize all available nutrients (e.g., Laws and Redalje, 1979). True "eutrophication," which is nutrification to the degree that organic carbon buildup occurs in bottom waters and sediments (e.g., Cockey *et al*., 1996), results in further change in benthic-community structure including domination by opportunistic taxa (Table 1) that can tolerate episodic anoxia (e.g., Alve, 1995).

A critical application of the FI is differentiation between nutrification-induced decline in coral dominance in a reef environment and decline in response to episodic stress or mortality events (e.g., temperature extremes or hurricanes) that are independent of water quality. While the immediate cause of coral population decline is often a mortality event, if chronic nutrification has also occurred, coral populations continue to decline rather than recover from that event.

3. Methods

3.1 Sample Collection and Processing

Several sample collection procedures have been successfully used by numerous researchers who have assessed foraminiferal assemblages in surface sediments. For example, samples can be collected by SCUBA divers using a scoop and plas-

Table 1. Functional Groups of Foraminifers Used in Coral Reef Assessments

Functional Group	*Order*	*Family*	*Genus*	*Distribution*
Symbiont-Bearing	Rotaliida	Amphisteginidae	*Amphistegina*	Circumtropical
		Calcarinidae	5 genera	Indo-Pacific
		Nummulitidae	*Heterostegina*	Circumtropical
			3 other genera	Indo-Pacific
	Miliolida	Alveolinidae	*Alveolinella*	Indo-Pacific
			Borelis	Circumtropical
		Peneroplidae	Several genera	Circumtropical
		Soritidae	*Sorites*	Circumtropical
			Amphisorus	Circumtropical
			3 genera	Caribbean
			Marginopora	Indo-Pacific
Opportunistic*	Trochamminida	Trochamminidae	Several genera	Cosmopolitan
	Textulariida	Lituolidae	Several genera	Cosmopolitan
	Buliminida	Bolivinidae	Several genera	Cosmopolitan
		Buliminidae	Several genera	Cosmopolitan
	Rotaliida	Rotaliidae	*Ammonia*	Cosmopolitan
		Elphidiidae	*Elphidium*	Cosmopolitan
Other Small Taxa	Miliolida	Most except larger taxa noted above		Cosmopolitan
	Rotaliida	Most except those noted above		Cosmopolitan
	Textulariida	Most		Cosmopolitan
	Other	Most		Cosmopolitan

*Full range of opportunistic genera under local conditions is not well known.

tic bags (e.g., Donnelly, 1993) or minicore (e.g., Cockey *et al*., 1996). When grab samples or box cores are routinely taken for invertebrates and/or sediment analyses in larger monitoring efforts (e.g., McRae *et al*., 1998; Engle, 2000), a small surface subsample (upper 2 cm) for foraminiferal analysis can simply be processed separately.

The ideal sample size is 10 grams dry weight, which is a volume of approximately 10–20 cm^3. A sample of this size can be split in half, with one half saved as backup or archived. The other half is divided into an approximately 1 gram portion and a 4 gram portion. The 4 gram portion is used for routine sediment grain-size analysis (Folk, 1974). If such analysis is being performed as part of the larger monitoring effort, then it need not be repeated on the foraminiferal sample.

The 1-gram portion of the sample is washed with fresh water over a 63-μm mesh sieve to remove mud-size sediments, then dried on filter paper at 40–50ºC until the sample is thoroughly dry. The dried sample is gently disaggregated, thoroughly mixed, and poured into a mound on a clean, smooth surface. With a fine spatula, a small scoop of the sample (approximately 0.1 g) is removed from the center of the mound and weighed to the nearest milligram. The weighed subsample is sprinkled over a small,

gridded tray and examined using a conventional stereomicroscope or a video-imaging system. A very fine artist's brush (tip size 3/0 to 5/0), moistened with water, is used to remove foraminiferal specimens from the sediment (heavily worn and reworked specimens are excluded). Each specimen is placed onto a cardboard micropaleontological faunal slide, which is lightly coated with water-soluble glue. Then a preliminary count is made of each individual. If the number of foraminiferal specimens is approximately 150–200, the subsample is sufficient. If fewer specimens were present in the first portion, then a second portion is removed from the mound, weighed, and sorted. This procedure is repeated until 150–200 specimens are obtained or until the entire gram of sample is processed.

3.2 Data Analysis and Information Management

Once an adequate subsample is obtained, the foraminifers are sorted by genus and counted. Generic-level identification is recommended because it is historically well established and an excellent basic reference is available (Loeblich and Tappan, 1987); species-level identifications tend to be inconsistent across investigators. If deformed specimens are observed, the proportions of deformed specimens of abundant taxa should also be noted. Deformed foraminifers are well-known indicators of heavy-metal pollution (Alve, 1995; Yanko *et al*., 1998).

Raw counts are entered onto a spreadsheet, with appropriate sample location and identification codes, environmental data, and the weight of the sample picked. Basic data from the counts include relative abundance (proportions of the subsample) and absolute abundance (# specimens/gram of sediment) of each genus identified. Information management should be standardized to that of the larger monitoring program (e.g., McRae *et al*., 1998; Engle, 2000). As resources permit, data analyses such as multivariate and multidimensional analyses can be performed consistent with those applied to other data sets from the monitoring program.

Procedures for calculating the FI are presented in Table 2. Foraminiferal relative-abundance data are summed into functional groups, which include taxa of larger foraminifers that host algal symbionts, pollution-tolerant opportunistic foraminifers that dominate high-stress environments, and small taxa that proliferate in response to nutrification. The basic premise upon which this index is based is that environments suitable for proliferation of symbiont-bearing organisms have sediments in which at least 25–30% of the foraminiferal tests were produced by taxa that hosted algal symbionts. A sample that contains 25% larger foraminiferal tests and 75% tests of other small taxa has a FI = 4. Environments with sediments devoid of larger foraminiferal tests by definition have a FI ≤ 2. FI values between 2 and 4 in sediments from areas with existing coral reefs indicate that conditions are marginal to unsuitable for recovery of coral communities after a mortality event. Several of the data sets upon which these interpretations are based are presented and discussed in Section 4.

Table 2. Calculating the FORAM Index (FI)

Step 1. From each subsample examined, sort all foraminiferal specimens by genus, count, and record in a spreadsheet, with genera arranged by functional group. (See Table 1.)

Step 2. Calculate the proportion (P) of specimens for each functional group by summing the specimens of each genus of that group (N) and dividing by the total number of specimens counted (T).

a) $P_s = N_s/T$, where subscript "s" represents symbiont-bearing foraminifers

b) $P_o = N_o/T$, where subscript "o" represents opportunistic foraminifers

c) $P_h = N_h/T$, where subscript "h" represents other small, heterotrophic foraminifers

Step 3. Weight proportions to calculate the FORAM Index (FI):

$FI = (10 \times P_s) + (P_o) + (2 \times P_h)$

Step 4. Interpretation:

FI > 4 indicates environment conducive to reef growth

FI varying between 3 and 5 indicates environmental change (Coefficient of Variation > 0.1)

2 < FI < 4 indicates environment marginal for reef growth and unsuitable for recovery

FI < 2 indicates stressed conditions unsuitable for reef growth

3.3 QUALITY ASSURANCE

Foraminifers can be used as benthic indicators in new or existing monitoring programs that include routine sampling for analysis of sediment parameters (e.g., texture, chemical pollutants, nutrients) and/or benthic invertebrates. Basic Quality Assurance and Quality Control (QA/QC) procedures developed for field sampling, laboratory processing and data analysis for benthic data under EMAP guidelines are ideal (e.g., Engle, 2000). Foraminiferal assemblage analysis is relatively insensitive to the method of sediment collection employed, although it is important to collect the sediment surface layer, and it is important that the surface layer be undistrubed until it is sampled. Whatever collection method is employed, the sampling team should be instructed in the technique and should use it consistently.

To ensure comparability of taxonomic identification, the scientist or technician performing the identifications should be trained and supervised by a specialist in benthic foraminiferal identification, and QA/QC procedures should be employed (e.g., Engle, 2000). For monitoring efforts in remote areas or developing countries where resources are severely limited, technicians can be trained and selected samples can be sent to a specialist at a local university or even in another country to check for consistency in identifications.

3.4 MONETARY COSTS

The monetary costs of collecting foraminifers in sediment samples depends upon the type of monitoring program into which this procedure is being incorporated.

If grab samples or box cores are already being collected for benthic invertebrates and sediment characterization, the per-sample cost to include foraminiferal samples is minimal. Supplies required are small plastic bags or vials and labels. A maximum of 5-10 minutes/sample is needed for label preparation, sample collection, sample sealing, and sample recording. The major cost of including foraminiferal assemblages in monitoring studies is the cost of a technician to analyze samples. The procedure described above provides not only data needed for the FI, but also assemblage data that can be incorporated in more extensive multidimensional analyses. Using this procedure, one dedicated technician can analyze up to three samples per day, depending upon other responsibilities. If screening of large numbers of samples is a priority for the project, an experienced technician can directly count the foraminifers into the three functional groups described above without separating specimens onto slides, roughly tripling the number of samples that can be processed per day. These samples can be economically stored for later detailed analyses as time and resources permit.

Preferred minimum qualifications for the foraminiferal analyst are a Bachelor's degree in a biological or geological science with some experience in taxonomic identification and statistical analysis; Master's-level education with specialized training in foraminiferal ecology is ideal. Basic laboratory needs include a stereomicroscope, a computer to routinely enter data, taxonomic resources (i.e., Loeblich and Tappan, 1987, and local references), and assorted supplies. Recurring costs include supplies and computer and software upgrades.

The FI can be economically adopted in developing countries. Slides and holders can be made at minimal cost from glue, paint, recycled cardboard and aluminum beverage cans (Bayu Ludvianto, Personal Communication). Samples can be collected from a canoe or raft, if necessary, using a small grab, which can be locally fabricated, or by a proficient snorkel or SCUBA diver. Because data required for the FI are simple counts, basic calculations and graphics can be done by hand or with an inexpensive hand calculator. A computer is required only to archive and analyze data further. A researcher at a field laboratory could easily perform sample collection, microscopic analysis, data recording and FI calculations. Data sheets can then be sent to an in-country research center or university or to a project coordinator in another country for more detailed analyses of data sets. Also, because unprocessed samples are relatively small and do not require refrigeration, they can be shipped relatively inexpensively from a field location to a laboratory for processing and analysis.

4. Response Variability

4.1 SAMPLE SIZE

Historically, most foraminiferal researchers have counted 300 specimens per sediment sample to obtain data for community analyses. To determine if smaller sample sizes provide consistent data, Dix (2001) used the basic procedure outlined previ-

ously to pick three subsamples of approximately 100 foraminifers per subsample from each of 12 samples. Each subsample was picked, the foraminifers identified to genus, and the relative abundances of each genus calculated for that subsample. The raw data from each set of three subsamples were pooled and used as the "expected" distribution for relative abundances. The Kolmogorov-Smirnov Goodness of Fit test was used to compare all pairs of subsamples, as well as all individual subsamples against their respective pooled "expected" distribution. Out of the 72 resultant comparisons, only one pair of subsamples was significantly different at the 0.05 probability level. Dix concluded that, for generic identifications, a sample size of 150-200 provided a useful compromise between the added precision of larger samples (i.e., 300) and added cost of processing (i.e., double the time of picking and identification).

4.2. SPATIAL AND TEMPORAL VARIABILITY

Two major data sets illustrate spatial variability in the FI and its ability to reflect decadal-scale decline of environmental conditions in the Florida Keys. The changes in dominant taxa reflect changes in the suitability of Keys environments for the symbiotic organisms essential to coral-reef habitats (Figure 1). In 1961, sediment samples were taken along two traverses off Key Largo, Florida. Published reports on these samples (Rose and Lidz, 1977; Lidz and Rose, 1989) provided baseline data for comparison with a limited set of samples taken from the same traverses in 1982, and more extensive sets collected in 1991 and 1992 (Cockey *et al*., 1996). Mean FI values for samples collected from thriving reef environments in 1961 were 7, with a coefficient of variation (CV) of 0.04 (Table 3). In 1982, the mean FI had plummeted to 4, while the CV had increased to 0.15. By the early 1990s, the mean FI had stabilized at approximately 3, and the CV had returned to < 0.04.

The temporal differences between index values in 1991 and 1992 reflect seasonal differences more than interannual differences. The 1991 samples were taken in September at the end of a climatologically quiet summer and represent peak accumulation of smaller tests of heterotrophic foraminifers. The 1992 samples were taken in May and reflect the effects of higher energy conditions during the winter months. Sites more exposed to storm waves show higher values that reflect those seasonal effects. The 1982 samples are particularly interesting because they reflect a reef ecosystem under stress (e.g., Dustan and Halas, 1987), but not yet in the collapse observed in the 1990s (Jaap *et al*., 2001). In 1982, shells of smaller foraminifers dominated locally, but in locations more exposed to wave energy, the long-term accumulation of larger foraminiferal shells had not yet been overwhelmed by the more recent production of smaller, more easily sorted shells.

4.3. DISCRIMINATORY ABILITY

Another set of FI values (Figure 2) was calculated from samples collected in 1985 along onshore-offshore transects at La Parguera, Puerto Rico (Donnelly, 1993).

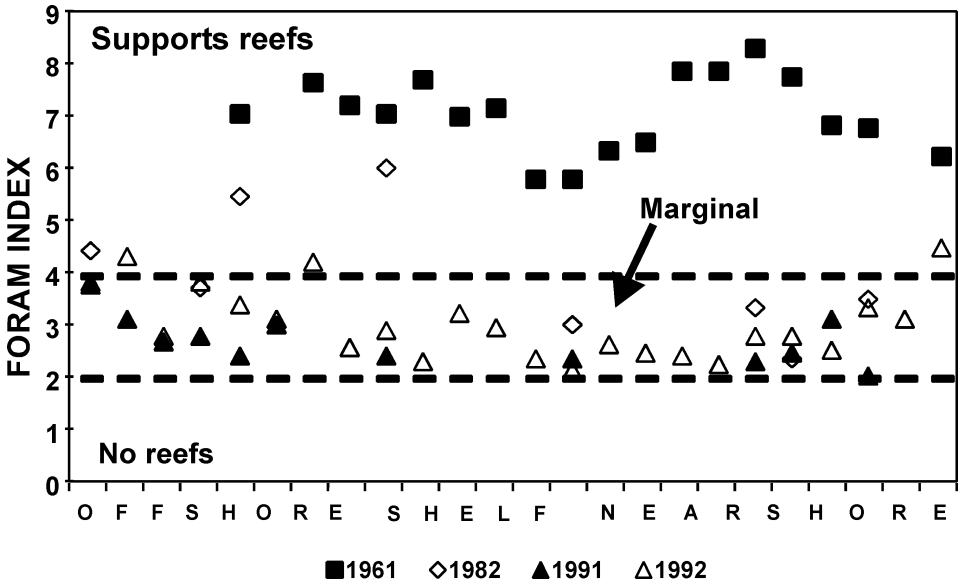

Figure 1. Spatial and temporal variability and interdecadal changes in the FORAM Index for samples from traverses off Key Largo, Florida.

Table 3. Intersample variability in FI values presented in Figures 1 and 2.

Location	*Comparison*	*# Samples*	*Mean FI*	*CV**
Key Largo	1961	18	7.09	0.039
Key Largo	1982	8	4.02	0.145
Key Largo	1991	12	2.75	0.038
Key Largo	1992	24	3.07	0.028
Puerto Rico	Inshore	20	2.69	0.026
Puerto Rico	Midshelf	19	3.74	0.197

*Coefficient of Variation

Inshore reefs were in collapse from coastal nutrification and mid-shelf reefs were exhibiting stress (Hallock, 1988). FI values from mid-shelf samples are higher and more variable than nearshore FI values. The shells of smaller foraminifers locally overwhelmed the larger foraminiferal shells that had accumulated over decades of reef growth, although the larger taxa were still common at midshelf sites. On the inner reefs the shells of smaller, fast-growing foraminifers overwhelmingly dominated in the sediments.

An early concern with the FI was that the index might be unduly influenced by sediment grain size. However, plotting indices against median grain size indicates

that, particularly in the most common sediment-size ranges of medium to coarse sands, the FI seems to be relatively unaffected (Figure 3). Intuitively, it is obvious that the shells of smaller foraminifers, as well as juveniles and fragments of larger taxa, should be concentrated in fine sands and muds (phi > 3). However, it is also well known that coral reefs thrive where there is significant water motion, so the presence of muddy sediments can indicate a relatively unfavorable environment, particularly if muddy sediments cover slightly older reef sands and hardbottoms. Hallock (1988) noted that nutrification promotes the production and accumulation of carbonate muds in reef environments for three reasons: (1) Limited nutrification may increase growth and production by calcareous green algae, which break down to mud-size sediments; (2) Nutrification increases rates of bioerosion of reef substrate by endolithic sponges, which etch out mud-size fragments; and (3) Nutrification can promote the growth of algal and bacterial biofilms and mats that baffle and bind finer sediments, allowing those sediments to accumulate. During sampling of inner reefs at La Parguera, Puerto Rico, in 1985 and at Tennessee Reef, Florida Keys, throughout the 1990s, several centimeters of gelatinous carbonate muds overlying sand, rubble and dead-reef substrate in depressions among diseased and heavily bioeroded corals was commonly observed (Pamela Hallock, Personal Communication). The very presence of abundant gelatinous muds in a reef environment indicates a declining environment and will be reflected by a low FI.

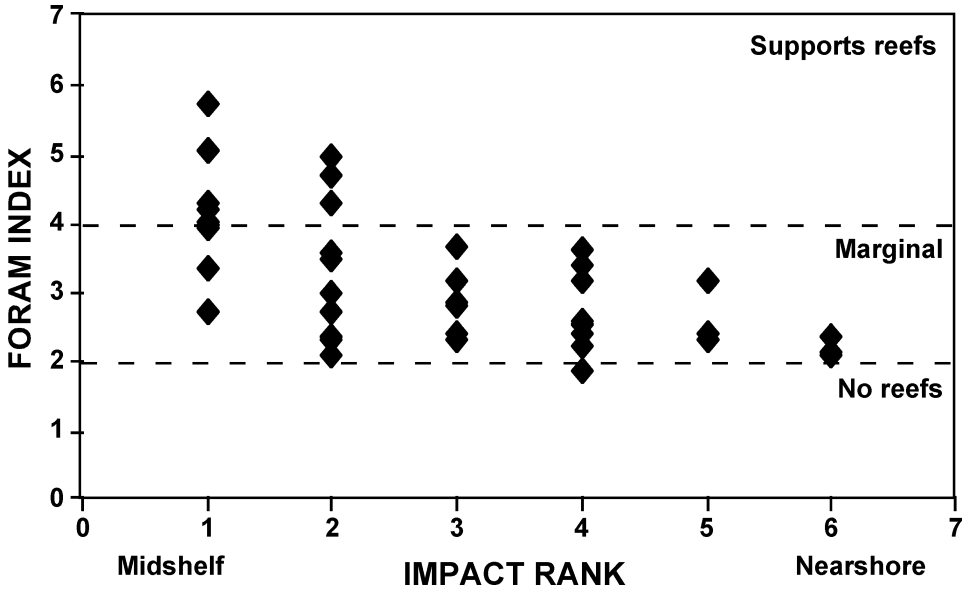

Figure 2. FORAM Index for samples collected from a declining reef system off La Parguera, Puerto Rico.

Equally intuitive is the assumption that coarse grain sizes should be biased toward larger foraminifers. However, the frequency of FI in the 2–4 range (Figure 3) indicates that, where the environment favors the proliferation of smaller foraminifers, they can overwhelm the larger taxa even in samples dominated by coarser sediment sizes, an observation first noted by Cockey *et al*. (1996). Additional testing of the FI on reefs in the Indo-Pacific is needed to resolve whether values from coarse grain sizes are consistently reliable. However, larger foraminifers are important contributors to beach sands of Indo-Pacific reef environments where water quality favors coral growth. Hottinger (Personal Communication) found that nutrification by agricultural runoff to nearshore waters of Mauritius in the Indian Ocean resulted in the loss of *Amphistegina*-sand beaches.

The FI is also independent of sample depth (Figure 4). Incorporating both the shallower-dwelling larger Miliolida (Table 1) and the reef-margin-favoring *Amphistegina* spp. minimizes the potential for depth bias and extends the applicability of the FI from nearshore patch reefs to reef-margin conditions.

5. Interpretative Utility

According to Engle (2000, p. 3–14), "The value of an index lies in its applicability across large geographical areas and its ability to provide regional assessments of ecological condition." The FORAM Index has been developed using data from Puerto Rico (Caribbean), the Florida Keys (western Atlantic), Hawaii (Pacific),

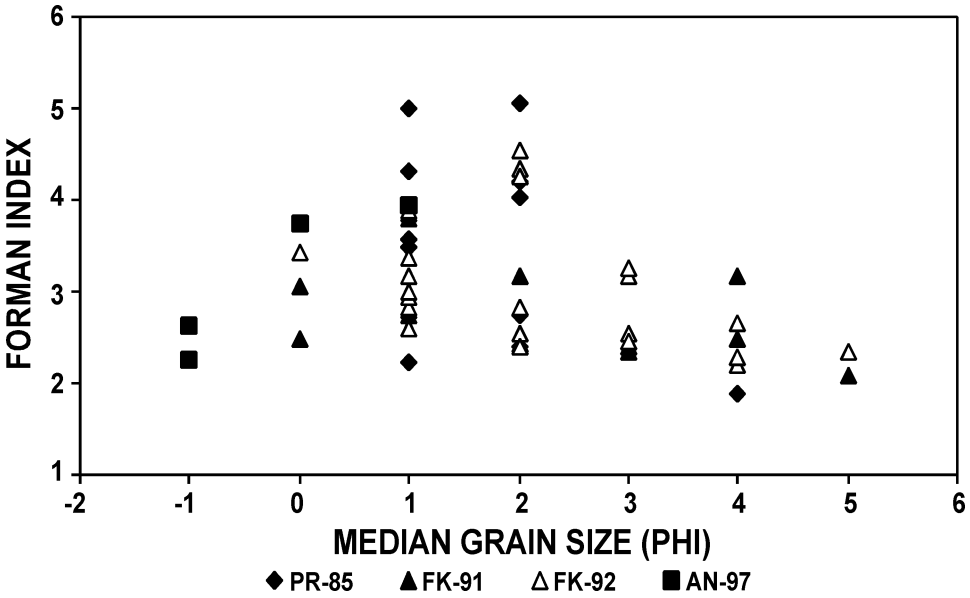

Figure 3. FORAM Index plotted against grain size for reef samples from the Florida Keys (FK), Puerto Rico (PR) and Antigua (AN); year collected is also shown.

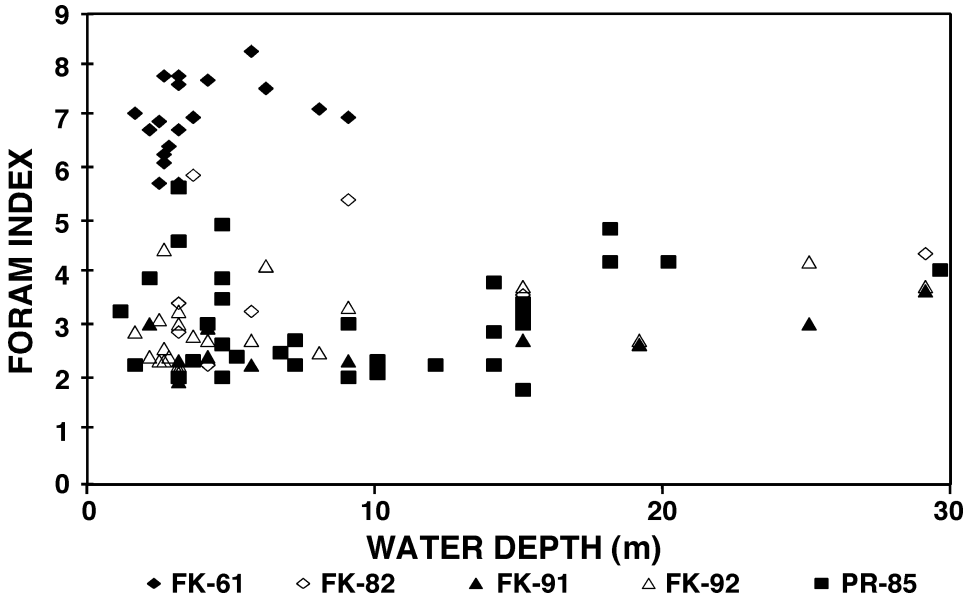

Figure 4. FORAM Index plotted against water depth for reef samples from the Florida Keys (FK) and Puerto Rico (PR); year collected is also shown.

and the Australian Great Barrier Reef (Pacific). Although additional testing in Indo-Pacific reef environments is needed, the FI should have global applicability.

The range of reef-associated habitats that the larger foraminifers occupy indicates that an index weighted for larger foraminifers can be used in both nearshore and offshore reef-associated environments to at least 20-m depth. The larger Miliolida (worldwide, but especially in the western Atlantic and Caribbean), many Calcarinidae and one species of *Amphistegina* (in the Indo-Pacific) are shallow-dwelling taxa and are abundant in nearshore environments where water quality is high. Cockey *et al*. (1996) showed that nearshore larger taxa decline in abundance as nearshore conditions decline and that reef-margin taxa, particularly *Amphistegina* spp., decline as environmental conditions decline at the reef margin (see Figure 1). This diversity of larger foraminifers in reef-associated habitats expands the usefulness of these foraminifers as indicators in reef-associated environments.

6. Discussion

The purpose of EMAP is to provide information on the condition of the Nation's ecological resources (Summers *et al*., 1995). A new bioindicator is not needed to meet that goal in reef environments; percent live coral cover is probably adequate, with values less than 10% indicative of serious decline (e.g., Dustan and Halas, 1987; Hughes, 1994; EPA, 1998). Most of the Nation's coral reefs, particularly

those in the western Atlantic region (i.e., including the Caribbean and Gulf of Mexico) have dramatically declined over the past 30 years as a result of three major problems: new diseases, coral bleaching, and declining water quality. How interrelated these problems are, i.e., coral bleaching and disease, or disease and water quality, is still not fully known. Certainly coral bleaching is related to anomalously high sea-surface temperatures over the past 25 years, implicating global warming. Synthesis of global climate models and coral-bleaching studies indicates that coral reefs may cease to exist as ecosystems over the next 20 to 50 years (Hoegh-Guldberg, 1999). Ozone depletion and resultant increased intensities of biologically damaging ultraviolet radiation (UV_b) have also increased over the past 25 years and very likely contribute to both temperature stress and susceptibility to disease.

Thus, the major hope for the future of western Atlantic coral reefs as ecosystems is that surviving corals can adapt to temperature stress and disease, and that their descendants can repopulate reef environments. New studies of coral bleaching indicate that surviving corals may exchange lost symbionts for more heat- or light-tolerant strains (e.g., Rowan, 2000; Baker, 2001). In addition, the possibility exists that scientists can genetically engineer heat- and disease-resistant strains of corals and zooxanthellae that can be reintroduced to reef environments. But for either of those optimistic scenarios to be possible, water quality of coastal environments either must be maintained or, where currently contributing to the decline of mixotroph-based communities, must be improved.

Thus, a major question remains unanswered in areas such as the Florida Keys reefs, where the vast majority of coral populations have been lost over the past 25 years and where the reefs will presumably lack significant coral populations for the foreseeable future. How can resource managers recognize whether environments are suitable for coral-reef regrowth if wild populations or genetically engineered corals can adapt to global change? That is one basic question that the FI can address. Larger foraminifers are not dependent upon corals per se, but on the high water quality commonly associated with coral reefs.

Many Indo-Pacific reefs were severely damaged by the 1997–98 mass bleaching event (Hoegh-Guldberg, 1999; Wilkinson, 2000). Nevertheless, there are still significant surviving coral populations and, of course, much higher diversities within coral communities (e.g., Veron, 1995). With very high oceanic water quality offshore from reef resources, for example, in Hawaii, Guam, the Mariana Islands, and American Samoa, the prognosis for survival of Pacific reef resources is much better than in the Florida Keys. Thus, the FI can be applied more conventionally to provide an independent assessment of the suitability of local environments for continued reef growth or recovery in the event of a mass mortality event. Further targeted testing of the index in Pacific reefs is needed to confirm and refine it where regional (oceanic) conditions still support reef growth.

7. Summary

Coral reefs are among the most threatened ecosystems worldwide. The FORAM Index provides a metric for determining whether water quality is suitable for mixotroph-based (i.e., algal-symbiotic-dominant) communities. In the western Atlantic region, where disease and bleaching have profoundly damaged coral communities, the FI can be used to assess whether water quality is sufficient to support reef recovery even in the absence of significant coral populations. In the Indo-Pacific, where significant coral communities still exist, the FI can provide a local, independent indicator of environmental suitability for the continuation of reef growth following a mass mortality event resulting from bleaching, a typhoon, or ship grounding.

Acknowledgments

Development and assessment of foraminifers as bioindicators was funded by the U.S. Environmental Protection Agency ORD-STAR-GAD-R825869. Funding contributing to collection of the foraminiferal data sets includes the National Science Foundation EAR-8407781 and OCE-9203278; U.S. Geological Survey 1434-94-A-1185 and 99HQAG0004; and the National Oceanic and Atmospheric Administration National Undersea Research Program Subcontracts No. 9120, 9204.4, 9221, 9322, 9515, 9609, 9703.66 and 9922. Sampling in the Florida Keys was carried out under Florida Department of Natural Resources Permit Numbers 92S-0031, 93S-0156, and 94S-0034; Florida Department of Environmental Protection Permit Numbers 95S-00063, 96S-016, and 00S-016; and Florida Keys National Marine Sanctuary Permit Numbers KLNMS-23-92, FKNMS 09-93, -(UR)-09-94, 07-95, -(UR)-29-96, -006-97, and -2000-011. We thank Drs. D. Griffin, B. Melzian, L. Robbins, T. Smith, and four unidentified reviewers for their helpful comments on the manuscript.

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