

The FoRAM Index revisited: uses, challenges, and limitations

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Abstract. The FoRAM Index (FI) was proposed as a foraminiferal-based indicator to distinguish whether water quality supports recruitment and proliferation of calcifying, photosynthesizing holobionts. The rationale for a non-coral indicator was based on observations that adult coral colonies tolerate environmental conditions that no longer support recruitment as revealed by failure of coral populations to recover after mortality events. The FoRAM Index utilizes assemblages of foraminiferal shells in sediment samples. Where shells from small, heterotrophic taxa overwhelmingly dominate (FI ~2), environmental conditions favor autotrophic and heterotrophic organisms over calcifying symbioses. Shells of larger foraminifers that host algal symbionts raise the FI; for example, when shells of larger taxa make up $\geq 25\%$ of the foraminiferal assemblage, the FI will be ≥ 4 . Where 100% of the shells are those of larger taxa, FI = 10. Smaller taxa are further distinguished as “stress-tolerant” or “other”. Prevalence of stress-tolerant taxa (FI <2) typically indicates high biological oxygen demand, euryhaline conditions, or other stressors.

Although proposed for western Atlantic-Caribbean reefs, the FI has been used as a coastal water-quality indicator in Puerto Rico, Florida, Brazil, Pacific Islands, Australia, and Greece. However, the FI may not be useful in Indonesia where large Calcarinidae thrive in mesotrophic waters. Moreover, where larger foraminifers have historically been major sediment producers, relict shells can be abundant where these taxa no longer live. The recommended depth range for collection of samples for FI analysis is approximately 3-15 m as shallower sediments may be too wave worked and deeper sediments tend to accumulate finer sediments including shells of smaller heterotrophic foraminifers.

Key words: Foraminifera, Bioindicators, Water Quality, Algal Symbiosis, Coral Reefs.

Introduction

Scientists, resource managers and the concerned public widely recognize that coral reefs and other coastal resources are being degraded worldwide. Even in areas where coastal and watershed management are most effective, the inevitable impacts of ever-increasing human populations can result in declining water quality. Beginning in the mid-1990s, environmental management agencies accelerated the pursuit to find applicable bioindicators to understand the integrity for a variety of ecosystems (e.g., Jackson et al. 2000 and references therein).

The Foraminifera in Reef Assessment and Monitoring (FoRAM) Index (Hallock et al. 2003) was developed in response to the U.S. Environmental Protection Agency's interest in the development of bioindicators for coral reefs. The idea to use reef-dwelling foraminifers, with particular emphasis on taxa hosting algal symbionts, was proposed at a workshop exploring possible low-cost indicators of reef health that would have application in countries with strong human resources but limited technological

resources (Hallock Muller 1996). These papers emerged from observations that clear reef waters tended to be characterized by high coral cover and by sediments dominated by the shells of larger foraminifers (Hallock 1988).

The earliest known report of pollution effects on reef-dwelling foraminifers was that of Hirshfield et al. (1968) from Eniwetak Atoll, where smaller foraminifers replaced the larger taxa near the sewage outfall from the marine laboratory. The observed response of reef-dwelling foraminifers to compromised water quality was consistent and contemporaneous with application of foraminiferal assemblages in pollution studies in temperate coastal waters (e.g., Bandy et al. 1965; Schafer 1973). The interest in utilizing foraminifers in pollution studies increased greatly following papers by Yanko et al. (1994) and Alve (1995) that documented the broad applicability of foraminiferal assemblages in coastal environments. In particular, Alve (1995) described a model progression of responses of foraminiferal assemblages with increasing proximity to a point source of pollution.

The FoRAM Index was a natural extension of previous research, with the added goal of developing a single metric index that could be used in reef environments.

The FoRAM Index

The basic premise of the FORAM Index is that the assemblage of foraminiferal shells in sediments reflects water and sediment quality (Hallock et al. 2003). Well flushed subtropical/tropical coastal and shelf environments with limited flux of inorganic or organic nutrients historically supported proliferation of hypercalcifying mixotrophs, notably reef-building corals. In such environments, the shells of larger foraminifers typically made up a significant proportion of the foraminiferal shells in the sediments and often dominated the total sediment composition. Where the input or residence time of nutrients was sufficient, the benthos instead was dominated by autotrophs, including micro- and macroalgae, and heterotrophs, along with weak- or non-calcifying mixotrophs such as sponges, soft corals, and octocorals. The sediments in such environments tended to have higher proportions of fragments of calcareous algae, molluscan shells, and bioeroded coral (e.g., Lidz and Hallock 2000), while the foraminiferal assemblages were dominated by smaller heterotrophic species that proliferated on the relatively abundant food (Hallock 1988).

In coastal environments where nutrient input or residence times allow excess of organic matter to accumulate in sediments, water transparency is generally insufficient to support photosynthesis at depths greater than a few meters. In such environments, detritus and filter feeders may dominate the benthos, and the foraminiferal assemblages generally lack larger foraminiferal shells. Instead, the assemblages have substantial percentages of stress-tolerant taxa, especially *Ammonia* spp. (e.g., Carnahan et al. 2009). Where eutrophication is intermittent or generally does not induce hypoxia, *Elphidium* spp. or other taxa that retain chloroplasts are often abundant (Renema 2006). Prior to human influence, coastal environments with abundant nutrient and organic-carbon resources were commonly estuarine or mangrove habitats, where salinity fluctuations can be associated with intermittent hypoxia. *Ammonia* and a variety of agglutinated genera typically dominate the sediments in euryhaline and euryoxic environments. Abundant food sources with intermittent hypoxia in consistently normal marine salinities are favorable environments for *Ammonia* spp., often with abundant boliviniids rather than agglutinated taxa. Typically, abundances

of *Ammonia* and of symbiont-bearing foraminifers are inversely correlated.

The FoRAM Index enumerates foraminiferal taxa into three functional groups as defined by Hallock et al. (2003), with terminology modified by Carnahan et al. (2009). The FORAM Index is calculated as follows:

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

Where $P_s = N_s/T$, $P_o = N_o/T$, $P_h = N_h/T$, and T = total number of foraminiferal specimens counted, N_s = number of specimens of large, algal symbiont-bearing taxa, N_o = number of specimens of stress-tolerant taxa, N_h = number of specimens of other small, heterotrophic foraminiferal taxa.

Uses

Since its introduction by Hallock et al. (2003), the FoRAM index has been applied in reef environments in Australia (e.g., Scheuth et al. 2008; Uthicke and Nobes 2008; Uthicke et al. 2010, 2012), Florida (Ramirez 2008; Williams 2010), the Caribbean (Velazquez et al. 2011; Oliver et al. in review), and Brazil (Barbosa et al. 2009). In Australia, the FI is part of an ongoing large scale inshore reef monitoring program (<http://www.gbrmpa.gov.au/about-the-reef/how-the-reefs-managed/science-and-research/our-monitoring-and-assessment-programs/reef-rescue-marine-monitoring-program>).

Moreover, applications have included non-reefal environments including subtropical estuaries (Carnahan et al. 2009; Narayan et al. 2010), and even in the eastern Mediterranean (Koukousioura et al. 2011). In the latter case, *Amphistegina* spp. have invaded oligotrophic coastal environments so that their decline in abundance with proximity to human population densities can be used as first-order indicators of decline in water quality.

While diversity indices are widely used in water-quality studies (e.g., Borja et al. 2011), the FI was developed in part because diversity indices can be easily misinterpreted when applied to foraminiferal assemblages. Jorissen et al. (1995) explained that, along a nutrification gradient from point source to unimpacted conditions, the peak in diversity should be where additional food sources increased both abundance and diversity of taxa over unimpacted food-limited assemblages, but where oxygen was still readily available within the sediments. This diversity peak is even more dramatic in subtropical and tropical waters where higher temperatures and therefore higher metabolic rates limit diversity and abundance of heterotrophic foraminiferal taxa in environments dominated by mixotrophic taxa hosting algal symbionts. There are at least 10-20 times more of the

smaller heterotrophic species than larger mixotrophic species extant in mid- and low-latitude coastal and shelf waters. Thus, species richness of foraminifera tends to be much higher in waters where organic-carbon sources are relatively abundant but not sufficiently high as to create intermittent hypoxic conditions. Sediments beneath nutrient-poor (oligotrophic) waters are typically characterized by species that host algal symbionts, but because there are relatively few symbiont-bearing taxa, the overall species richness typically declines (Table 1). However, as Renema (2006) have noted, diversity of only obligate symbiont-bearing foraminifera is a useful indicator of increasing nutrient availability.

Metric	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Water Transparency	High	Medium	Low	Very low
Species Richness	Medium	High	Medium	Low or absent
Total abundance	Medium	High	Highest	Low or absent
FoRAM Index	High: >4	Medium: ~3-5	Low: ~1-3	<2 or none

Table 1: Relative nutrient flux or organic carbon supply, corresponding water transparency, and relative characteristics of the foraminiferal assemblage with respect to species richness, abundance and the FoRAM Index.

Challenges and Limitations

The geographic and environmental range of applications of the FoRAM Index has been surprising, given that Hallock et al. (2003) cautioned that local or regional modifications of the formula might be required. Moreover, there are environments where specialized large taxa can dominate, such as mangrove areas in the western Atlantic and Caribbean that tend to be hypersaline more than hyposaline and are home to *Androsina lucasi* (Levy 1991).

Consistent with the original caution, Renema (2008, 2010) has noted that the Calcarinidae in Indonesia tend to increase with increased macroalgal cover. However, Hohenegger (2006) observed that nearshore nutrient flux that induces growth of nutriphilic green algae such as *Ulva* may not be conducive to carbonate sand production, even by calcarinids. In the western Atlantic and Caribbean, chlorophyte-bearing archaiaisine taxa similarly thrive in inshore algal and seagrass habitats. The dinoflagellate-bearing *Sorites* spp. also thrive on the seagrass, *Thalassia testudinum*, in the Western Atlantic and Caribbean (Hallock and Peebles 1993 and references therein). However, Fujita and Hallock (1999) found that *Sorites* is sensitive to eutrophication that results in heavy epiphyte loads on *Thalassia*. Moreover, the proportional increase in

shells of smaller taxa tends to numerically overwhelm the increase in larger taxa when food sources are sufficient. *Archaias angulatus*, which can be abundant even in heavily epiphytized seagrass (Hallock et al. 1986; Fujita and Hallock 1999), is extremely sensitive to hypoxia and therefore will decline if nutrient flux increases to that degree (Carnahan et al. 2009). Moreover, as Baker et al. (2009) demonstrated, archaiaisine foraminifera are highly light dependent and decline in abundance in reef habitats as water transparency declines. In such habitats, *Amphistegina* and *Heterostegina* dominate the larger taxa at depths greater than about 10 m, though the smaller foraminifera dominate the foraminiferal assemblage overall (e.g., Ramirez 2008; Stephenson 2011).

Residence Time in the Sediments

An issue of concern is sediments that have been historically dominated by larger foraminiferal shells, such that even where water quality is obviously in decline, the sediments are still dominated by these shells. This issue can be especially problematic in beaches and in other high energy environments.

There are several strategies to address this problem. The most obvious is to study the live assemblage rather than the dead or total assemblage of foraminiferal shells. There are numerous papers arguing both sides of the live versus dead versus total assemblage of foraminifera in sediments. Murray and Alve (1999), Martinez-Colon et al. (2009), among others, have discussed this controversy in some detail. In reef-related environments above normal wave base, most foraminifera live in phytal or hard substrata, not in wave-worked sediments. When the sediment is undisturbed for sufficient periods, algal-bacterial growth can stabilize sediments and provide food sources, allowing foraminifera to colonize them (i.e., days to a few weeks, or seasonally). Often, the living assemblage in sediments is low or dominated by fast-growing small taxa. Buzas et al. (2002) observed that live assemblages in sediments are characterized by “pulsating patches” that, when sampled over space or time, provided a good representation of what lived in the sediments of the area, but any given sample simply represented what might be living at that spot at that moment.

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.” Hallock and others (2003) argued that this

information is precisely what the total assemblage of foraminiferal tests in the sediments can provide.

But what about shells that accumulated in the sediments before substantial anthropogenic influence versus shells that have accumulated under anthropogenic influence? Addressing this dilemma requires several considerations, including sediment texture, degree of shell alteration and rates of shell accumulation in the sediments.

Hallock et al. (2003), Carnahan et al. (2009), and other studies compared the FoRAM Index with sediment texture, anticipating that coarser sediments would have consistently higher indices. Remarkably, in the data sets examined, sediment textures were not correlated with the FoRAM Index for western Atlantic and Caribbean samples with median grain sizes in the medium- to coarse-sand range; very fine sands and muddy sediments, of course, tended to accumulate small foraminiferal shells. Surprisingly, the coarsest sediments did not exhibit the highest indices. Hallock et al. (2003) recommended that sediment texture be evaluated when testing or applying the FoRAM Index, especially in regions where it had not been used previously.

Fortunately for foraminiferal researchers, shells tend to exhibit more physical degradation in sand-dominated (or coarser sediment) environments, and often some dissolution or discoloration in quiet, organic-rich environments. In either case, those shells should not be included in counts for FoRAM Index assessments. On the other hand, combining FoRAM Index and taphonomic assessments, as reported by Barbosa et al. (2009), might elucidate changes between pre-impact and post-impact assemblages.

Carilli and Walsh (in press) approached the use of larger foraminifera in the sediments by comparing proportions of live versus dead shells of larger foraminifera across a gradient of human impact in the Kirimati Islands of the Pacific. Even though live larger foraminifera generally are much less abundant in sediments than on more rigid substrata, Carilli and Walsh found that live specimens were significantly more common in sediments collected at more pristine sites than near human impact.

There is a long-standing paradox relating to the residence times of carbonate beach sands. Beach erosion has been dramatically observed in some areas impacted by human activities (e.g., Hohenegger 2006 and references therein). Estimates of residence times of beaches and coastal sediments based on carbonate production by larger benthic foraminifera are generally consistent with the observed susceptibility of such sediments to anthropogenic changes. At the same time, residence times of shells as estimated from

carbon-14 dates indicate that individual grains may be a thousand years old or more (e.g., Resig 2004).

Muller (1976) used abundances and other population-dynamics parameters to estimate sediment production in coastal waters around O'ahu, Hawai'i, USA. She estimated residence times of decades for *Amphistegina* spp., the dominant sediment producers in Hawaiian waters. This estimate is consistent with observations in Hawai'i, Mauritius and elsewhere that decline in coastal water quality is accompanied by loss of carbonate sand beaches. Decadal residence times are also consistent with observations in the eastern Mediterranean where production of shells by invasive *Amphistegina* have literally altered beach composition and changed rocky beaches to sandy beaches (e.g., Streftaris and Zenetos 2006). Another study that found fairly short residence times was Crevison et al. (2006), who examined short sediment cores from the Florida reef tract. Interestingly, the high turnover rates of smaller taxa, combined with bioturbation, resulted in seasonal differences in foraminiferal assemblages more than 10 cm downcore.

The paradox of these estimates of rapid loss or replacement is that carbon-14 dates for larger foraminifera in beach sediments often indicate that foraminiferal shells in the beach sands can be a 1000 years old or more (Resig 2004 and references therein). However, foraminifera do not live on beaches, and beach sands are strongly influenced by physical abrasion and sorting, which tend to concentrate larger foraminiferal shells. Beach sands also can be influenced by eroding paleoshoreline deposits (e.g., Resig 2004). Thus, beach sand samples should not be used in FoRAM Index assessments. Rather, foraminiferal assemblages from reef flat and reef sediments in the 3-15 m depth range appear to best reflect the water quality under which they accumulated.

Assessment of Live Assemblages

Sampling of live assemblages can provide the best indication of existing water quality, if appropriate substrata are sampled and if time and resources are available for the greater effort required. If representatives of the live assemblage are to be evaluated effectively, one must sample a range of substrata or a well-defined set of substrata such as reef rubble (e.g., Hallock Muller 1996; Baker et al. 2009) or macroalgae (Koukousioura et al. 2011) and describe the limitations of methodology accordingly.

As noted above, live assemblages in reef-sediment samples might not indicate much other than hydrodynamic conditions immediately preceding sampling. Days or weeks of low wave energy

provides fast-growing taxa the opportunity to bloom as algal-bacterial mats grow and stabilize the sediment. Conversely, high energy conditions can transport live specimens from hard substrata into sediments, regardless of whether they can live there. Typically, live specimens in a reef-related sediment sample make up a relatively small percentage of the total assemblage of foraminiferal shells present in that sample. Thus, assessing the live assemblage requires substantially more time and expertise in sampling, sample fixation and staining, combined with roughly ten-fold more time required for sample picking, assuming an average of 10% live among the foraminiferal shells in a typical sediment sample, as indicated by staining.

Conclusions

Strategies for using benthic foraminifera as bioindicators in reef and associated coastal environments depend upon a) goals of the project; b) personnel and facilities available for field collection and sample processing and analyses; and c) funding and time constraints for the project. The FoRAM Index was originally proposed as an indicator of whether water quality in an area is likely to support significant net production of reefs or carbonate sands by marine calcifiers that host algal endosymbionts, specifically zooxanthellate corals and larger foraminifera (Hallock et al. 2003).

The FoRAM Index as originally proposed, or as modified for local conditions, has been shown to be useful in studies of nutrient-impact gradients in habitats as diverse as the Great Barrier Reef of Australia (e.g., Uthicke and Nobes 2008) and islands in the eastern Mediterranean, which are far from any coral reef (Koukousioura et al. 2011). This index can reveal gradients of human impact on water and sediment quality that may not be discernible in the coral community (Oliver et al. submitted). Given the challenges of defining “true” reference sites and of depths of bioturbation in carbonate sediments, several projects that have used the FI have successfully applied “gradient” sampling designs, with the parameter of distance from known impacts or point sources.

The basic protocols require simple field sampling procedures, basic laboratory equipment, and a researcher trained to identify foraminifera using a stereomicroscope. Small sediment samples can be collected using grab samplers, or by SCUBA divers or snorkelers, and sampling can easily be incorporated in other field sampling strategies at minimal cost of time. Sample processing and analysis are moderately time consuming, through some simple modifications,

such as only identifying and counting specimens based on three categories (symbiont-bearing, stress-tolerant, and other), rather than routinely indentifying to genus, would substantially reduce assessment time.

The FoRAM Index was designed for basic assessment and for monitoring on time intervals of several years to detect environmental change. Results from FoRAM Index assessments or other observations can reveal the need for more detailed assessment strategies such as water and sediment-quality assessments, combined with, e.g., bioassay or cellular biomarker studies of key biota. Such strategies require more expertise, technology and financial resources. Because foraminifera are living at the benthic boundary and they tend to be abundant, expanding their use in bioassay or cellular biomarker studies (e.g., Prazeres et al. 2011, 2012) is an important direction of ongoing and future research.

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