

Tropical Foraminifera as indicators of water quality and temperature

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Abstract. Managing local water quality in coastal marine ecosystems is fundamental for the long-term protection of diversity and carbonate production, to maintain reef accretion. Although there are numerous indicators to measure the resilience and health of reef environments, the use of foraminifera is building momentum. Key mechanisms controlling productivity in benthic ecosystems can be assessed by investigating foraminiferal calcification and physiology in response to changing water quality (primarily nutrients) and temperature. Benthic foraminifera are among the most abundant protists in the shallow reef marine environment yet, even in low abundance, the ecological record they leave in the sediments is extremely useful for reconstructing past and present environmental conditions. This application can enable studies to pinpoint the duration and timing of long-term influence of eutrophication in coastal marine ecosystems. This is largely due to their biology and sensitivity to environmental conditions, high taxonomic diversity (ca. 4,000 extant species) and relatively short life cycles (months to a year or more). However, altering ecological conditions influence species differently, so the community and physiological responses needs to be clearly identified. For example, the host-algae association is complex and typically photosymbiont-bearing marine organisms suffer adverse metabolic effects directly from sediment runoff, inorganic nutrient runoff, light and temperature. Therefore, validation is recommended when applying indices created in one region to another.

Key words: FORAM index, photosymbiont-bearing foraminifera, benthic carbonate production, nitrification.

Introduction

Localised impacts of declining water quality are associated with modern changes in land use, principally occurring within the past century. The main components constraining water quality parameters include nutrients, sedimentation, turbidity, and light attenuation. The response may become evident within days to years depending on the ecosystem response and the magnitude and duration of the disturbance. The main foraminiferal indicators used to assess changes in water quality are community shifts (e.g. trophic shifts), photosymbiont physiology, and density. The broad ecological response of functional trophic groups and specific foraminiferal species contributes to their utility as biological indicators of water quality.

Within shallow-water tropical marine environments, benthic foraminifera contribute a significant proportion of the carbonate sediment (Murray 1991). In isolated patches, autochthonous sediment production can be attributed to a mono-species population of foraminifera, for example *Amphisorus kudakajimensis* from Ryukyu Islands in Japan (Fujita

et al. 2000) and *Baculogypsina sphaerulata* from Lizard Island in Australia (Hyams-Kaphzan and Lee 2008). On the contrary, highly diverse communities (> 30 species) can be found within 10cc of sediment, while anoxic sediment will yield only highly tolerant species, if any. As the biology of more species is understood so too is their ecological importance as biological indicators of environmental alterations.

The aim of this paper is to provide a short review on the current use and knowledge of benthic foraminifera as indicators of water quality.

Foraminifera as biological indicators

The FORAM index (Hallock et al. 2003) was originally developed in the Caribbean for rapid assessment and suitability of water quality to support reef growth. This index is calculated by grouping foraminiferal taxa in three groups, photosymbiont-bearing, opportunistic, and other heterotrophic taxa. So it largely reflects the uneven distribution of these three functional groups. The utility of the FORAM index (FI) was shown to provide regional (Puerto Rico, Florida Keys) and temporal (30 year

comparison) assessment of ecological conditions (Hallock et al. 2003). From the first use in the Great Barrier Reef (GBR), it became apparent the applicability of the index is suitable for reef systems outside the western Atlantic and Caribbean (Schueth and Frank 2007). For example, the FORAM index was correlated to the distance from the mainland along a known water-quality gradient in the GBR, which also reflected decreasing nutrient and increasing light availability (Uthicke and Nobes 2008). Supplementary examples of the use of benthic foraminifers in coastal marine systems can be found in Table 1.

Even though benthic foraminiferal composition has provided a reliable indication of water quality changes, it doesn't appear to be correlated with coral or algae cover (Uthicke et al. 2010; Velasquez et al. 2011). As shown from the Colombian Caribbean, no clear trends were observed when correlating the percent of coral or algal cover with the FI (Velasquez et al. 2011). Similarly, coral assemblages from the GBR were found to vary from similar environmental conditions, even though foraminiferal assemblages and variation in the FI was largely explained by water quality parameters (Uthicke et al. 2010). The Brazilian reefs dominated by chapeirões (isolated columnar mushroom-shaped corals) present some of the best coral cover in the Abrolhos area, however the fine-grained sediment below yields a low FI value (Barbosa et al. 2009). Perhaps, these differences are due to a broader number of controlling factors influencing coral/algal cover, e.g., herbivorous predation, tropical storms and light attenuation. Therefore, it would seem foraminifera are more effective than corals at detecting water quality alteration.

Other indices for foraminifera have been developed to quantitatively analyse water quality, for example, the *Ammonia-Elphidium* index (Sen Gupta et al. 1996) and test deformities (Alve 1995; Yanko et al. 1998). The high occurrence of *Ammonia* spp., in contrast to *Elphidium* spp., suggests increased pollution (from fertilizers, heavy metals and hydrocarbons), low salinity and/or hypoxic environments (Sen Gupta et al. 1996; Frontalini and Coccioni 2008; Carnahan et al. 2009; Debenay and Fernandez 2009). Test deformities can also reflect intraspecific variation; however among free living species a larger percentage is generally found in highly polluted areas (Alve 1995). More specifically, Jayaraju et al. (2008) observed the nature and concentration of a pollutant could be indicated by morphological abnormalities among benthic foraminifera. Yet, descriptive indices such as diversity, evenness and richness appear to be

less specific for the evaluation of resilience and water quality. Paradoxically, foraminifer diversity has been found to decrease as nutrient conditions improve (Barbosa et al. 2009; Velasquez et al. 2011), while the same can be said for highly polluted areas (Alve 1995), therefore highlighting species specificity as well as possible inconsistent interpretation coming from different ecological indices.

The importance of the photosymbiont

Housing photosymbiont algae is an advantage to many marine organisms living in oligotrophic conditions, as energy-rich photosynthate carbon is translated to the host. Due to the possibility that some, but not all photosymbiont-bearing foraminifera may harbor two or, rarely, three varieties of endosymbiotic algae, for example diatoms, dinoflagellates, unicellular chlorophytes, unicellular rhodophytes and/or cyanobacteria (Lee et al. 1980), it would appear foraminifera are particularly good partners for the establishment of photosymbioses (Lee 2006). This would suggest light as main factor controlling the distribution and growth of these species; however, this was not confirmed in laboratory and field experiments from the Central GBR (Nobes et al. 2008). On the contrary, it would appear essential nutrients (e.g., nitrogen and phosphorus) influenced internal competition for carbohydrates that drive host growth (Reymond et al. 2011), which produces a negative exponential correlation between the multiplication of the photosymbiont and the translocation of photosynthate to the host (Dubinsky and Berman-Frank 2001).

Bleaching among photosymbiont-bearing species is a generalised process triggered by a multitude of environmental conditions. Hallock et al (1986) first recognized the loss of photosymbionts (bleaching) to occur among *Amphistegina* spp. due to photic stress, while subsequent field and laboratory studies further collaborated the sensitivity of foraminifera photosymbiosis to photo-oxidative stress (Hallock et al. 1995; Talge and Hallock 2003; Williams and Hallock 2004). Additionally, partial bleaching (mottled appearance) was observed in *Amphistegina* spp. from the western Australian shelf at temperatures less than 25°C (Hallock 2000) In an example from Belize, *Sorites dominicensis*, photosymbiont bleaching was associated to elevated water temperatures, high levels of irradiance, influx of freshwater and extended periods of aerial exposure (Richardson 2009). Furthermore, heat stress (32-33°C) during a 6d period measured a loss in photosynthetic activity, Chlorophyll *a* and photosymbiont density in three prominent reef species, *Amphistegina radiata*, *Heterostegina depressa*, and

Calcarina hispida (Schmidt et al. 2011). As shown by both field and laboratory experiments, it is highly likely photosymbiont-bearing species will be negatively impacted by predicted increases in sea surface temperatures. For a detailed review on the implications of bleaching in photosymbiont bearing foraminifera refer to Hallock et al (2006).

Historical records of modern eutrophication

As foraminiferal tests (calcareous exoskeleton) are well preserved in sedimentary deposits, they constitute an important ecological source for reconstructing past environmental conditions (Murray 2006). This presents a useful tool for understanding the baseline environmental conditions prior to human induced and land derived eutrophication and pollution in the coastal marine environment. The effect of coastal eutrophication via anthropogenic agricultural activity and waste water outflows has resulted in marked faunal transitions around the world, for example in the northern Adriatic Sea (Barmawidjaja et al. 1995) and in the GBR (Uthicke et al. 2012). In Japan, the development of modern benthic foraminiferal composition coincides with the industrial revolution in the early 1900s. Here historical records show that a shift occurred towards high-density/low-diversity assemblages (Tsujimoto et al. 2008). More recent assemblages are characterised by hypoxic-tolerant species, such as *Ammonia beccarii*, *Eggerella advena*, and *Trochammina hadai*, and are still prevailing in Osaka Bay, Japan 30 years after the imposition of discharge restrictions (Tsujimoto et al. 2008). The striking community shifts in these examples emphasises the ecological connection between land use and benthic ecosystems as well as the lack of recovery of community composition to pre-industrial conditions.

Preventative management building resilience

Establishing biological time series based on foraminifera is a relatively easy and cost-effective way to evaluate changes in the environment through time (Hallock et al. 2003). From the cellular to the community level, foraminifera are indicators of water quality and temperate changes, as shown by shifts in photophysiology effectiveness, abnormal test formation, and assemblage composition (Table 1). However, the applicability of foraminifera to management depends on the level of specificity, the amount of environmental stress and the response time. The response time is largely dependent on the specificity of the parameter measured, for example bleaching can occur within days of high temperature and light exposure, whereas community shifts may

take weeks to months to be evident in the sediment record (summarised in Fig. 1). Therefore, preventative management at the community and ecosystem level might be achieved by understanding early warning thresholds at the cellular and organism level. However, a generalized model of cause and effect at the organism level does not necessarily predict the same outcomes for all ecosystems in the same way. In this sense, it is why a combination of ecological data and physical parameters are needed to understand the responses of individual systems to water quality.

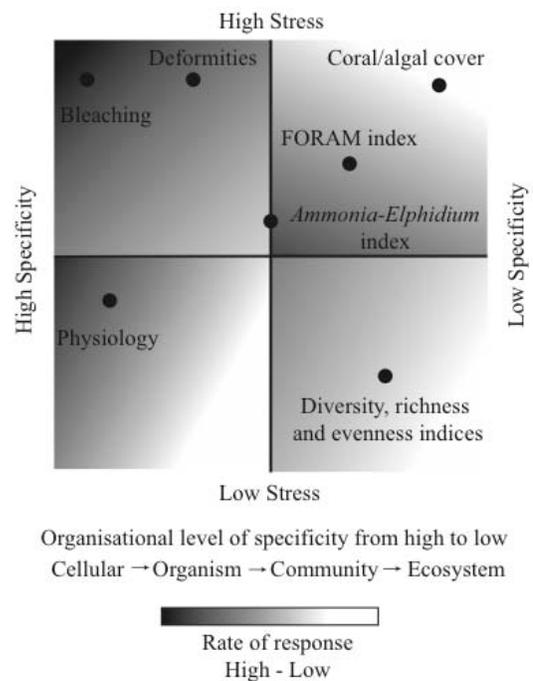


Figure 1. Conceptual diagram summarising the use of foraminifera at different organisational resolution (i.e., cellular to ecosystem), response times (e.g., days to years) and the level of stress. Coral/algal cover is included as an example of a larger ecosystem process.

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Table 1. Examples of studies using benthic foraminifera as bioindicators to investigate the effect of eutrophication, light and temperature. This is not an exhaustive list but rather highlights key papers. Abbreviations, FI for FORAM (Foraminifera in Reef Assessment and Monitoring) Index, MPA for Marine Protected Area, Non-MPA for Non-Marine Protected Area).

Source of stress and response	Species	Location	Reference
<i>Eutrophication</i>			
Benthic foraminiferal associations indicate a steadily increasing nutrient load with a marked foraminiferal transition coinciding with increase agricultural and waste water disposal.	Total community	Po delta, Adriatic Sea	Barmawidjaja et al. 1995
Development of the FORAM index (FI). Identified temporal and regional symptoms of stressed caused by nutrification.	Total community	Key Largo and Puerto Rico	Hallock et al. 2003
Despite differences in proximity to the coast, Heron Is. and Low Isles both have FI > 4 indicating good water quality.	Total community	Great Barrier Reef	Schueth and Frank 2007
Bottom-water hypoxia during the early stage of eutrophication caused a shift to less diverse highly tolerant faunal assemblage.	Total community	Osaka Bay, Japan	Tsujimoto et al. 2008
A shift in assemblage composition towards larger photosymbiont-bearing taxa from the turbid inner shelf reefs towards clearer outer shelf reefs.	Total community	Great Barrier Reef	Uthicke and Nobes 2008
Populations of photosymbiont-bearing taxa decreased in the past 65 years, while stress-tolerant taxa, especially <i>Ammonia</i> spp., have increased in predominance.	Total community	Biscayne Bay, Florida	Carnahan et al. 2009
Discrepancy between the FI and coral cover. The foraminiferal assemblage appears to be responding greatest to sediment textures and physical conditions, such as hydrodynamics and light availability.	Total community	East Brazilian margin	Barbosa et al. 2009
Positive correlation of FI to distance from coast, significant difference between FI to substrate and regions.	Total community	Morton Bay, SE Queensland	Narayan and Pandolfi 2010
Decreased FI with increasing proportions of fine grain sediments and high organic matter content.	Total community	Great Barrier Reef	Uthicke et al. 2010
A shift from mixotrophic assemblages in oligotrophic environments to smaller heterotrophic dominated assemblages (particularly <i>Ammonia</i> sp.) closer to sewage outfall.	Total community	Aegean Sea, NE Mediterranean	Koukousioura et al. 2011
Growth rates increased when associated effect of eutrophication and temperature was reduced.	<i>Marginopora vertebralis</i>	Laboratory and field experiments	Reymond et al. 2011
Lower diversity and FI were calculated in MPA compared to non-MPA sites. Likely due to higher impact from tourism and agriculture. Additionally, the FI was not correlated to coral or algae cover.	Total community	Columbia	Velasquez et al. 2011
<i>Light/ Ultraviolet radiation</i>			
Growth rate increased with more light intensity, however at 40 $\mu\text{E}/\text{m}^2$ there were signs of mottled or pale photosymbionts at the end of the experiment, while those grown at lower light levels retained a rich brown color.	<i>Amphistegina</i> spp.	Laboratory experiments	Hallock et al. 1986
Increased proportion of living population was found to have mottled or test deformities in spring and recovery in the winter.	<i>Amphistegina gibbosa</i>	Field observations	Hallock et al. 1995
Growth was significantly inhibited when UVB was 0.105 W m^{-2} .	<i>Amphistegina gibbosa</i>	Laboratory experiments	Williams and Hallock 2004
Increased maximum quantum yield (F_v/F_m) in the lower light conditions.	Mixed photosymbiont species	Laboratory experiments	Nobes et al. 2008
Demonstrated oscillation of maximum quantum efficiencies according to the light-dark cycle after a 48h exposure to different light treatments.	Mixed photosymbiont species	Laboratory experiments	Ziegel and Uthicke 2011
<i>Temperature</i>			
At 13–15 $\mu\text{mole photons m}^{-2} \text{ s}^{-1}$ PAR individuals exhibited deterioration of photosymbionts and increase degraded endoplasm. While, at 6–8 $\mu\text{mole photons m}^{-2} \text{ s}^{-1}$ PAR and 32°C, the number of photosymbionts declined but degraded endoplasm did not increase.	<i>Amphistegina gibbosa</i>	Laboratory experiments	Talge and Hallock 2003
Elevated temperature of 31°C in addition to extremely low spring tides causes 13-16% of the population to bleach.	<i>Sorites dominicensis</i>	Belize and Florida	Richardson 2009
Temperatures > 30°C appeared to stress the foram–diatom endosymbiosis indicated by colour changes associated with the effects of bleaching.	Mixed photosymbiont species	Laboratory experiments	Schmidt et al 2011

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