Marine Pollution Bulletin xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Benthic foraminiferal assemblages from Moreton Bay, South-East Queensland, Australia: Applications in monitoring water and substrate quality in subtropical estuarine environments

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ARTICLE INFO

Keywords:
Moreton Bay
Benthic foraminifera
Bio-indicators
Estuary
Water quality
FORAM Index

ABSTRACT

We assess species composition, assemblage structure and distribution of the benthic foraminiferal assemblages from diverse substrates in Moreton Bay, South-East Queensland, Australia. Analysis of 47 surface sediment samples revealed 69 species, three distinct foraminiferal assemblages and six sub-assemblages. The assemblages from the western Bay are characterized by stress tolerant taxa and the lowest diversity, whereas the assemblages from the eastern Bay are characterized by symbiont-bearing taxa and high diversity. We found a correlation between foraminiferal assemblages and substrate conditions that was indicative of strong environmental gradients (substrate type, water quality and salinity), from an urban-impacted assemblage in the westernmost part of the Bay, to a hyposaline, estuarine-influenced assemblage in the western Bay to a nearly normal marine to hypersaline assemblage in the eastern Bay. The FORAM Index was consistent with the changes in water and sediment quality gradient, from the western shoreline to the eastern Bay. Thus the foraminiferal assemblages of Moreton Bay make excellent bio-indicators of environmental changes in a subtropical, estuarine setting in eastern Australia.

1. Introduction

The response of benthic foraminifers to natural and anthropogenic stressors has several applications for investigation of environmental change in estuarine and reef studies (Carnahan et al., 2009; Hallock et al., 2003; Richardson, 2006; Sabean et al., 2009; Schueth and Frank, 2008; Scott et al., 2005; Tsujimoto et al., 2006; Uthicke and Nobes, 2008). Foraminifera are increasingly used in assessing marine environments and in resource monitoring (Carnahan et al., 2009; Debenay and Fernandez, 2009; Luan and Debenay, 2005), particularly in coastal regions where impacts from increasing human populations are leading to rapid degradation of nearshore ecosystems (Jackson et al., 2001; Lotze et al., 2006; Pandolfi et al., 2003). The development of foraminiferal indices for use in regional ecological assessment and monitoring strategies have provided a useful tool for carrying out baseline studies and in understanding ecological changes in marine communities (Carnahan et al., 2009; Hallock et al., 2003).

Benthic foraminifers are recognized as exceptional bio-indicators because of their (1) short life cycles; (2) preservation in marine sediments; (3) diversity and abundance; (4) sensitivity to rapidly changing environmental conditions; and (5) easy collection with minimal impact to the environment (Carnahan et al., 2009; Murray, 2006; Scott et al., 2005). Statistical analyses of foraminiferal assemblages have been the most common method for carrying out environmental studies, however, more recent applications are utilizing foraminiferal indices as tools for understanding overall ecosystem states and changes (Carnahan et al., 2009; Hallock et al., 2003; Schueth and Frank, 2008). This strategy has the advantage of providing marine park managers with a single, cost-effective indicator for assessing and monitoring impacts on marine resources (Carnahan et al., 2009).

In reef settings, the Foraminifera in Reef Assessment and Monitoring Index (FORAM) developed by Hallock et al. (2003) utilizes large benthic foraminifers (LBFs) as bio-indicators of the environmental conditions that support algal symbiont-bearing organisms and thus reflects environments conducive to optimal/healthy coral reef growth (Cockey et al., 1996; Hallock, 2000; Hallock et al., 2003). Symbiont-bearing foraminiferal assemblages should parallel coral abundance where water quality is the major factor controlling distribution (Schueth and Frank, 2008). Although developed in the Caribbean region, Hallock et al. (2003) recommend application of the FORAM Index reefs worldwide. Other

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doi:10.1016/j.marpolbul.2010.07.012

studies have utilized modified indicator functions to determine species with a broad to specialized tolerance to environmental conditions in nearshore and reef settings (Carnahan et al., 2009; Renema, 2008; Sen Gupta et al., 1996).

The aims of this paper are to: (1) assess benthic Foraminifera species composition and assemblage structure from the subtropical estuary of Moreton Bay, South-East Queensland, Australia; (2) describe the benthic assemblages and their spatial distribution in relation to substrates and environments; (3) apply the FORAM Index (FI) to assess whether the substrate/water quality conditions are influencing the taxonomic composition of the foraminiferal assemblages; and (4) determine the potential for utilizing foraminifers as indicators of environmental change in subtropical Moreton Bay Marine Park.

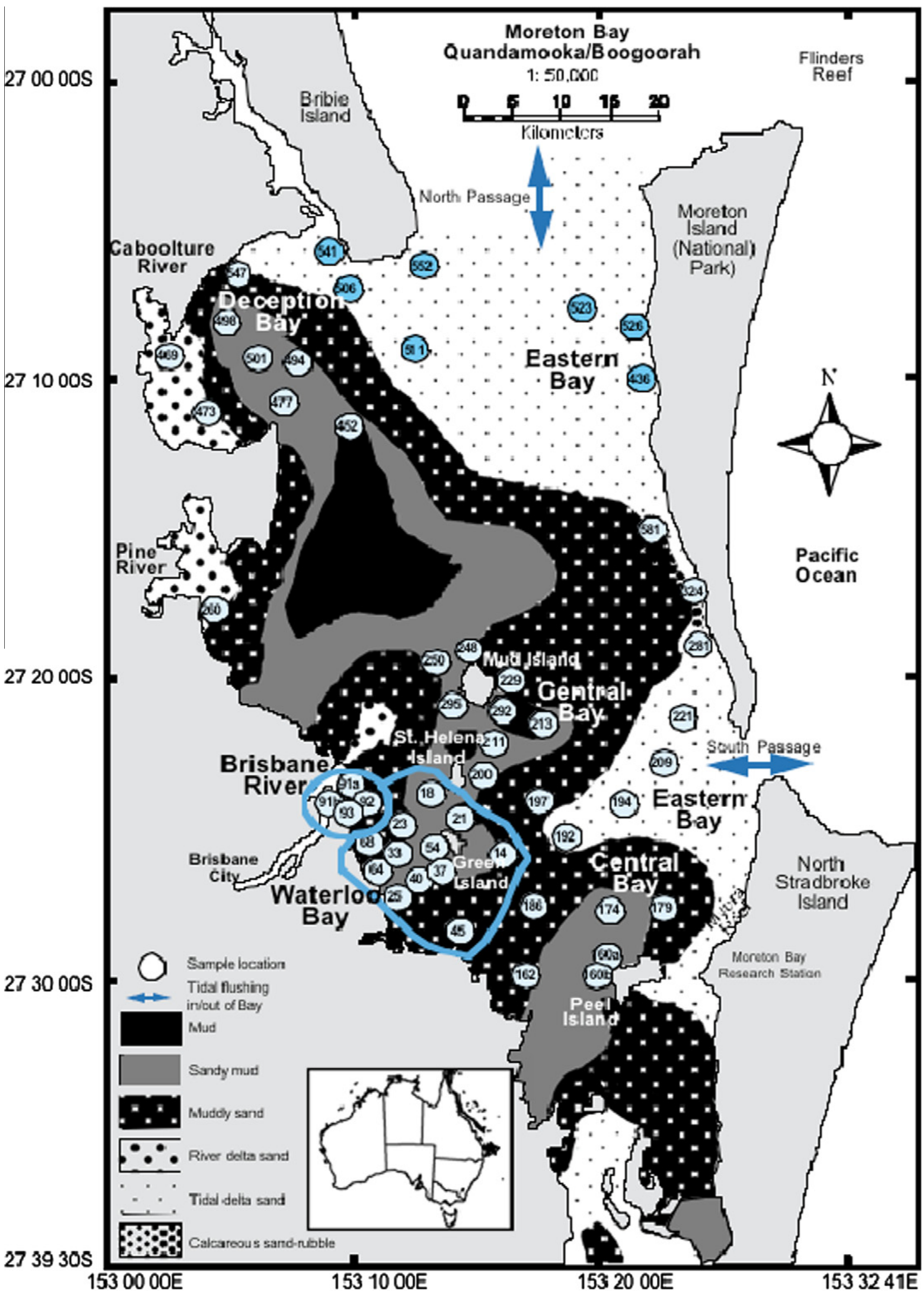

Fig. 1. Map of the Moreton Bay Marine Park, South-East Queensland, showing the approximate location of the study samples. The distribution of the substrate types discussed in this study are illustrated (modified from Heggie et al., 1999). Seven samples collected from the northern Bay (shown in darker-coloured circles) did not yield sufficient numbers of foraminifer individuals for analysis.

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2. Study location

Moreton Bay is located at approximately 27°S, 153°E in South-East Queensland, Australia (Fig. 1). It is a large (ca. 1500 km^2), mesotidal, semi-enclosed, estuarine embayment, which is relatively shallow (<25 m), approximately 80 km long and 35 km wide (Lang et al., 1998). The Bay is sheltered from the Pacific Ocean by a series of sand barrier islands to the east (Moreton, North Stradbroke and South Stradbroke islands) and to the northwest (Bribie Island) (Kelley and Baker, 1984). Moreton Bay receives sediment run-off from five major catchments (Logan, Brisbane, Pine and Caboolture rivers and Pumicestone Passage; Fig. 1) with a combined catchment area of 21,220 km^2 (Dennison and Abel, 1999). The Brisbane River is the largest catchment (13,100 km^2) and runs through the metropolitan city of Brisbane, capital of Queensland and the fastest growing city in Australia (Australian Bureau of Statistics, 2009). The highest population density occurs along the Brisbane River, with major industrial ports occurring near the mouth of the river (Cox and Preda, 2005).

The ebb and flood tidal currents, which predominantly flow north and south, respectively (via the North Passage), have created tidal deltas in the northeastern and eastern regions of the Bay (Harris et al., 1992; Robinson, 1960; Stephens, 1978) (Fig. 1). Circulation inside the Bay follows a clockwise pattern with northward water movement on the western side and southward movement on the eastern side of the Bay. This pattern is due to the prevailing winds and tidal flow over a spring and neap cycle (of ~14 days) (Dennison and Abel, 1999). Oceanic exchange occurs mainly via the North Passage, with restricted exchange occurring through the South Passage (Dennison and Abel, 1999) (Fig. 1). Due to its shallow bathymetry, water circulation is generally restricted in the western Bay and overall residence time is approximately 45 days for the entire Bay (Dennison and Abel, 1999).

The climate in this region is subtropical with hot, humid, wet summers and mild, dry winters that are subject to the El Niño Southern Oscillation (ENSO) (Eslami-Andargoli et al., 2009). The average annual rainfall is approximately 1186 mm (Brisbane International Airport), ~70% of which occurs during the wet summer season (November–April; Australian Bureau of Meterology, 2010). The annual mean temperature ranges between 15.7 °C and 25.4 °C (Australian Bureau of Meterology, 2010). The prevailing winds are from the southeast during the winter, with northeasterly winds occurring during the summer season. The region falls close to the boundary where the subtropical gyre, the East Australian Current, which is a high speed warm-water current, separates from the coast (~32°S, 152°E) and flows southwestwards into the Tasman Sea (Yassini and Jones, 1995).

3. Materials and methods

3.1. Sampling

The collection of surface sediment samples from Moreton Bay was carried out during September 2007 to January 2008. The sampling locations were approximated from the 1970s Geological Survey of Queensland's (GSQ) field studies (Jones and Stephens, 1981; Palmieri, 1976a), using the Queensland Topographic Sheet 9543 Brisbane (1:10,000 scale) map. To investigate the relationship between foraminifera species composition and substrates we sampled from the following geographic regions: Brisbane River estuary (BR), Deception Bay (DB), Waterloo Bay (WB), Central Bay (CB) and Eastern Bay (EB); and the major substrate types in Moreton Bay including: (1) river delta sand; (2) muddy sand; (3) sandy mud; (4) tidal delta sand; (5) tidal delta muds; and 6) calcareous sand and rubble substrate (Fig. 1 and Supplementary Table S1) (Heggie et al., 1999; Stephens, 1992).

In the field, an area of approximately 10 cm^2 of the upper few centimeters of the surface sediment was collected using a 4 Litre Eckman grab sampler or by scooping the surface sediment into a wide necked plastic jar. We examined the thanatocoenosis (total assemblage) of 47 of the 54 sediment samples collected as they contained greater than 200 individuals. The total assemblage provides us with information about the overall conditions that have accumulated over time, whereas the living assemblages reflect microhabitat conditions at the time in which the sample was collected (Alve and Nagy, 1986; Carnahan et al., 2009).

Seven samples (436, 506, 511, 523, 526, 541 and 552; Fig. 1) collected from the northern Moreton Bay tidal sand flats, contained fewer than 50 specimens per sample and therefore were not considered in the analysis. Strong currents, low nutrients and sandy substrates associated with high oceanic exchange via the North Passage, results in constant re-suspension and transport of sediments and is a possible reason for poor test accumulation and preservation in these samples (Dennison and Abel, 1999; Heggie et al., 1999). In other samples, we found specimens stained with a brownish-orange colour (ferric ions). These were reworked from older pre-Holocene sediments (Palmieri, 1976a) and were excluded from our counts.

3.2. Laboratory preparation

The sediment samples were first wet-sieved through a 63 micron (μm) mesh sieve (to separate the fine silt and clay size particles) and air dried overnight. Next they were placed in a sieve shaker for 10 min, dry-sieved into six grain size fractions (2.0 mm = −1Ø (phi), 1.0 mm = 0Ø, 0.5 mm = 1Ø, 0.25 mm = 2Ø, 0.125 mm = 3Ø and 0.63 mm = 4Ø) following Hallock et al. (2003) and weighed for grain size distribution. The raw weights were converted to weight percents for each sample. Sediments were classified into gravel, sand and mud/clay fractions using the standard Udden-Wentworth scale for grain size analysis (Folk, 1974). Sediments were weighed and the percent gravel (greater than 2.0 mm), sand (2.0 mm to 0.125 mm) and mud/clay (<0.63 mm) fractions were determined for each sample (Supplementary Table S1).

Based on previous determinations of ideal quantitative counts, between 200 and 300 individual foraminifer specimens were handpicked for identification from each sample (Murray, 2006; Patterson and Fishbein, 1989; Scott et al., 2001). Benthic foraminiferal specimen were collected from the 2.0 mm to 0.125 mm size fraction and where possible for identification from the 0.063 mm size fraction. The taxonomic assignments were determined using a standard binocular dissecting microscope. Images were captured using the JSM-6400F Scanning Electron Microscope at the Centre for Microscopy and Microanalysis, The University of Queensland. The common Foraminifera species identified in this study are listed in Appendix 1 and a few are illustrated in Plate 1. The systematic (suprageneric) classification follows Loeblich and Tappan (Loeblich and Tappan, 1988). Species were identified using several Australian and Indo-Pacific region taxonomic monographs (Albani, 1974, 1978, 1979; Christie, 1994; Collins, 1958; Jones, 1994; Lobegeier, 1995; Loeblich and Tappan, 1994; Michie, 1982, 1987; Yassini and Jones, 1995).

3.3. Analysis of foraminiferal assemblages

For each of the samples we determined the species relative abundance and indices for richness (d), equitability (J) and diversity (H' and Fisher alpha). The relative abundance (RA) was calculated from the number of individuals of a species (n) and the total number of individuals in the sample (T), where RA = $n \times 100/T$. We calculated frequency of occurrence (FO), as the ratio between the number of samples where the species occurred (p) and the total

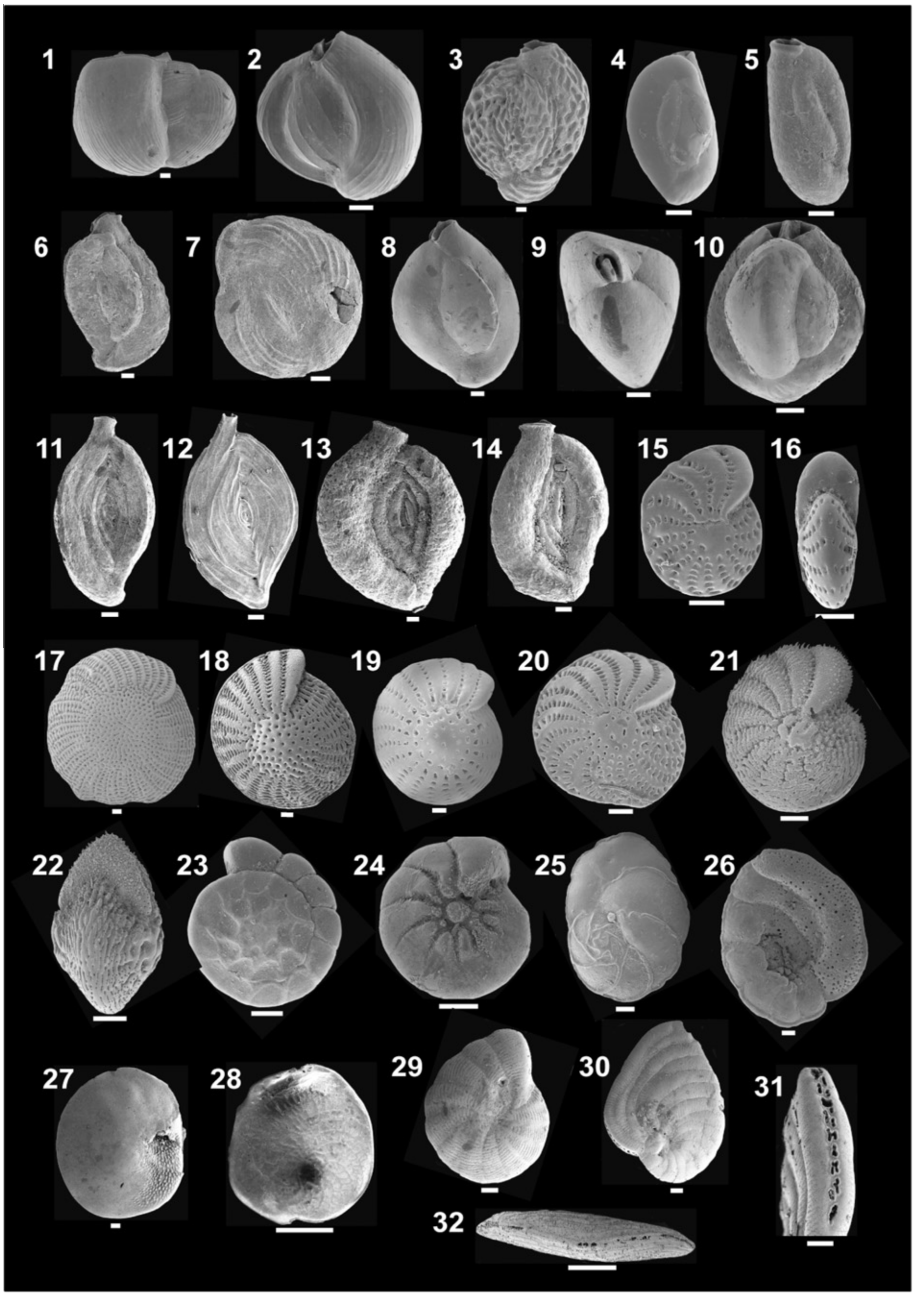

Plate 1. 1,2: *Flintina bradyana* Cushman, 1921 (scale bar = 100 μm); 3: *Quinqueloculina philippinensis* Cushman, 1921 (scale bar = 100 μm); 4: *Quinqeloculina seminula* (Linne, 1767) (scale bar = 100 μm); 5: *Trioculina oblonga* (Montagu, 1803) (scale bar = 100 μm); 6: *Quinqueloculina subpolygona* Parr, 1945 (scale bar = 100 μm); 7: *Pseudomassilina macilenta* (Brady, 1884) (scale bar = 100 μm); 8,9: *Quinqueloculina lamarckiana* D'Orbigny, 1839 (scale bar = 100 μm); 10: *Triloculina trigonula* (Lamarck, 1804) (scale bar = 100 μm); 11: *Spiroloculina communis* Cushman and Todd, 1954 (scale bar = 100 μm); 12: *Spiroloculina corrugata* Cushman, 1917 (scale bar = 100 μm); 13: *Spiroloculina scorbiculata* (Lamarck, 1804) (scale bar = 100 μm); 14: *Spiroloculina rugosa* (Cushman and Todd, 1944) (scale bar = 100 μm); 15,16: *Elphidium advenum* (Cushman, 1922) (scale bar = 100 μm); 17: *Elphidium craticulatum* (Fichtel and Moll, 1798) (scale bar = 100 μm); 18,19: *Elphidium discoidalis multiloculum* Cushman and Ellisor, 1945 (scale bar = 100 μm); 20: *Elphidium crispum* (Linne, 1758) (scale bar = 100 μm); 21,22: *Elphidium hispidulum* Cushman, 1936 (scale bar = 100 μm); 23,24: *Ammonia beccarii* (Linne, 1767) (scale bar = 100 μm); 25,26: *Poroeponoides lateralis* (Terquem, 1878) (scale bar = 100 μm); 27: *Amphistegina lessoni* D'Orbigny, 1826 (scale bar = 100 μm); 28: *Heterostegina depressa* D'Orbigny, 1826 (scale bar = 1 mm); 29: *Peneroplis pertusus* (Forskål, 1775) (scale bar = 100 μm); 30,31: *Peneroplis planatus* (Fichtel and Moll, 1798) (scale bar = 100 μm); 32: *Alveolinella quoyi* (D'Orbigny, 1826) (scale bar = 1 mm).

number of samples analyzed (P), where $FO = p \times 100/P$ (Araújo and Machado, 2008).

Margalef's richness index (d) was calculated as: $d = (S - 1)/\text{In}(n)$, where S is the number of taxa and n is the number of individuals. Peilou's equitability index (j) was calculated as: $j = H(s)/H(\text{max})$, where $H(s)$ = Shannon index and $H(\text{max})$ = the theoretical maximum value of $H(s)$ if all species in the sample were equally abundant (Pielou, 1966). The Shannon–Wiener diversity index was computed on the basis of the relative abundance data: $H(S) = -\sum((n_i/n)\ \text{In}\ (n_i/n)$, where n = the total number of individuals and n_i = number of individuals of taxon i (Murray, 2006; Shannon, 1948). For comparison with the Shannon Diversity, the Fisher Alpha Diversity index was also calculated as $S = a^*\ln(1 + n/a)$ where S is number of taxa, n is number of individuals and a is the Fisher's alpha. A one-way analysis of variance (ANOVA) was used to test the null hypothesis of no difference in the assemblage means for both the different substrates and the different regions in Moreton Bay. One-way ANOVA, Kolmogorov–Smirnov (to test for normal distribution) and Tukey's pair-wise comparison tests were performed using PRISM version 5.0 software.

We examined the relationship between the species composition of the foraminiferal assemblages and their associated substrates using multivariate non-parametric techniques (Clarke and Ainsworth, 1993). Foraminifer relative abundance data were fourth root transformed to lessen the influence of the more prevalent species and increase the weight of rare species (Clarke and Green, 1988; Clarke et al., 2006). Hierarchical cluster analysis (group average) and ordination by non-metric multidimensional scaling (NMDS) using the Bray-Curtis similarity index was used to display the spatial patterns in faunal variability across the Bay and across the different substrates and geographic regions. The null hypothesis (H_0) of no difference in species composition among the substrate types and among the geographic regions was tested using one-way analysis of similarity (ANOSIM) (Clarke, 1993). The ANOSIM test statistic (R) is close to 1 when there are large differences in species composition among groups compared to within groups and close to 0 when there are no group differences (Clarke, 1993).

Similarity percentages (SIMPER analysis) were carried out to determine which taxa contributed the most to the average (percent) similarity within each substrate type and which taxa contributes to the dissimilarity among the different substrate groups (Clarke, 1993; Uthicke and Nobes, 2008). SIMPER analysis provides several statistical parameters (total similarity/dissimilarity, average abundance, average similarity/dissimilarity, ratio similarity/dissimilarity to standard deviation and percent contribution) for each of the component species. Multivariate analysis was performed using PRIMER-e version 6.0 software (Clarke and Warwick, 1994).

3.4. Water and sediment quality assessments

The study of large reef dwelling benthic foraminiferal assemblages led to the development of the Foraminifers in Reef Assessment and Monitoring (FORAM) Index (FI) (Hallock et al., 2003). This is an index for assessing whether a benthic environment is hospitable to symbiont-bearing organisms (i.e., corals and reefal foraminifers) thus providing a measure of water and sediment quality (Hallock, 2000; Hallock et al., 2003; Schueth and Frank, 2008).

We placed our foraminifera species into three functional groups as defined by Hallock et al. (2003): (a) symbiont-bearing taxa (s), which include forms that possess endosymbionts and usually occupy similar environments to corals; (b) opportunistic taxa (o), which are tolerant of stressful and hypoxic conditions; and (c) other small heterotrophic taxa (h), which commonly include the Miliolida (Hallock et al., 2003; Schueth and Frank, 2008; Uthicke and Nobes, 2008). Next, the proportion of individuals in each of the three functional groups (P) was determined by the total number of individuals in each functional group (N) divided by the total number of individuals in the sample (T):

$$(a)P_s = N_s/T, \quad (b)P_o = N_o/T, \quad (c)P_h = N_h/T$$

The FI is calculated by adding the three proportions in the following formula:

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

FI values of 4 or greater correspond with environments with good water quality conditions that are conducive to coral growth (i.e., contain at least 25–30% symbiont-bearing foraminifers) (Hallock et al., 2003; Schueth and Frank, 2008). Values that fall between 2 and 4 indicate a marginal environment for reef growth, but one that has the potential for faunal recovery after damage (Hallock et al., 2003). FI values that fall below 2 indicate that the sediment and water quality are too inhospitable for symbiont-bearing organisms to flourish (Hallock et al., 2003; Schueth and Frank, 2008).

4. Results

4.1. Moreton Bay substrates and environments

We recognised the following substrate types in Moreton Bay (Fig. 1; Supplementary Table S1): (1) river delta sand (greater than 90% immature quartz/lithic sand); (2) muddy sand (50–90% fine to very fine sand); (3) sandy mud (50–90% mud/silt); (4) mud (greater than 90% mud/silt smaller than 0.064 mm) (5) tidal delta sand (greater than 90% mature, medium-grained quartz sand); and (6) calcareous sand/rubble (greater than 90% calcareous biogenic sand/rubble). The first five substrates have been previously reported for Moreton Bay (Flood, 1978; Heggie et al., 1999; Lang et al., 1998; Palmieri, 1976a; Stephens, 1992), but the last (calcareous sand/rubble) had not. The calcareous sand/rubble substrate occurred off western Moreton Island in approximately five to eight meters water depth and consists of medium to fine carbonate sand with abundant coralline algal and foraminiferal rubble. This substrate type is characteristic of subtropical Hervey Bay, located to the north of Moreton Bay (Bassi et al., 2009; Lund et al., 2000). Coralline algae or rhodoliths are important constituents of the calcareous, bioclastic, gravelly sediments in Eastern Australia (Bassi et al., 2009; Lund et al., 2000).

The sediments in the westernmost river channels and river delta sand-mud flats (Brisbane, Pine and Caboolture River estuaries) consist predominantly of siliceous (feldspathic), immature quartz sand that is characterized by a light brown-gray colour (Supplementary Table S1). Grain sizes range from medium (0.25–0.50 mm) to fine (0.125–0.250 mm) sand and are often rich in organic debris. Two samples contained mud fractions greater than 88% and occurred close to dredge spoil locations, while one sample (from Deception Bay) consisted of mud greater than 90% derived from the Brisbane River delta (Supplementary Table S1).

The Waterloo Bay region occurs adjacent to and south of the Brisbane River delta (Fig. 1) and consists of muddy sand and sandy mud substrates rich in biogenic and organic components. Grain sizes generally ranged from very fine (0.063–0.125 mm) to fine (0.125–0.250 mm) sand with gravel-sized (>2 mm) fractions of calcareous debris (Supplementary Table S1). This region is estuarine and hyposaline. Waterloo Bay occurs west of the fringing reef islands. Coral and mollusk shell rubble is a common constituent of the gravel-sized sediments (>4 mm) (Fig. 1).

The central Bay (surrounding central coral islands including Mud, St. Helena, Green and Peel; Fig. 1) consists of muddy sand and sandy mud substrates, rich in organic and bioclastic constituents including mollusk shells and fragments, skeletal debris, coralline algae, bryozoans, foraminifers, ostracods, diatoms, dinoflagellates, corals (and coral rubble), tube worms, crustaceans and seagrass. Grain sizes generally ranged from very fine (0.063–0.125 mm) to fine (0.125–0.250 mm) sand with gravel-sized (>2 mm) fractions of calcareous debris (Supplementary Table S1). The vast majority of the shell material was fragmentary and weathered.

The Deception Bay (Fig. 1) substrates are similar to that of the central Bay muddy sand and sandy mud substrates. This region is regularly exposed to oceanic conditions (from the North Passage). Grain sizes ranged from medium sand in the river delta to very fine sand and mud (one sample) in the estuarine flats (Supplementary Table S1). No reefs occur in this region, although patchy seagrass beds are common.

The tidal delta sand flats and channels of the northeastern and eastern Bay are characterized by light grey coloured, mature sand composed of medium-grained (0.250 mm) quartz sand

(Supplementary Table S1). In the eastern Bay (adjacent to the South Passage; Fig. 1) dense seagrass habitats characterize the tidal delta.

4.2. Species composition and assemblage structure

We identified 69 species belonging to 35 genera within the orders Textularida, Miliolida and Rotaliida (Appendix 1; Fig. 2a). Opportunistic species, which can tolerate a wide range of stressful conditions such as low oxygenic and anthropogenic pollution (Hallock et al., 2003), are most common throughout the Bay, particularly in the western Bay. They are significant components of the river delta sand (RDS) substrate (Supplementary Table S2; Fig. 2b). Symbiont-bearing foraminifers, which are indicative of clear water, low nutrient, normal-marine conditions (Hallock et al., 2003) occur in several samples from the tidal delta sand (TDS) substrate of eastern Moreton Bay (Supplementary Table S2). Only three species of agglutinated foraminifers are represented and occurred mainly in the samples from the river delta sand flats, western Bay (Supplementary Table S2).

The species with the highest frequency of occurrence (FO) in the Moreton Bay samples is the opportunistic rotalid *Elphidium discoidalis multiloculum* (92%) (Table 1). This is followed by (opportunistic) *Ammonia beccarii* (81%), (heterotrophic) *Quinqueloculina phillipinensis* (78%) and (opportunistic/heterotrophic) *Elphidium hispidulum/Flintina bradyana* (75%) (Table 1).

The number of species (S) identified per sample ranged between 5 and 29 (Fig. 3), with the most species occurring in the Eastern TDS and the least in the RDS. The Margalef species richness index (D) ranges between ∼0.9 and 5.9 and mean richness is highest in the MDS and the Waterloo Bay region (Fig. 4). Significant differences (one-way ANOVA, $F = 4.5$, $p = 0.004$) are observed between the foraminiferal assemblage from the RDS (lowest richness) and MS/SM (highest richness) (Fig. 4a). Significant differences ($F = 9.5$, $p < 0.0001$) are observed across all regions of Moreton Bay (Fig. 4d). Pielou's equitability index (J) ranges between ∼0.4 and 0.8. Approximately 60% of the samples show an equitability greater than 0.7 (Fig. 3). No significant differences are observed across the different substrates or regions (Fig. 4b and e). The Shannon–Wiener diversity index ranges between ∼0.9 and 2.6 (Fig. 3). No significant differences are observed in the population means among substrates (Fig. 4c). However, significant differences (one-way ANOVA, $F = 5.0$, $p = 0.002$) were observed across regions BR vs. WB, BR vs. CB, and BR vs. EB (Tukey's post-test; Fig. 4f).

There are significant differences in species composition among substrate types (ANOSIM $R = 0.6$, $p < 0.001$) (Table 2a). The pairwise tests show significant differences between all groups, except between MS and SM substrates, which show little separation (Table 2a). Significant differences are observed across the different regions of the Bay, except between Waterloo Bay (WB) and central Bay (CB), which show little separation and are characterized by MS and SM substrates (Table 2b). The non-metric multidimensional scaling (nMDS) ordination for 47 sediment samples from the Moreton Bay substrates shows marked separation among samples from the western RDS and eastern tidal delta sand TDS and CS substrates (Fig. 5). Hierarchical cluster analyses results show the grouping of the samples into the following general region/substrate types (with >60% similarity): (A) Brisbane (Pine) River delta sands; (B) Deception Bay/Caboolture) River delta sand/mud; (C) Waterloo Bay muddy sand/sandy mud; (D) Central Bay muddy sand/sandy mud; (E) Deception Bay muddy sand/sandy mud; (F) eastern Bay tidal delta sand; and (G) eastern Bay calcareous sand/rubble similarity (Fig. 5b).

Similarity percentages (SIMPER) show a strong western to eastern Bay gradient in species composition (Table 3). The RDS and TDS substrates show highest (within group) average similarity (60%)

Table 1
The frequency of occurrence (FO) of the dominant (>50%) and other common (>25%) foraminiferal species in Moreton Bay sediments. The FO is the ratio between the number of samples in which the species occurred and the total number of samples analyzed.

Species	Functional group	FO (%)
Elphidium disc. multiloculum	Opportunistic	91.5
Ammonia beccarii	Opportunistic	80.9
Quinqueloculina phillipinensis	Heterotrophic-other	78.7
Elphidium hispidulum	Opportunistic	74.5
Flintina bradyana	Heterotrophic-other	74.5
Elphidium crispum	Opportunistic	70.2
Spiroloculina angulata	Heterotrophic-other	70.2
Triloculina tricarinata	Heterotrophic-other	68.1
Elphidium craticulatum	Opportunistic	66.0
Triloculina trigonula	Heterotrophic-other	59.6
Spiroloculina antillarum	Heterotrophic-other	51.1
Spiroloculina scorbiculata	Heterotrophic-other	51.1
Quinqueloculina lamarckiana	Heterotrophic-other	48.9
Peneroplis pertusus	Symbiont-bearing	46.8
Pseudomassilina macilenta	Heterotrophic-other	44.7
Peneroplis planatus	Symbiont-bearing	42.6
Pararotalia venusta	Heterotrophic-other	40.4
Ammonia tepida	Opportunistic	38.3
Poroeponoides lateralis	Heterotrophic-other	38.3
Elphidium advenum	Opportunistic	31.9
Quinqueloculina pittensis	Heterotrophic-other	31.9
Trochammina globigeriformis	Heterotrophic-other	31.9
Quinqueloculina subpolygona	Heterotrophic-other	29.8
Amphistegina radiata	Symbiont-bearing	27.6

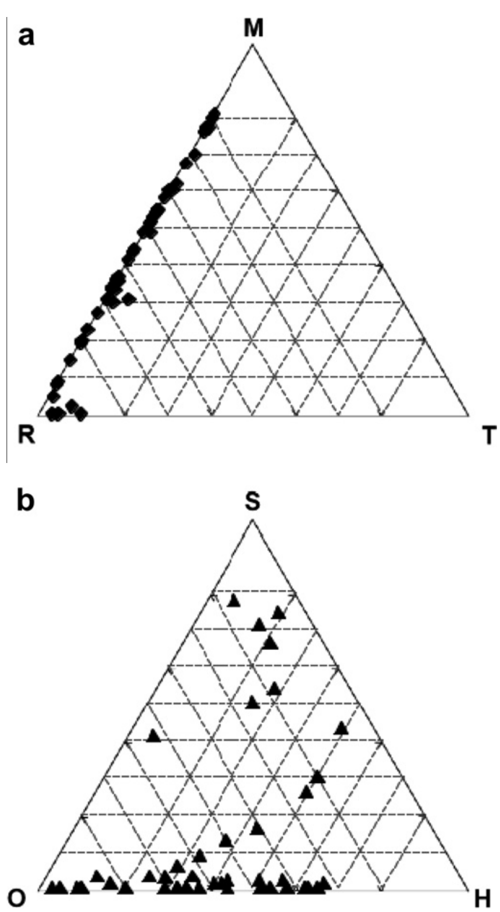

Fig. 2. Ternary diagram of (a) Foraminifera orders, where: M = Miliolida, R = Rotaliida, T = Textulariida(triangular corners represent 100% of the labeled component:);and (b) functional groups,where: S = symbiont-bearing, O = opportunistic, H = other small-heterotrophic (triangular corners represent 100% of the labeled component).

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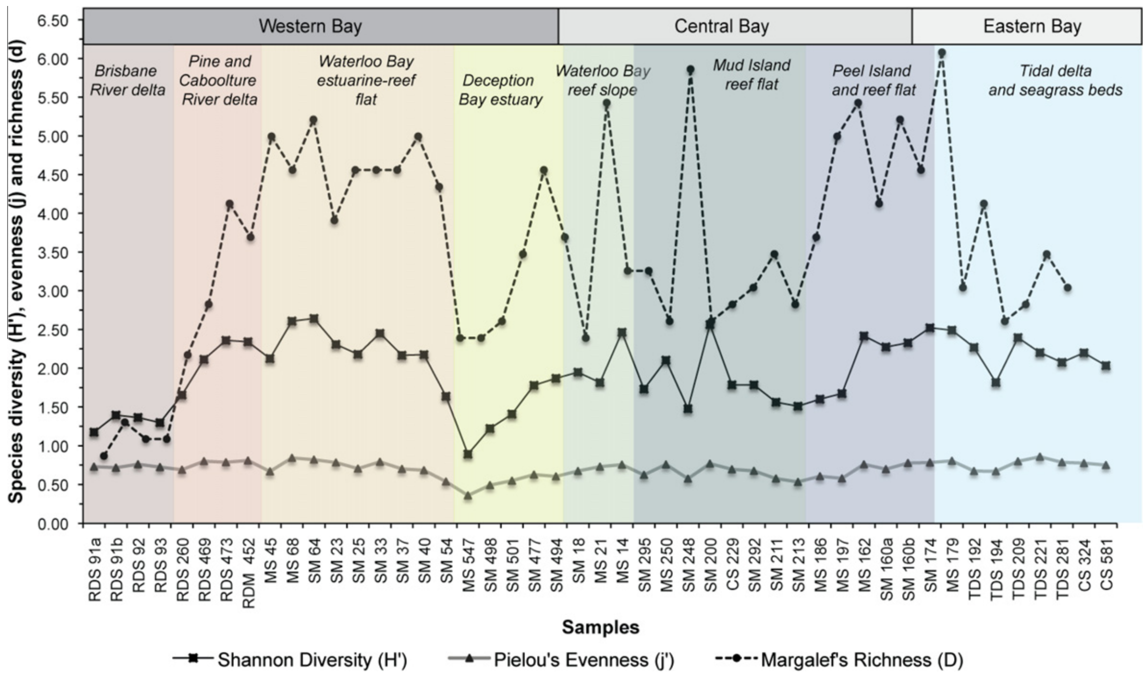

Fig. 3. The Shannon–Wiener diversity (H'), Pielou's evenness (J') and Margalef's richness (D) indices for each of the 47 sediment samples analyzed across the different substrate types from the western to eastern Bay, including: river delta sand (RDS), river delta mud (RDM), muddy sand (MS), sandy mud (MS), tidal delta sand (TDS) and calcareous sand-rubble (CS).

and the MS substrate shows the lowest (36%; Table 3). The highest total dissimilarity (89%) occurs between the RDS and CS substrate types (Table 4). The Brisbane River delta has the highest within region average similarity (~80%) and the central Bay the lowest (~32%). The highest dissimilarity occurred between the Brisbane River delta and the Eastern Bay (91%) and the lowest between the central Bay and Deception Bay (64%) followed by Waterloo Bay and central Bay regions (67%).

4.3. FORAM Index

The FORAM Index (FI) values ranged between 1 and 8 (Table 5 and Supplementary Table S2). Most samples (70%) had FI values less than two. Approximately 11% of the samples fell between two and four; 9% between four and six; 9% between six and eight; and only 2% have an FI value between eight and ten. The FI values correlate positively with an increase in distance from the western shoreline ($r^2 = 0.6$, $p < 0.001$) (Fig. 6a). The highest mean FI values are associated with the tidal delta sand and calcareous sand/rubble substrates in eastern Moreton Bay (Fig. 6b and c). Low values are characteristic of the upper estuarine regions and we found the lowest mean FI values to be associated with the river delta sand substrates of the Brisbane River estuary (Fig. 6b and c). The one-way ANOVA analysis shows that the mean FI of the eastern Bay substrates is significantly different from that of the other groups (Fig. 6b).

5. Discussion

5.1. Foraminiferal distributions in Moreton Bay

Based on our nMDS, cluster and SIMPER analysis, we recognize three distinct foraminiferal assemblages (A, B and C) with six subassemblages in Moreton Bay: Assemblage A-1, Assemblage A-2, Assemblage B-1, Assemblage B-2, and symbiont-bearing Assemblage C-1 and C-2 (Table 5). These assemblages show an association with the different substrate conditions in Moreton Bay (Table 5 and Supplementary Table S2). The species composition, diversity and distribution patterns reflect strong environmental gradients (substrate type, water quality and salinity), from an urban-impacted-hypoxic assemblage in the western Bay's river delta; hyposaline influenced assemblage in the Waterloo Bay region, hyposaline to moderate marine central Bay and a normal marine to hypersaline assemblage in the eastern Bay's tidal delta sand flats (Fig. 1 and Table 5). Water depth and temperature were not critical factors controlling foraminiferal distribution patterns in Moreton Bay. Water depth is relatively shallow (~0 to 10 m) and water temperatures are constant (~16 °C to 26 °C) throughout the Bay (Palmieri, 1976a). However, it appears that wave energy and the degree of exchange with open marine waters influences water and sediment quality and foraminiferal distribution, particularly in the Northern Bay where tidal exchange via the North Passage increases exposure to oceanic conditions (Fig. 1). Sluggish, hyposaline conditions found in the Waterloo Bay (western) region contribute to greater accumulation of organic rich sediments and nutrients, whereas the clean, quartz sand substrates of the eastern Bay are regularly flushed with normal marine waters, resulting in low nutrient, normal marine to hypersaline conditions (Dennison and Abel, 1999; Heggie et al., 1999).

5.1.1. Urban-influenced river delta environments

The westernmost river delta sand/mud flat samples are the most impacted by anthropogenic pressures. This region is adjacent to intense urban development of one of Australia's fastest growing cities (Brisbane) and subject to deposition of fine-grained sediments, storm-water input, high nutrient loads and contamination by pollutants from industrial (i.e., port facilities, refineries), urban and rural sources (Cox and Preda, 2005; Healthy Waterways, 2007; Hossain et al., 2004). While salinity is low, indicating a brackish environment, a previous study has demonstrated that the pH levels vary widely from six to seven at the surface to three at approximately ten centimeter depth in sediment cores (Cox and

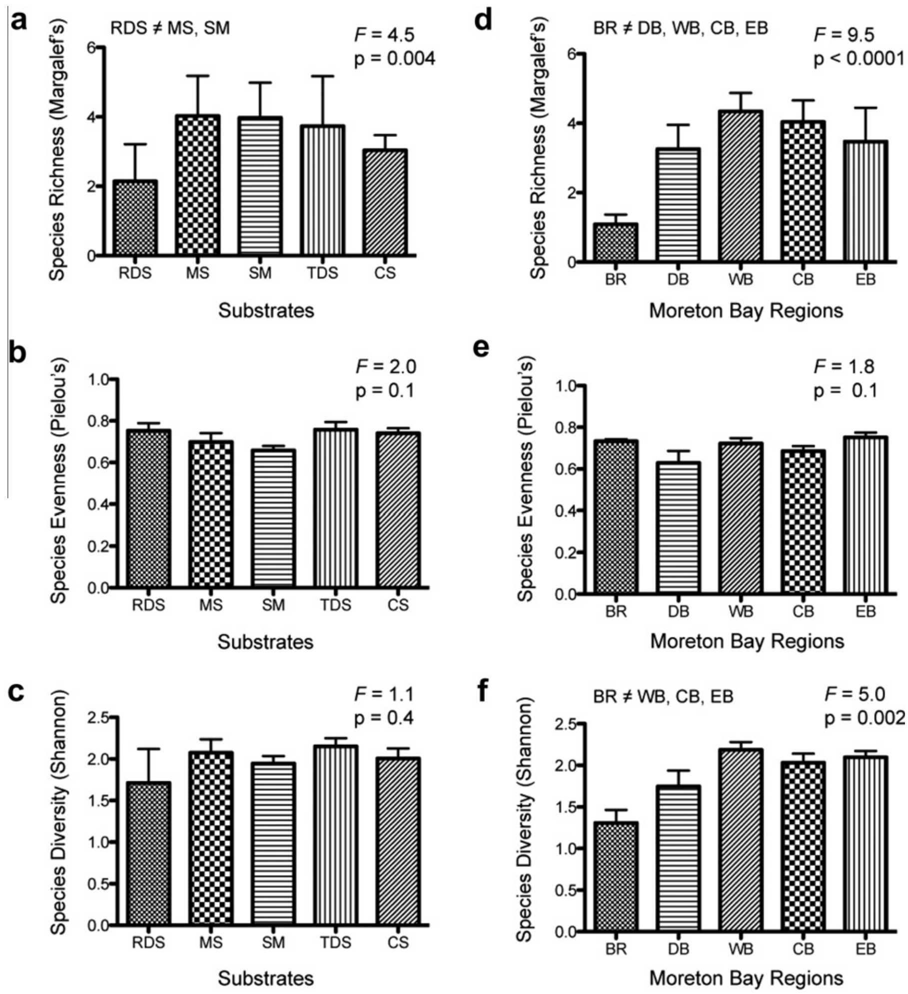

Fig. 4. The mean (a and d) Margalef's richness (D), (b and e) Pielou's evenness (J'), and (c and f) Shannon–Wiener diversity (H') with 95% confidence intervals, for the substrate types: river delta sand (RDS), muddy sand (MS), sandy mud (SM), tidal delta sand (TDS) and calcareous sand (CS) (a)–(c); and regions: Brisbane River delta (BR), Deception Bay (DB), Waterloo Bay (WB), central Bay (CB) and eastern Bay (EB) (d)–(f). A one-way analysis of variance (ANOVA) was carried out to test for significant differences between the means. Pairwise test comparisons were made using Tukey's post-test. Significant differences are denoted by the open vs. shaded symbol (i.e. RDS ≠ MS and RDS ≠ SM).

Preda, 2005). High levels of organic matter and nutrients likely supplied by catchment run-off from agricultural and urban areas, naturally accumulate at the river mouths or areas with the muddy sediments (Hayward et al., 2004b). Sulfide oxidation has occurred below the surface in these areas (Ward and Hacker, 2006). The lowering of pH at depth is likely due to increased organic matter oxidation (Hayward et al., 2004a). Unfavorable acidic conditions would lead to decline in living calcareous species and/or to the post-mortem dissolution of calcareous foraminifera (Alve, 1995; Hayward et al., 2004a; Luan and Debenay, 2005).

Foraminiferal assemblages A-1 and A-2 occur in the river delta sand and mud flats and are dominated by *Ammonia beccarii*, *Ammonia tepida*, few *Elphidium* spp., and rare to few agglutinated *Trochammina* spp. (Table 5 and Supplementary Table S2). Assemblage A-2 differs from A-1 by the lack of *Trochammina* spp. and inclusion of other *Elphidium* spp. and miliolids (*Flintina brady* and *Quinqueloculina philippinensis*), which are more common in the adjacent mixed-estuarine Assemblage B-2. While assemblage A-1 is characteristic of the Brisbane River delta, A-2 is associated with the Caboolture River delta in Deception Bay (Fig. 1). Foraminiferal Assemblage A corresponds with the lowest species diversity in western Moreton Bay (Fig. 4) and has been linked to upper estuarine benthic conditions, including brackish to hyposaline waters, hypoxia, low pH (<8) and high pollution levels or unfavorable conditions (Palmieri, 1976a; Scott et al., 2005; Sen Gupta et al., 1996; Wang and Chappell, 2001). The occurrence of *Ammonia beccarii* and *A. tepida* usually suggests tolerance to chemical and thermal pollution (fertilizers, heavy metals and hydrocarbons) (Frontalini and Coccioni, 2008); and the agglutinated species *Trochammina inflata* suggests proximity to vegetation (i.e., mangroves and salt marsh) and has been suggested as an indicator of stressed environments (Luan and Debenay, 2005; Tsujimoto et al., 2006; Zalensky, 1959). Samples from the river delta sites falling within Assemblage A have the lowest median FI value (1.3) of any group, reflecting stressed conditions too inhospitable for symbiont-bearing organisms (Hallock et al., 2003; Schueth and Frank, 2008).

Our findings are generally consistent with a previous regional study that associated the Brisbane River (and Boat passage) delta with the *A. beccarii* Assemblage A (Palmieri, 1976a). However, we found fewer agglutinated taxa, which suggests a possible shift in the assemblage since the 1970s, from a brackish (containing dominant agglutinated *Ammobaculites* spp. and *Trochammina* spp.) to a more hyposaline-tolerant assemblage found presently (Palmieri, 1976a). The importance of the *Ammonia beccarii* assemblage in marine pollution monitoring of estuarine environments is that it is a consistent indicator of low salinity and hypoxic environments that are impacted by urban and agricultural pollutants world-wide (Carnahan et al., 2009; Debenay and Fernandez, 2009; Sen Gupta et al., 1996).

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Table 2
(a) ANOSIM (one-way, pair-wise) test for significant differences in foraminiferal species composition among substrate types: river delta sand (RDS), muddy sand (MS), sandy mud (SM), tidal delta sand (TDS) and calcareous sand-foraminiferal/algal rubble (CS). (b) ANOSIM test for the significant differences in foraminiferal composition among the major geographic regions in Moreton Bay: Brisbane River Estuary (BR), Waterloo Bay (WB), central Bay (CB), eastern Bay (EB) and Deception Bay (DB) (*R* = ANOSIM test statistic).

Substrates compared	*R*-value	*P*-value
Global effect	*0.6*	*0.001*
MS and SM	0.1	0.018
MS and RDS	0.7	0.001
MS and TDS	0.8	0.001
MS and CS	0.7	0.003
SM and RDS	0.8	0.001
SM and TDS	0.9	0.001
SM and CS	0.9	0.001
RDS and TDS	1.00	0.003
RDS and CS	1.0	0.006
TDS and CS	0.9	0.002
Regions compared		
Global effect	*0.7*	*0.001*
CB and WB	0.3	0.001
CB and BR	1.0	0.001
CB and EB	0.8	0.001
CB and DB	0.3	0.003
WB and BR	1.0	0.004
WB and EB	1.0	0.001
WB and DB	0.8	0.001
BR and EB	1.00	0.003
BR and DB	0.9	0.002
EB and DB	1.00	0.001

5.1.2. Waterloo Bay estuarine sand and mud flats – hyposaline environment

Seasonal, intense flooding from nearby river catchments tends to reduce salinity and increase terrigenous sedimentation and turbidity (Moss, 1998; Neil, 1998; Wallace et al., 2009). The hyposaline, turbid environments adjacent to the river delta are shallow (two to five meter depths) and have restricted water circulation due to the presence of coral islands in the central Bay. The Waterloo Bay region of western Moreton Bay contains a diverse assemblage (Fig. 4) belonging to foraminiferal Assemblage B-1 (Table 5). Assemblage B-1 is characterized by large, opportunistic rotalid species including *Ammonia beccarii*, *Elphidium craticulatum, Elphidium discoidalis multiloculum and Elphidium hispidulum* and few miliolids (Table 1 and Supplementary Table S2). While *A. beccarii* is present, it is not found in high abundances; instead, the abundance of *Elphidium* spp. suggests nearshore, hyposaline and turbid water or natural estuarine conditions (Michie, 1982; Murray, 2006; Palmieri, 1976a). *Elphidium discoidalis multiloculum* and *E. hispidulum* are the dominant species in this assemblage. While *E. discoidalis multiloculum* occurs throughout the Bay, *E. hispidulum* was more common in the muddier, fine-grained samples (Palmieri, 1976a). Assemblage B-1 differs from Assemblage B-2 in having greater average abundance of *Elphidium craticulatum*, *E. hispidulum* and *Quinqueloculina subpolygona*.

The prevalence of *Elphidium* spp. over *Ammonia* spp. in the Waterloo Bay estuarine-lagoonal environments suggests that food supply can be variable and that the surficial sediments are not as oxygen depleted than the adjacent river delta environment (Sen Gupta et al., 1996). The presence of large (up to 5 mm diameter) *Elphidium craticulatum*, which can switch to mixotrophic sources during periods of limited food supply, supports highly variable nutrient conditions (Lopez, 1979). *Elphidium craticulatum*, characteristic of assemblage B-1 is also associated with shallow, reefal sediments from the tropical Queensland shelf and elsewhere (Christie, 1994; Jell et al., 1965; Lobegeier, 1995; Loeblich and Tappan, 1994; Palmieri, 1976b; Renema, 2008). *Elphidium craticulatum* is known to be capable of (microalgal) chloroplast retention; therefore it does not depend on symbionts for food production (Lopez, 1979). It appears to occur in habitats at the upper limits of symbiont-bearing species and is tolerant to adverse conditions, such as high turbidity and low salinity that are not favorable for other large symbiotic foraminifers (Lee and Anderson, 1991; Lopez, 1979; Renema, 2008).

5.1.3. Deception Bay and central Moreton Bay estuarine sand and mud flats

Foraminiferal Assemblage B-2 occurs in the muddy sand and sandy mud flats of Deception Bay (in northern Moreton Bay) and the central Bay (Fig. 1; Table 5 and Supplementary Table S2). It contains a mixed assemblage of common rotalids (*Elphidium* spp.) and the miliolids *Flintina bradyana* and *Quinqueloculina philipinensis*. While *E. discoidalis multiloculum* commonly occurs in high densities throughout the Bay, the presence of *F. bradyana* and *Q. philipinensis* suggests association with the coarse to medium sand substrate dominated by high tidal current velocities and normal estuarine conditions (Michie, 1982). The large, robust and pitted tests of *Q. philipinensis* are resistant to abrasion and transport. The porcellaneous test of *F. bradyana* is also large, strong and fairly resistant to wave energy. The Deception Bay region is affected by high-energy conditions as tidal exchange occurs via North Passage (Fig. 1). However, coral communities do not occur in northern Moreton Bay.

5.1.4. Marginal reefs of central Moreton Bay

Moreton Bay's subtropical, marginal reefs are unique and differ from the coral communities outside the Bay such as Flinders reef (Fig. 1) with its higher diversity communities (Wallace et al., 2009). Living coral communities include 64 species found surrounding Mud Island, St. Helena Island, Green Island, King Island, Wellington Point, Peel Island, Goat-Bird Island and Myora Point (Johnson and Neil, 1998a; Wallace et al., 2009). The reefs occur in close proximity to a highly urbanized region and are exposed to variable conditions including storm and flood events and regular sediment re-suspension resulting in high turbidity and hyposaline conditions (Johnson and Neil, 1998a; Neil, 1998; Pandolfi et al., 2003; Wallace et al., 2009).

In the great barrier reef (GBR), (~500 km) north of Moreton Bay, the foraminiferal assemblages are characterized by several large symbiont-bearing species including *Calcarina* spp. and *Marginopora* spp. (Christie, 1994; Jell et al., 1965; Lobegeier, 1995, 2002). In Moreton Bay, the modern reef flats consist of a diverse assemblage of generally smaller opportunistic and commonly non-symbiont dominated species (Palmieri, 1976a). Symbiont-bearing taxa (*Peneroplis planatus*) are found to occur in low abundances in the central Bay reef flats (Palmieri, 1976a; Riek, 1938).

The reef flats surrounding south-west peel island are characterized by symbiont-bearing *Peneroplis planatus, P. pertusus, Alveolinella quoyi, Amphistegina lessoni, A. radiata, Heterostegina depressa, Operculina ammonides, Planorbulina acervalis* and *Spirolina acicularis;* the opportunistic *Ammonia beccarii* and *Elphidium crispum* and small heterotrophic *Triloculina tricarinata* and *T. trigonula* of Assemblage C-1 (Table 5 and Supplementary Table S2). In the central Bay, *Peneroplis planatus* and *P. pertusus* have been recovered in small numbers both in the channels between the reef islands (Green Island and King) and in the western Bay estuarine flats (where seagrass beds occur) and this is consistent with previous studies (Palmieri, 1976a; Riek, 1938).

Peneroplis spp. have been reported to have their highest densities in hypersaline to normal marine waters (salinities of 33–53 ppt) of shallow-water lagoonal and reefal environments that

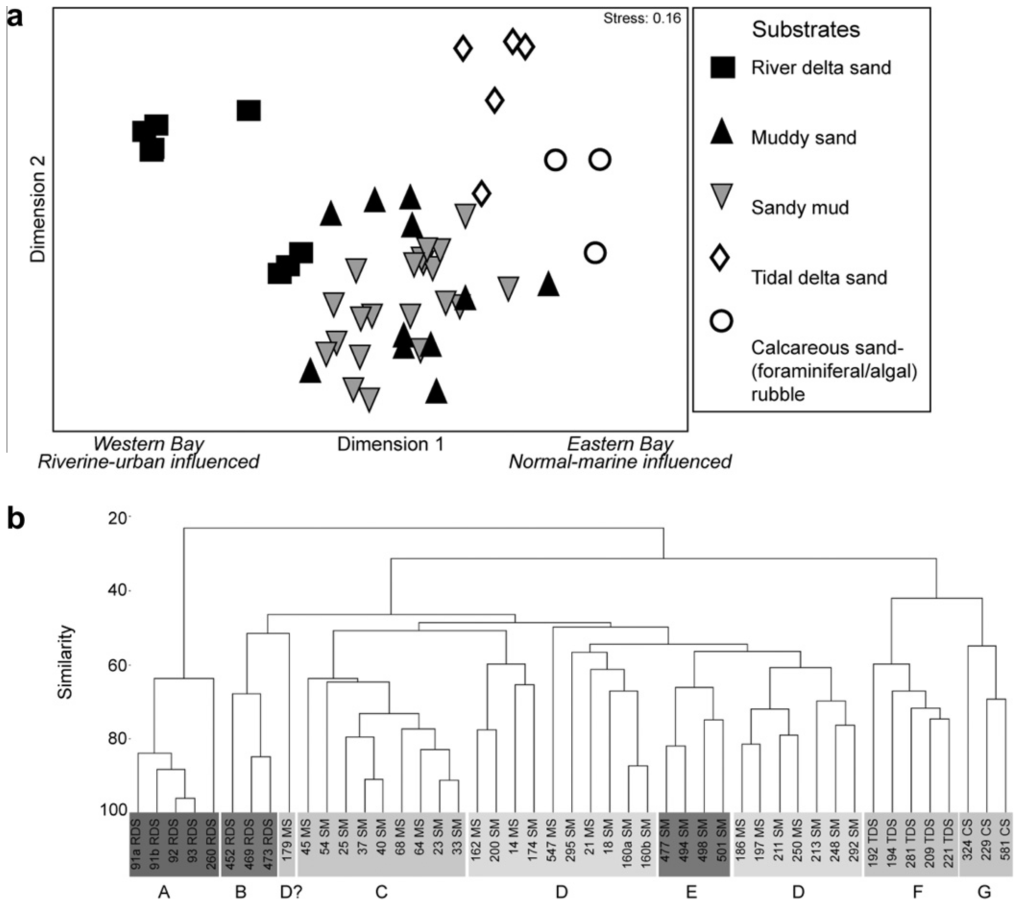

Fig. 5. (a) Non-metric multidimensional (NMDS) ordination of the 47 sediment samples collected in Moreton Bay, showing a clear relationship between benthic foraminiferal species composition and substrate. Species composition from western and eastern Bay shows a marked separation, while the central Bay samples from muddy sand and sandy mud substrates show substantial overlap. Dimension 1 represents a spatial gradient from western-urban influenced (left) to eastern normal-marine conditions in Moreton Bay (right). (b) The dendrogram from the cluster analysis shows the general grouping (>60% similarity) of the samples into the following regions/substrates: (A) Brisbane (Pine) River delta sand; (B) Deception Bay/Caboolture River delta sand/mud; (C) Waterloo Bay muddy sand/sandy mud; (D) Central Bay muddy sand/sandy mud; (E) Deception Bay muddy sand/sandy mud; (F) eastern Bay tidal delta sand; and (G) eastern Bay calcareous sand/rubble.

consist of clean quartz sand substrates and may experience high-energy conditions, such as in eastern Moreton Bay (Christie, 1994; Davies, 1970; Lobegeier, 1995; Michie, 1982; Murray, 2006; Palmieri, 1976a; Renema, 2002). Foraminiferal Assemblage C-1 also occurs at Myora Reef, North Stradbroke Island, which is dominated by the only living stand of the sensitive *Acropora* corals so far reported from the modern environments of Moreton Bay (Harrison et al., 1998; Johnson and Neil, 1998a; Wallace et al., 2009).

5.1.5. Eastern Moreton Bay tidal delta sand flats

The eastern Moreton Bay shallow-water tidal sand flats (Moreton Banks), which are composed of medium grained, clean, quartz sand substrates and oligotrophic conditions, contain extensive (non-reefal) seagrass meadows. This environment is also associated with Assemblage C-1. The epiphytic, symbiont-bearing and non-symbiont species are found living attached to seagrass roots and leaves of mainly *Halophila* spp. and the large *Zostera* spp. This region is characterized by clear water conditions, low nutrients, normal to hyperaline conditions and high energy environments because it is continuously flushed by oceanic waters entering the Bay via the South Passage (Fig. 1) (Dennison and Abel, 1999; Wallace et al., 2009).

Off of western Moreton Island foraminiferal Assemblage C-2 is associated with the calcareous sand-rubble (calcareous algal rhodoliths) substrate in the tidal channels (~5–8 m water depth) of eastern Moreton Bay. It is characterized by several symbiont-bearing taxa: *Alveolinella quoyi*, *Amphistegina* spp., *Heterostegina depressa*, *Operculina ammonoides* and *Peneroplis* spp., the opportunistic (chloroplast-retaining) *Elphidium craticulatum*, *Elphidium discoidalis multiloculum* and the heterotrophic *Quinqueloculina phillipinensis* (Table 5 and Supplementary Table S2), indicative of normal to hypersaline marine conditions (Jell et al., 1965; Palmieri, 1976b).

The presence of *Alveolinella quoyi* suggests strong currents are present and capable of mobilizing 100 to 200 μ sized sediment particles to re-suspend the large and robust *A. quoyi* tests and concentrate them at the sediment–water interface (Severin and Lipps, 1989). Symbiont-bearing foraminifer (mainly *A.quoyi* and *Amphistegina* spp.) are the main biogenic contributors to the calcareous sand substrate. *Alveolinella quoyi*, a large, living, fusiform, symbiont-bearing species is rare in the modern sediments of Moreton Bay (Palmieri, 1976a; Severin and Lipps, 1989). It was found more commonly and in higher abundances throughout the reef flat and slope environments of Moreton Bay during the mid-Holocene (6500 ybp) (Palmieri, 1976a). In Heron Island Reef (GBR) sediments, *A. quoyi* is rarely found in the reef flat sediments but commonly occurs in the channels between Heron and adjacent Wistari reefs, in water depths greater than 10 meters (Jell et al., 1965). Elsewhere, *A. quoyi* and *Heterostegina depressa* have been associated with high energy environments composed of hard substrates such as gravel or rubble substrates and/or low energy sandy

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Table 3
Similarity percentage (SIMPER) analysis of the foraminiferal species composition data within substrate types from Moreton Bay, SE Queensland, Australia. SIMPER analysis values included are: total similarity (T. Sim), average abundances (Av. Abund), average similarity (Av. SIm) of a species in the substrate type, ratio of average similarity and standard deviation (Sim:SD) and percent contribution of species to total similarity (%).

Substrate	T. SIm	Species	Av. Abund	Av. Sim	Sim:SD	%
River delta sand (RDS)	61.6	*Ammonia beccarii*	38.2	30.8	2.6	50.0
		Ammonia tepida	18.7	13.0	2.4	21.1
		Elphidium disc. multiloculum	16.2	11.5	2.4	18.7
		Elphidium advenum	4.7	1.5	0.6	2.5
Muddy sand (MS)	36.0	*Elphidium disc. multiloculum*	24.7	12.2	1.2	34.0
		Quinqueloculina philippinensis	11.8	5.0	0.7	13.8
		Elphidium craticulatum	10.5	4.9	0.8	13.6
		Elphidium hispidulum	9.6	4.9	0.8	12.0
		Flintina bradyana	5.1	4.3	0.6	5.4
Sandy mud (SM)	39.0	*Elphidium disc. multiloculum*	21.4	12.5	1.2	32.0
		Flintina bradyana	15.1	7.3	0.8	18.7
		Elphidium hispidulum	13.4	6.0	0.9	15.4
		Quinqueloculina philippinensis	8.9	2.6	0.5	6.7
		Elphidium craticulatum	5.3	2.2	0.6	5.6
Tidal delta sand (TDS)	61.3	*Peneroplis planatus*	26.8	20.1	2.9	32.8
		Peneroplis pertusus	16.8	13.5	2.9	22.0
		Triloculina tricarinata	11.5	7.3	1.8	11.8
		Ammonia beccarii	9.9	6.0	2.3	9.8
		Planorbulina acervalis	6.9	4.5	2.3	7.3
Calcareous sand (CS)	37.6	*Alveolinella quoyi*	15.7	8.6	1.0	22.8
		Amphistegina radiata	14.8	6.8	0.7	18.1
		Elphidium craticulatum	15.4	5.7	1.1	15.1
		Heterostegina depressa	7.9	3.6	0.6	9.5
		Quinqueloculina philippinensis	6.4	3.4	2.6	9.2

substrate environments, below wave base and the lower part of the photic zone (Langer and Hottinger, 2000; Renema, 2008).

5.2. Moreton Bay's water and substrate quality

The FORAM Index (FI) has been shown to be a suitable indicator for assessing nutrient impacts and regional water quality in eastern Australian reefs (Schueth and Frank, 2008; Uthicke and Nobes, 2008). In Moreton Bay, approximately eighty percent of the samples had low FI values ranging between 0 and 4. Western Bay environments are either not favorable (FI < 2) or marginal (FI = 2–4) for coral or symbiont-bearing foraminifer growth (Fig. 6) (Hallock et al., 2003; Schueth and Frank, 2008). Opportunistic species dominate western Moreton Bay environments including the chloroplast-retaining species (*Elphididum craticulatum*), whereas symbiont-bearing species (*Penerolplis planatus and Alveolinella quoyi assemblages*) are more predominant in the eastern Bay reefs.

Our low FI values obtained for reef environments in Moreton Bay, confirms marginal, adverse conditions for coral growth. The modern coral communities in western Moreton Bay are found living adjacent to mangrove habitats in turbid water conditions (high terrigenous sediment flux) with regular re-suspension of fine sediments, low salinity, high nutrients (from nearby agricultural activity and urban development in the catchments) and are subject to damage from flood and storm events (Johnson and Neil, 1998b; Neil, 1998). Generally, colonies in the western Bay tend to be small favid coral colonies (Johnson and Neil, 1998a; Wallace et al., 2009). The rare occurrence of sensitive acroporid-dominated species found at one location in eastern Moreton Bay (Myora Reef) suggests clearer water quality conditions predominate here compared to reef communities elsewhere in the Bay (Johnson and Neil, 1998a). Few (2–5%) symbiont-bearing foraminifers are found in the reef flat and slope environments associated with the western-central Bay coral communities (Wellington Point, St. Helena and Green islands), compared to the eastern Bay communities where symbiont-bearing assemblages dominate (Peel and Goat Island and Myora Reef).

The reef flats surrounding Peel Island, in the eastern Bay had an average FI value of greater than 4, suggesting conditions favorable for coral and symbiont-bearing foraminifer growth (Hallock et al., 2003; Schueth and Frank, 2008). This location is influenced by tidal exchange through the South Passage (Johnson and Neil, 1998a). The appearance of the epiphytic, symbiont-bearing *Peneroplis planatus* in great abundance is a good indicator of clear, nutrient-poor water quality and normal marine to hypersaline conditions (Hallock, 1999; Langer, 1993; Palmieri, 1976a; Richardson, 2006; Schueth and Frank, 2008). The eastern Bay samples showed the highest FI values (>6) indicating good water quality conditions (Hallock et al., 2003; Schueth and Frank, 2008).

The FORAM Index, based on foraminiferal composition data, provides a simple measure for determining whether water and sediment quality is conducive to coral reef growth (Hallock et al., 2003). Both symbiont-bearing foraminifers and zooxanthellate corals respond similarly to water quality conditions, while benthic foraminifers are a better indicator of rapid environmental changes (Cockey et al., 1996). Although, the FI was not specifically developed for use in subtropical, estuarine environments, overall results suggest that it can provide resource managers with a cost-effective, single-metric indicator for assessing and monitoring assessing and monitoring the overall state of an ecosystem, (Carnahan et al., 2009). This study provides preliminary results to support the FORAM Index as useful in assessments and potential monitoring of subtropical estuaries in Australia.

5.3. Implications for monitoring Moreton Bay's habitats

Moreton Bay is internationally recognized for its biodiversity and ecological significance (Chilvers et al., 2005; Dennison and Abel, 1999; Healthy Waterways, 2007). Established in 1993 MBMP, which is highly accessible to recreational and commercial activities, provides a wide array of habitats including mangroves, wetlands, seagrass meadows, mud and sand flats and fringing coral reefs (Abal et al., 1998; Chilvers et al., 2005; Duke et al., 2003; Johnson and Neil, 1998a; Neil, 1998; Wallace et al., 2009).

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Table 4
Dissimilarity analysis of the foraminiferal species composition data between substrate types (as in Table 3). SIMPER analysis values included are: total dissimilarity (T. Diss), average abundances (Av. Abund), average dissimilarity (Av. Diss) in two different substrate types, ratio of average similarity and standard deviation (DIss:SD) and percent contribution of species to total dissimilarity (%).

Substrates	T. Diss	Species	Av. Abund (1)	Av. Abund (2)	Av. Diss	Diss:SD	%
MS (1) and SM (2)	63.20	*Elphidium disc. multiloculum*	24.7	21.4	10.3	1.2	16.3
		Flintina bradyana	5.1	15.1	6.6	1.1	10.4
		Quinqueloculina philippinensis	11.8	8.9	6.5	1.2	10.4
		Elphidium hispidulum	9.6	13.4	6.1	1.1	9.7
		Ammonia beccarii	3.6	8.7	5.0	0.6	7.9
		Elphidium craticulatum	10.5	5.3	4.6	1.3	7.3
MS (1) and RDS (2)	75.95	*Ammonia beccarii*	3.6	38.2	17.3	2.6	22.8
		Ammonia tepida	0.8	18.7	9.0	1.9	11.8
		Elphidium disc. multiloculum	24.7	16.2	8.6	1.0	11.3
		Quinqueloculina philippinensis	11.8	3.4	5.6	1.1	7.4
		Elphidium craticulatum	10.5	0.7	5.1	1.2	6.7
		Elphidium hispidulum	9.6	3.1	4.4	1.2	5.8
SM (1) and RDS (2)	74.19	*Ammonia beccarii*	8.7	38.2	17.0	2.4	22.9
		Ammonia tepida	0.2	18.7	9.3	2.0	12.5
		Elphidium disc. multiloculum	21.4	16.2	7.1	1.4	9.6
		Flintina bradyana	15.1	1.5	7.1	1.1	9.6
		Elphidium hispidulum	13.4	3.1	6.1	1.0	8.2
		Quinqueloculina philippinensis	8.9	3.4	4.8	0.8	6.4
MS (1) and TDS (2)	88.81	*Peneroplis planatus*	0.9	26.8	13.0	2.6	14.6
		Elphidium disc. multiloculum	24.7	0.3	12.2	1.1	13.7
		Peneroplis pertusus	0.9	16.8	8	3.1	9.0
		Quinqueloculina philippinensis	11.8	0.9	5.7	1	6.4
		Triloculina tricarinata	1.6	11.5	5.2	1.7	5.8
		Elphidium craticulatum	10.5	0.6	5.0	1.1	5.7
SM (1) and TDS (2)	86.80	*Peneroplis planatus*	2.9	26.8	12.1	2.3	14.0
		Elphidium disc. multiloculum	21.4	0.3	10.5	1.4	12.1
		Peneroplis pertusus	1.2	16.8	7.8	2.9	9.0
		Flintina bradyana	15.1	0.1	7.5	1.1	8.7
		Ammonia beccarii	8.7	9.9	6.7	1.0	7.7
		Elphidium hispidulum	13.4	0.2	6.6	1.0	7.6
RDS (1) and TDS (2)	84.46	*Ammonia beccarii*	38.2	9.9	14.2	2.1	16.8
		Peneroplis planatus	0.00	26.8	13.4	2.8	15.9
		Ammonia tepida	18.7	1.1	8.8	1.9	10.4
		Peneroplis pertusus	0.00	16.8	8.4	3.4	9.9
		Elphidium disc. multiloculum	16.2	0.3	7.9	2.1	9.4
		Triloculina tricarinata	2.4	11.5	4.8	1.5	5.7
MS (1) and CS (2)	78.14	*Elphidium disc. multiloculum*	24.7	9.2	9.7	1.0	12.4
		Alveolinella quoyi	0.00	15.7	7.8	1.7	10.0
		Amphistegina radiata	1.1	14.8	7.1	1.4	9.1
		Elphidium craticulatum	10.5	15.4	6.4	1.3	8.2
		Quinqueloculina philippinensis	11.8	6.4	5.2	1.3	6.7
		Elphidium hispidulum	9.6	0.00	4.8	1.1	6.2
SM (1) and CS (2)	81.55	*Elphidium disc. multiloculum*	21.4	9.2	8.2	1.3	10.1
		Alveolinella quoyi	0.6	15.7	7.7	1.7	9.4
		Flintina bradyana	15.1	0.3	7.4	1.1	9.1
		Amphistegina radiata	0.1	14.8	7.3	1.4	9.0
		Elphidium hispidulum	13.4	0.00	6.7	1.0	8.2
		Elphidium craticulatum	5.3	15.4	6.5	1.2	7.9
RDS (1) and CS (2)	89.38	*Ammonia beccarii*	38.2	0.3	18.9	3.0	21.2
		Ammonia tepida	18.7	0.1	9.3	2.0	10.4
		Alveolinella quoyi	0.00	15.7	7.8	1.7	8.8
		Elphidium craticulatum	0.7	15.4	7.5	1.2	8.4
		Amphistegina radiata	0.00	14.8	7.4	1.4	8.3
		Elphidium disc. multiloculum	16.2	9.2	5.2	1.4	5.8
TDS (1) and CS (2)	74.42	*Peneroplis planatus*	26.8	9.6	9.8	1.6	13.2
		Elphidium craticulatum	0.6	15.4	7.4	1.2	10.0
		Amphistegina radiata	1.3	14.8	7.0	1.4	9.4
		Alveolinela quoyi	2.2	15.7	6.8	1.5	9.1
		Peneroplis pertusus	16.8	4.7	6.5	1.8	8.7
		Triloculina tricarinata	11.5	0.00	5.8	1.8	7.7

Currently, protected "no-take" or green zones cover 16% of the Bay, an increase from 0.5% since 2008 (EPA, 2008). Moreton Bay habitats, particularly the river estuaries of the Western Bay, are facing severe threats from both anthropogenic and natural stressors, including increased sediment and nutrient loading from modification of the catchment areas, flood and drought events, intense shipping and boating activities and recreational and commercial fisheries (Capelin et al., 1998; Duke et al., 2003; Pandolfi et al., 2003). The effects of historical European land management practices (cropping, grazing and forestry) are well documented since

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Table 5
Summary of benthic foraminiferal assemblages from Moreton Bay, showing characteristic species (with most abundant species in bold type), associated substrate types, the mean diversity (Shannon–Wiener) and the FORAM Index (FI).

Foraminifera assemblage	Characteristic species	Substrate – region/habitat	Median and mean diversity	Median and mean FI	Sample numbers
A-1	*Ammonia beccarii*	River delta sand	1.4	1.1	91a, 91b, 92, 93, 260
	Ammonia tepida	Brisbane and Pine River Estuary	1.4 ± 0.2	1.1 ± 0.03	
	Elphidium advenum				
	Elphidium discoidales multiloculum				
	Pararotalia venusta				
	Trochammina globigeriformis				
	Trochammina inflata				
A-2	*Ammonia beccarii*	Mixed river delta and muddy sand or mud	2.3	1.3	452, 469, 473
	Ammonia tepida	Caboolture River Estuary	2.3 ± 0.1	1.3 ± 0.02	
	Elphidium discoidales multiloculum				
	Elphidium hispidulum				
	Flintina bradyana				
	Quinqueloculina phillipinensis				
B-1	*Elphidium craticulatum*	Muddy sand and sandy mud	2.2	1.5	23, 25, 33, 37, 40, 45, 54, 64, 68
	Elphidium discoidales multiloculum	Waterloo Bay, hyposaline reef and estuarine flats	2.2 ± 0.3	1.7 ± 0.4	
	Elphidium hispidulum				
	Pararotalia venusta				
	Quinqueloculina subpolygona				
	Spiroloculina angulata				
B-2	*Elphidium craticulatum*	Mixed muddy sand and sandy mud	1.8	1.6	14, 18, 21, 160a, 160b, 162, 174, 179, 186, 197, 200, 211, 213, 229?, 248, 250, 292, 295, 477, 494, 498, 501, 547
	Elphidium crispum	Central Bay reef and estuarine flats and Deception Bay	1.9 ± 0.5	2.0 ± 0.9	
	Elphidium discoidales multiloculum				
	Elphidium hispidulum				
	Flintina bradyana				
	Quinqueloculina lamarkiana				
	Quinqueloculina philipinensis				
	Spiroloculina spp.				
	Triloculina trigonula				
C-1	*Ammonia beccarii*	Tidal delta sand	2.2	7.2	192, 194, 209, 221, 281
	Amphistegina spp.	Peel Island reef flats, seagrass beds and eastern channels)	2.1 ± 0.2	6.8 ± 1.1	
	Peneroplis planatus				
	Peneroplis pertusus				
	Planorbulina acervalis				
	Triloculina tricarinata				
C-2	*Alveolinella quoyi*	Calcareous sand and algal-foraminifera rubble	2.0	7.6	229?, 324, 581
	Amphistegina spp.	W. Moreton Island, tidal channels	2.0 ± 0.2	7.6 ± 0.6	
	Elphidium craticulatum				
	Heterostegina depressa				

the 1830s (Capelin et al., 1998; Duke et al., 2003; Neil, 1998). Since European settlement (c. 1824) the Bay's catchments have undergone significant large-scale clearing (52% net loss of tidal wetlands; 79% loss of salt marshes, 33% loss of mangroves) and urbanization (Capelin et al., 1998; Duke et al., 2003; Neil, 1998). Presently, only 28% of the catchment area remains undisturbed (Eyre and McKee, 2002).

More recently, catchment areas have experienced high impact activities such as port development, sand extraction, spoil disposal, trawling and dredging (Duke et al., 2003; Heggie et al., 1999; Hossain et al., 2004). Nitrate and phosphate concentrations and pollutants (heavy metals and hydrocarbons) have increased (22 and 11-fold, respectively) in the Brisbane River during the last 50 years (Cox and Preda, 2005; Dennison and Abel, 1999; Duke et al., 2003). Currently, the South-East Queensland region is experiencing rapid growth with populations exceeding 2.7 million (1.6 million in the metropolitan of Brisbane) and expected to double by 2026 (Healthy Waterways, 2007; Australian Bureau of Statistics, 2009). While anthropogenic influences are suspected, natural impacts from climate and storm events have also been major influences on the Bay's environments and habitats, today and historically (Duke et al., 2003; Neil, 1998; Roberts and Harriott, 2003).

The assessment of benthic foraminiferal assemblages using quantitative univariate (diversity indices) and multivariate (nMDS, ANOSIM and SIMPER) methods in combination with water quality indices (FORAM Index) and an understanding of environmental characteristics (sediments, grain size, geochemical parameters, etc.) provides a complementary method for assessing the ecological status of local estuaries and reefs (Carnahan et al., 2009; Debenay and Fernandez, 2009). Since benthic foraminifers respond quickly to environmental changes, they can provide marine park managers with a cost-efficient and reliable proxy for assessing and monitoring water and sediment quality and in monitoring impacts at a microhabitat to Bay-wide scale. This can be further

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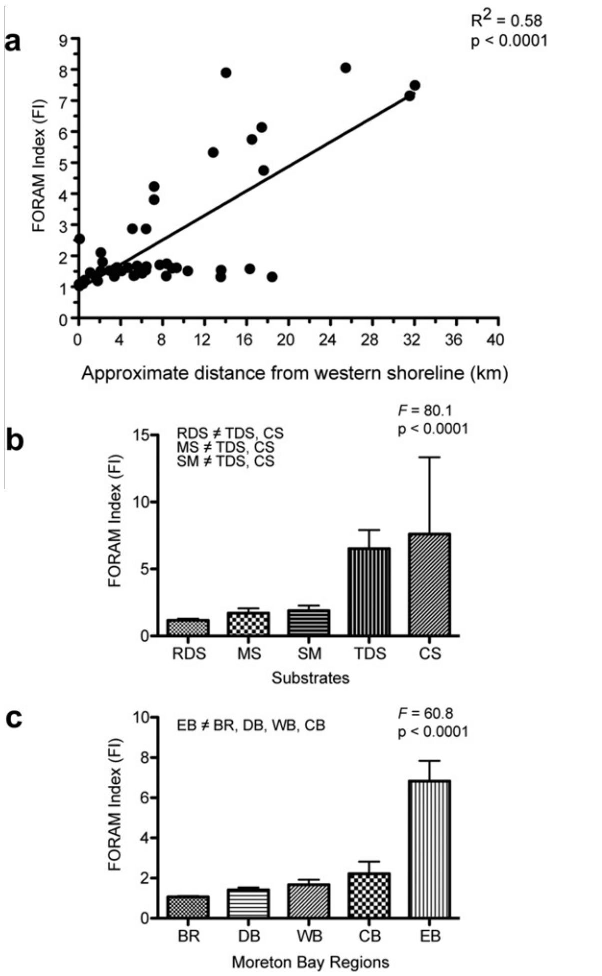

Fig. 6. (a) The FORAM Index (FI) as a function of the distance from the western shoreline for the 47 sediment samples collected across Moreton Bay, South-East Queensland, Australia. (b and c) The mean FI's with 95% confidence intervals are shown for the different substrates (b) and regions (c) in Moreton Bay.

applied to assessments of long-term changes to provide a historical perspective of environmental conditions (Alve et al., 2009; Hayward et al., 2004a; Scott et al., 2005).

6. Conclusions

(1) The benthic foraminiferal assemblages and their geographical distribution in Moreton Bay suggests that:
   (a) the western riverine-influenced region is characterized by a low-diversity fauna of foraminiferal Assemblage A. This assemblage is dominated by stress tolerant species *Ammonia beccarii*, *A. tepida*, other opportunistic, calcareous and few agglutinated species. Their distribution likely reflects close proximity to urban impacts and floodwater flux resulting in intermittent hypoxic conditions. The mean FI Index was low (1.0), indicating that water and sediment quality are unfavorable for symbiont-bearing species.
   (b) the western to central Bay estuarine sand and mud flats and marginal reefs, are characterized by foraminiferal Assemblage B. This is a highly mixed assemblage dominated by opportunistic *Elphidium discoidalis multiloculum* and *Quinqueloculina* spp. It is commonly found in semi-restricted estuarine conditions and indicative of hyposaline to moderate marine conditions. Although influenced by the proximity to the large river catchment of the Brisbane River, the taxonomic composition of this assemblage shows high diversity in Moreton Bay. The mean FI Index was low (1.6 in the western Bay to 2.3 in the central Bay) and suggests marginal conditions for symbiont-bearing organisms and reef growth. However, the large, chloroplast-retaining *Elphidium craticulatum* was a common occurrence in this region.
   (c) the eastern oceanic-influenced region of Moreton Bay, is characterized by foraminiferal Assemblage C and Assemblage D. These assemblages are dominated by epiphytic and symbiont-bearing species (*Alveolinella quoyi* and *Peneroplis planatus*) as well as other small heterotrophic miliolids (*Triloculina tricarinata*) indicative of clear water, normal-marine to hypersaline conditions. The mean FI Index was high (6.7) indicating hospitable water and sediment quality conditions for symbiont-bearing species.

(2) The FORAM Index, which reflects water and sediment quality, shows a positive correlation with distance from the western shoreline. The majority of the samples (~80%) from the western Bay resulted in low FI values indicating marginal marine conditions for symbiont-bearing organisms (corals and benthic foraminifers). The FI in conjunction with foraminiferal assemblage data (abundance, diversity, distribution) can provide marine park managers with a cost-effective tool for interpreting the environmental (anthropogenic and/or natural) influences on a subtropical estuary and monitoring ecosystem changes.

Acknowledgements

Major funding for Ms. R. Narayan's, Ph.D. studies came from the University of Queensland International Postgraduate Research Scholarship (IPRS). The project was supported by funds to J. Pandolfi by the Australian Research Council Centre of Excellence (ARC CoE) for Coral Reef Studies. We thank the Centre for Marine Studies, Marine Palaeoecology Laboratory members: Brian Beck, Tara Clark, Maria Gomez, Matt Lybolt, Claire Reymond, Alberto Rodriguez and George Roff, whose comments and reviews significantly improved this manuscript.

Appendix A. Foraminiferal species list

Suborder Texulariina Delage and Herouard, 1896
  Family Lituolidae de Blainville, 1827
    Ammobaculites agglutinans (d'Orbigny, 1846)
  Family Trochamminidae Schwager, 1877
    Trochammina globigeriniformis (Parker and Jones, 1860)
    Trochammina inflata (Montagu, 1808)

Suborder Miliolina Delage and Herouard, 1896
  Family Alveolinidae Ehrenberg, 1839
    Alveolinella quoyi (D'Orbigny, 1826)
  Family Ficherinidae Millet, 1898
    Vertebralina rupertina (Brady, 1884)
  Family Hauerinidae Schwager, 1876
    Cycloforina quinquecarinata (Collins, 1958)
    Flintina bradyana Cushman, 1921
    Miliolinella circularis (Bornemann, 1855)
    Miliolinella labiosa (D'Orbigny, 1839)
    Quinqueloculina crassicarinata Collins, 1958

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Appendix A (*continued*)

Quinqueloculina granulocostata Germeraad, 1946
Quinqueloculina lamarckiana D'Orbigny, 1839
Quinqueloculina parkeri (Brady, 1884)
Quinqueloculina philippinensis Cushman, 1921
Quinqueloculina pittensis Albani, 1974
Quinqueloculina poeyana D'Orbigny, 1839
Quinqueloculina seminula (Linne, 1767)
Quinqueloculina subpolygona Parr, 1945
Quinqueloculina tasmanica Albani, 1978
Pseudohauerina involuta (Cushman, 1946)
Pseudomassilina australis (Cushman, 1932)
Pseudomassilina macilenta (Brady, 1884)
Triloculina littoralis Collins, 1958
Trilloculina oblonga (Montagu, 1803)
Triloculina tricarinata D'Orbigny, 1826
Triloculina trigonula (Lamarck, 1804)
Family Ophthalmidiidae Wiesner, 1920
Edentostomina cultrata (Brady, 1881)
Family Peneroplidae Schultze, 1854
Monalysidium acicularis (Batsch, 1791)
Peneroplis pertusus (Forskål, 1775)
Peneroplis planatus (Fichtel and Moll, 1798)
Spirolina arietina (Batsch, 1791)
Family Soritidae Ehrenberg, 1839
Sorites marginalis (Lamarck, 1816)
Family Spiroloculinidae Weisner, 1920,
Spiroloculina communis Cushman and Todd, 1954
Spiroloculina corrugata Cushman, 1917
Spiroloculina lucida Cushman and Todd, 1944
Spiroloculina rugosa Cushman and Todd, 1944
Spiroloculina scorbiculata (Lamarck, 1804)
Suborder Rotaliina Delage and Herouard, 1896
Family Amphisteginidae Cushman, 1927
Amphistegina lessoni D'Orbigny, 1826
Amphistegina radiata (Fichtel and Moll)
Family Cymbaloporidae Cushman, 1927
Cymbaloporetta bradyi (Cushman, 1915)
Family Discorbidae Ehrenberg, 1838
Lamellodiscorbis dimidiatus (Jones and Parker, 1862)
Planodiscorbis sp. *A*
Family Ellipsolagenidae A. Silvestri, 1923
Glandulina laevigata D'Orbigny, 1826
Family Elphidiidae Galloway, 1933
Cribroelphidium poeyanum (D'Orbigny, 1839)
Elphidium macellum aculeatum (Silvestri, 1901)
Elphidium advenum (Cushman, 1922)
Elphidium craticulatum (Fichtel and Moll, 1798)
Elphidium crispum (Linne, 1758)
Elphidium discoidalis multiloculum Cushman and Ellisor, 1945
Elphidium hispidulum Cushman, 1936
Elphidium jenseni (Cushman, 1924)
Elphidium oceanicum Cushman, 1933
Elphidium schmitti Cushman and Wickenden, 1927
Elphidium simplex Cushman, 1933
Family Eponididae Hofker, 1951
Eponides cribrorepandus (Asano and Uchio, 1951)
Poroeponoides lateralis (Terquem, 1878)
Family Nodosariidae Ehrenberg, 1838
Dentalina sp. *A*
Family Nonionidae Schultze, 1854
Nonionella auris (D'Orbigny, 1839)
Family Nummulitidae De Blainville, 1827
Heterostegina depressa D'Orbigny, 1826
Operculina ammonoides (Gronovius, 1781)
Family Planorbulinidae Schwager, 1877
Planorbulina acervalis Brady, 1884
Family Polymorphinidae D'Orbigny, 1839
Guttulina pacifica (Cushman and Ozawa, 1928)
Guttulina problema (D'Orbigny, 1826)
Family Rotaliidae Ehrenberg, 1839
Ammonia beccarii (Linne, 1767)
Ammonia tepida (Cushman, 1926)
Pararotalia venusta (Brady, 1884)
Family Siphogenerinoididae Saidova, 1981
Rectobolivina raphana (Parker and Jones, 1865)
Siphogenerina striatula (Cushman, 1913)

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marpolbul.2010.07.012.

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Please cite this article in press as: Narayan, Y.R., Pandolfi, J.M. Benthic foraminiferal assemblages from Moreton Bay, South-East Queensland, Australia: Applications in monitoring water and substrate quality in subtropical estuarine environments. Mar. Pollut. Bull. (2010), doi:10.1016/j.marpolbul.2010.07.012

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