

Mudbank off Alleppey, India: A bane for foraminifera but not so for carbon burial

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Abstract

The calm conditions and extensive fishing, during monsoon season in the mudbank off Alleppey (Kerala), India creates a unique environment, distinctly associated with high suspended particulate matter in the water column. The effect of mudbank formation and associated activities on benthic foraminifera, however, has not been documented. Here, we have studied the seasonal variation in benthic foraminifera, from surface sediment samples collected during pre-monsoon, monsoon and post-monsoon season, to understand the foraminiferal response to physico-chemical changes and anthropogenic activities associated with the mudbank formation. Additionally, the seasonal changes in total carbon, calcium carbonate (CaCO_3), organic carbon (C_{org}) and C_{org} /nitrogen ratio ($\text{C}_{\text{org}}/\text{N}$) were also measured to understand the effect of mudbank and associated activities on the carbon burial. We report a significantly lower foraminiferal abundance in the mudbank. Benthic foraminiferal diversity is also low in the mudbank, during both the pre-monsoon and monsoon season, clearly suggesting a stressed environment. The agglutinated foraminifera dominate the living benthic foraminiferal population in the mudbank, suggesting that the area is carbonate under saturated and under the fresh-water influence. *Ammobaculites dilatatus* and *Ammobaculites exiguus* are the dominant agglutinated species abundant in the mudbank and thus can be used to reconstruct past changes in the mudbank. The CaCO_3 is consistently low during all seasons, at one of the core mudbank stations. The $\% \text{C}_{\text{org}}$ is, however, relatively higher in the core mudbank as well as the northern peripheral region. The $\text{C}_{\text{org}}/\text{N}$ is consistently uniform at all the stations indicating a similar source of organic matter in all the seasons. The higher $\% \text{C}_{\text{org}}$ and constant $\text{C}_{\text{org}}/\text{N}$ suggest that the food availability and its source is not a major factor affecting benthic foraminifera in the mudbank. The increased turbidity and low bottom water salinity are the main cause of seasonally stressed environment in the mudbank. Additionally, the C_{org} degradation coupled with fresh water influx induced drop in bottom water pH is responsible for the overall low foraminiferal population in the mudbank region, in all the seasons. The reduced calcareous benthic foraminiferal abundance, however, does not affect the overall carbon burial in the mudbank, due to higher $\% \text{C}_{\text{org}}$, as a result of better preservation in the fine-grained sediments.

Keywords: mudbank, Alleppey, benthic foraminifera, C_{org} , low salinity

1. Introduction

The huge sediment influx and characteristic hydrodynamic conditions near river mouth regions, result in the formation of mudbanks. The mudbanks have been reported from several regions and the processes leading to the mudbank formation vary. The mudbank off the coast of French Guiana at Kaw river mouth, forms due to the combined effect of sediment supply from the Amazon River and hydrodynamics of coastal currents (Lefebvre et al., 2004). The combined effect of currents, tides and waves also result in the formation of a mudbank plume off Brazil (Chevalier et al., 2008). The low-energy environment mudbanks are also reported from Florida Bay and are contrary to the high-energy environment mudbanks described from the nearshore areas around the Amazon River mouth (Taylor and Pukris, 2012). The coastal water of southeastern Arabian Sea, off Alleppey, Kerala, also becomes characteristically calm during the otherwise turbulent monsoon season. This calm coastal zone forms within 15 m water depth and is known as mudbank. It is distinctly associated with high suspended particulate matter in the water column (Shynu et al., 2017). The re-suspension of bottom mud is supposed to be the cause of very high turbidity in the mudbank (Kurup, 1977; Mallik et al., 1988; Tataavarti and Narayana, 2006). Along the southwest coast of India, other than Alleppey, mudbanks have been reported from a coastal area off Kozhikode near Beypore river mouth and off Narakkal (near Kochi) at Periyar river mouth (Rao, 1967). Of these mudbank occurrences, only the Alleppey mudbank continues to be persistent during the southwest monsoon season since the 1900s. Apart from its continued occurrence, Alleppey mudbank is different from the rest as it forms in nearshore setting away from river mouth (CMFRI, 1984). The characteristic calmness along the shoreline (CMFRI, 1984; Jiang and Mehta, 1996; Narayana et al., 2008) makes the Alleppey mudbank area important for fisheries. The mudbank shoreline becomes the avenue of extensive fishing when the rest of the coastline is highly unsafe to venture into the sea (Gopinathan and Qasim, 1974; Ragunathan et al., 1984; Aswathy and Sathiadhas, 2006; Shyam et al., 2016). The high socio-economic implications of mudbank, require a proper understanding of the mudbank dynamics, especially the changes in its spatial and temporal extent.

The unique marine environment of the mudbank and extensive anthropogenic activities invariably affect the marine organisms living in mudbank area, resulting in a characteristic distribution pattern (Damodaran and Hridayanathan, 1966). The seasonal disturbance of bottom mud would certainly affect the dominant unicellular benthic protozoan, foraminifera, as it lives in the top few centimeters of the substrate (Singh et al., 2017). The species-specific response of foraminifera is due to the sensitivity of these organisms to the changes in their inhabiting environment (Boltovskoy and Wright, 1976; Sen Gupta, 1999; Murray, 2006; Bouchet et al., 2012). Even the short-term

anthropogenic (Bouchet et al., 2007) or ecological stressors (Kurtarkar et al., 2011) leave a traceable signature in benthic foraminiferal population. Therefore, the objective of this work was to understand the effect of processes associated with mudbank formation, and other anthropogenic activities in the area, on benthic foraminifera. Additionally, as the calcareous benthic foraminifera are responsible for sequestering a large part of the carbon, efforts are also made to understand the effect of mudbank formation and anthropogenic activities on carbon burial. Benthic foraminiferal distribution from the eastern Arabian Sea, including off Kerala, has been extensively documented. The pioneering foraminifera related work dealt with detailed bathymetric distribution, zonal abundance and correlating faunal response to environmental parameters (Sethulakshmi, 1958; Antony, 1968; Seibold, 1975; Seibold and Seibold, 1981; Nisha and Singh, 2012). Our effort to document foraminiferal distribution from the mudbank off Alleppey is, however, different from the previous works, in being a seasonal study of faunal abundance. Moreover, the foraminifera response is studied specifically concerning the onset and offset of mudbank phenomenon in the area. The study of specific foraminiferal response will help to understand mudbank migration and intensity in the past and its influence on carbon burial.

Study Area : The areal extent of mudbank off Alleppey, Kerala is approximately 32 km². It extends for ~3 -4 km along the shore and ~8 - 10 km perpendicular to the shore (Gopinathan and Qasim, 1974; Manojkumar et al., 1998; Balachandran, 2004; Narayana et al., 2008). The mudbank forms during every monsoon season at Punnapra, with historical record available since 1885 (Damodarn and Hridyaanathan, 1966) (Fig. 1). The study area is devoid of any rivers/streams. The only source of fresh-water near the mudbank is the Vembanad Lake which is approximately 40 km inland from the coastal site of mudbank formation (National Wetland Atlas Kerala, 2010; Soman, 2013). The average annual rainfall in the study area is 2826 mm (<http://www.imd.gov.in/section/climate/extreme/alappuzha2.htm>), and the larger part of the precipitation is during the summer monsoon season. The seasonal coastal currents in the area remain southerly during the pre-monsoon season. The coastal currents remain weak and significantly nullified during the mudbank season. As the mudbank subsides during the post-monsoon, the currents change direction towards the north (Mathew et al., 1984; Gopinathan and Qasim, 1974).

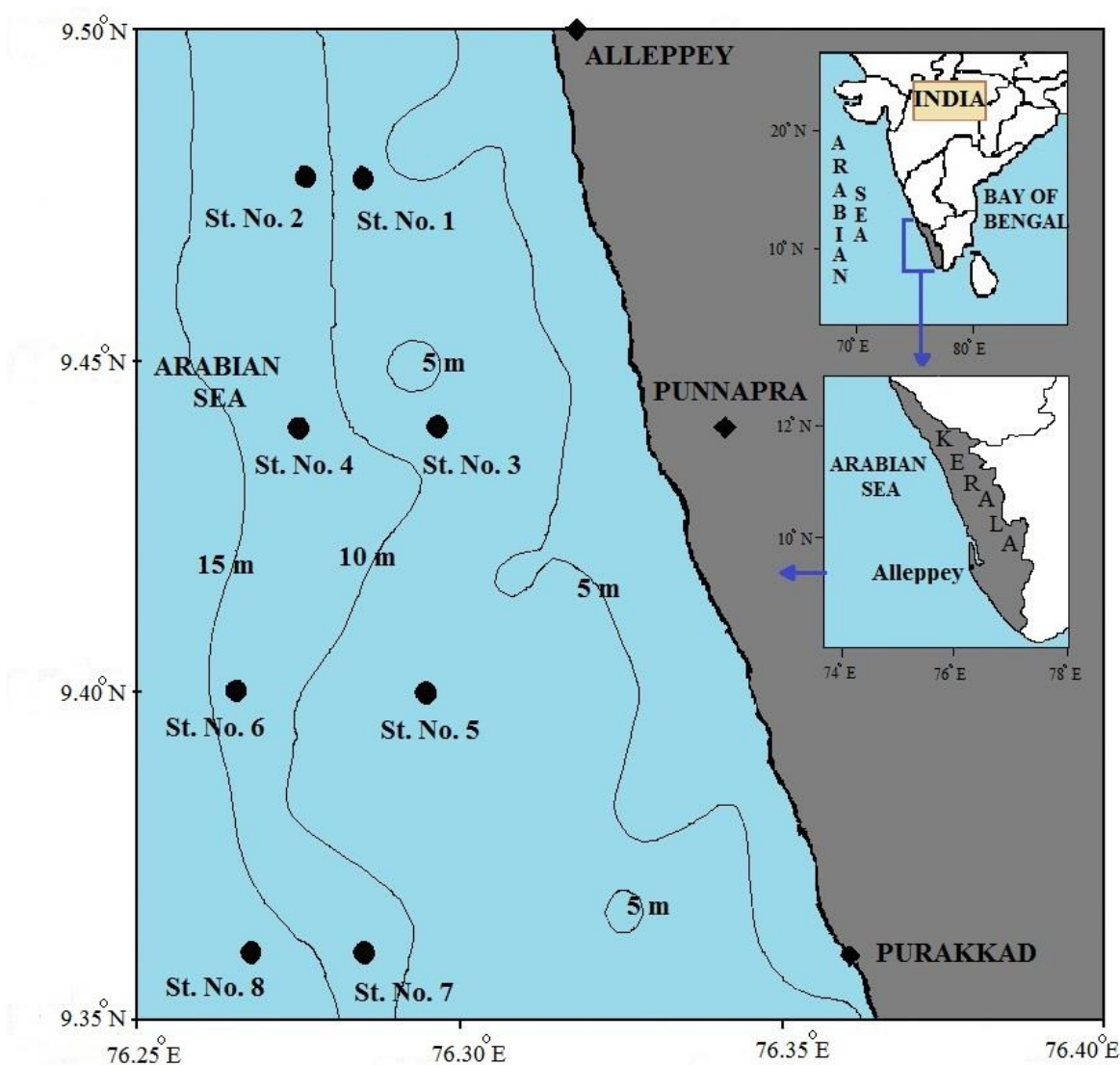


Figure 1. Map of the study area. The inset map is the location of Kerala state in India and the mudbank off Kerala. The depth is marked by black contours.

The primary productivity in the mudbank area off Alleppey, decreases during monsoon season (June-September), unlike the rest of the west coast of India. The productivity in the mudbank during pre-monsoon season (February-May) was 19.77 to 277.00 mg C/m³/h. The productivity decreased during monsoon season to 0.52 to 41.40 mg C/m³/h and was also low during the post-monsoon season (1.31 to 17.40 mg C/m³/h) (Nair et al., 1984). The drop in productivity was attributed to the reduction in the euphotic zone at the time of mudbank formation (Nair et al., 1984).

2. Materials and Methods

The core mudbank area, as well as both the north and south peripheral regions, were sampled, by using a grab sediment sampler, operated from a fishing trawler *Santa Cruz*. The sampling area falls within 9.48–9.36 °N latitude and 76.32–76.28 °E longitude. The sampling was done along four transects. Each transect had a couple of stations, one between 5 to 10 m water depth and another between 10 to 15 m water depth. Transect I has two stations, i.e. station number 1 and 2, and falls within the northern periphery of the core mudbank area. The stations 1 and 2 are henceforth referred as Northern Stations (NS). Transect II had station number 3 and 4, that fall within the mudbank area, and are referred as Core Mudbank Stations (CMS). Transects III and IV had station number 5, 6 and 7, 8, respectively, and constitute the Southern Stations (SS) (Fig. 1). The sampling was carried out during pre-monsoon (May 2015), monsoon (August 2015) and post-monsoon season (February 2016). The sampling time was decided by the presence and absence of the mudbank and does not exactly coincide with the meteorologically defined average monsoon seasons. The total area covered was 53.28 km². Immediately after sampling, approximately top 5 cm of the sediment, collected by grab sampler, was stained by using ethanol rose-Bengal solution to distinguish living benthic foraminifera. The top 5 cm of the sediments were stained as the studies suggest that the living benthic foraminifera are confined to this depth in the southeastern Arabian Sea (Singh et al., 2017). The sediments were processed following the standard procedure for foraminiferal study, after a minimum staining period of two weeks (Manasa et al., 2016).

A minimum of 300 living (stained) benthic foraminifera were picked from weighed aliquots of coarse fraction (>63 µm) of each sample. In a few cases, where sufficient specimens were not available, the entire coarse fraction was used to pick all the living specimens. To be sure of the stained status, the specimens were transferred to a petri-dish filled with water and examined under the microscope on a white base. The specimens with a wholesome mass of pink color in the shell were considered as living. The sediments also contained dead benthic foraminiferal shells. However, since the aim was to understand the effect of seasonal changes, only the living benthic foraminiferal assemblage was considered as the living population better represents short-term changes (Saalim et

al., 2017). Additionally, as the mudbank is associated with the disturbance of muddy substrate, there is a chance of old dead shells getting mixed with the recently dead shells, thus further complicating the signal. The marginal marine environments are characterized by both agglutinated and calcareous (hyaline) benthic foraminifera (Murray, 2006). Therefore, the living benthic foraminifera were segregated into agglutinated and calcareous forms. This basic classification is based upon the nature of exoskeleton of benthic foraminifera. The agglutinated foraminifera have an arenaceous/argillaceous shell and calcareous foraminifera secrete calcium carbonate shell. The shell character of foraminifera also tells about the nature of the environment they inhabit (Boltovskoy and Wright, 1976; Murray, 2006). The absolute abundance of total living agglutinated foraminifera (TLAN) and total living calcareous foraminifera (TLCN) was calculated. The TLAN and TLCN were normalized for 10 g of dried sediment. All the specimens were identified up to species level. At first, the specimens were identified at the generic level, following Loeblich and Tappan (1988). After that, species name for different specimens belonging to a particular genus, was ascertained by comparing detailed morphological features of the specimen with similar species described in previous research papers (Sethulakshmi, 1958; Matoba, 1970; Lutze, 1974; Seibold, 1975; Seibold and Seibold, 1981; Nisha and Singh, 2012), catalogs (Barker, 1960; Mc Culloch, 1977; Mc Culloch, 1981; Yassini and Jones, 1995; Ellis and Messina Catalogue of Foraminifera 2007), and thesis (Nigam, 1981; Khare, 1992; Pravin, 1993; Mayenkar, 1994; Mazumder, 2005). Each species was also compared with the type specimen, by using Ellis and Messina (2007) Catalogue of Foraminifera, to assign the final nomenclature to the specimens. The relative abundance of each species at each station for every season was also calculated. The seasonal distribution pattern of dominant species (with relative abundance >5 % in at least five sampling stations of each season), was plotted. The criterion of outlining the abundant species was taken into consideration to identify representative species for the area. The presence of a minimum percentage of a species (>5 %) in >50% of the area (5 sampling stations) is apt to define species response for the area under study.

To study the seasonal pattern of species diversity, Margalef's index (d) and Pielou's evenness index (J') were calculated. Margalef's index (d) is a measure of species richness in a sample. Margalef's index (d) follows the formula:

$$d = (S-1) / \log N$$

where S = Species richness, i.e., the total number of species in a sample

N = Total number of individuals in a sample

Pielou's evenness index is a measure of species evenness and is derived from Shannon-Wiener index. Shannon-Wiener diversity index is not affected by the sample size (Spellerberg, 2008). Mudbank being a relatively smaller area, the Shannon-Wiener Index was found most suitable to derive evenness. Shannon-Wiener Index was derived with \log_e . It comprises of Shannon function H' , such that:

$$H' = - \sum_i p_i \log(p_i)$$

where p_i is the proportion of total count of i^{th} species.

Pielou's evenness index (J') was derived Shannon-Wiener diversity index (H') by using the following formula:

$$J' = H' / H'_{max}$$

The species data was transformed to square root and analyzed for diversity by using Primer 7 software (Clarke et al., 2014).

The geochemical analysis of the sediments was done to provide supporting data. Total inorganic carbon (TIC) was measured by using UIC CM 5014 coulometer and total carbon (TC), and nitrogen (TN) was measured by using CE NCS 2500 elemental analyzer. The percentage organic carbon (%C_{org}) was calculated by subtracting TIC from TC.

3. Results

4.1 Spatial variation in benthic foraminifera

Since mudbank forms in shallow coastal settings, the absolute abundance of living agglutinated (TLAN) and calcareous (TLCN) foraminifera at Core Mudbank Stations (CMS), Northern Stations (NS) and Southern Station (SS) during the pre-monsoon (May 2015), monsoon (August 2015) and post-monsoon season (February 2016) was studied. In the core mudbank area, TLAN ranges from 19 to 28 individual per gram sediment during pre-monsoon and from 16 to 25 individual per gram sediment in monsoon. The TLAN, however, decreases during the post-monsoon season, ranging from 9 to 14 individual per gram sediment. The TLCN in CMS is 1 individual per gram sediment during pre-monsoon and 2 individual per gram sediment during monsoon. In the post-monsoon season, TLCN increases and ranges from 5 to 19 individual per gram sediment (Table 1). In the pre-monsoon and monsoon season, the agglutinated forms are relatively higher than calcareous forms. In the post-monsoon season, the calcareous foraminifera are more abundant (Fig. 2). The seasonal change in benthic foraminiferal abundance is prominent in NS (Fig. 2).

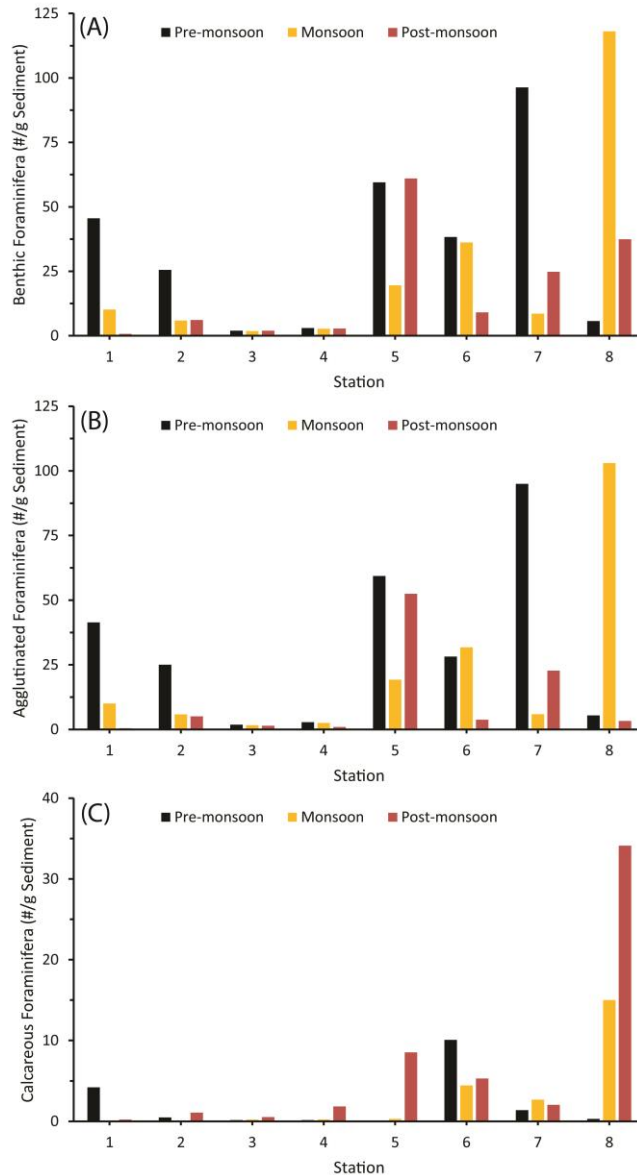


Figure 2. The absolute abundance (number/g dry sediment) of living benthic foraminifera (A), agglutinated benthic foraminifera (B) and calcareous benthic foraminifera (C), during pre-monsoon, monsoon and post-monsoon season.

The TLAN ranges from 250 to 414 individual per gram sediment in pre-monsoon, 58 to 100 individual per gram sediment in monsoon and 5 to 50 individual per gram sediment in post-monsoon. The TLCN continues to be less than TLAN in NS as well. During pre-monsoon TLCN ranges from 5 to 42 individual per gram sediment, decreases to 1 individual per gram sediment during monsoon and ranges from 2 to 11 individual per gram sediment during post-monsoon (Table 1). The living agglutinated and calcareous foraminiferal abundance is the highest in SS. The TLAN in the SS, ranges from 54 to 950 individual per gram sediment during pre-monsoon season, increasing to 59 to

1030 individual per gram sediment in monsoon season and decreasing to 33 to 525 individual per gram sediment in post-monsoon season. The TLCN varies from 1 to 101 individual per gram sediment in pre-monsoon, 3 to 150 individual per gram sediment in monsoon and 20 to 1214 individual per gram sediment in the post-monsoon season (Table 1). Contrary to CMS and NS, the TLCN in SS shows a consistent increase from pre-monsoon to monsoon to post-monsoon season (Fig. 2).

Table 1. Details of station locations, absolute abundance (number/g dry sediment) of living agglutinated benthic foraminifera (TLAN), living calcareous benthic foraminifera (TLCN) and percentage of organic carbon during (a) pre-monsoon, (b) monsoon and (c) post-monsoon season.

| Station No. | Longitude (°E) | Latitude (°N) | Depth (m) | TLAN (#/g dry Sediment) | TLCN (#/g dry Sediment) | %C _{org} |
|-------------|----------------|---------------|-----------|-------------------------|-------------------------|-------------------|
| 1 | 76.31 | 9.48 | 6 | 414 | 42 | 3.4 |
| 2 | 76.28 | 9.48 | 10 | 250 | 5 | 3.7 |
| 3 | 76.31 | 9.44 | 6 | 19 | 1 | 3.2 |
| 4 | 76.28 | 9.44 | 10 | 28 | 1 | 3.7 |
| 5 | 76.31 | 9.40 | 7 | 594 | 1 | 3.9 |
| 6 | 76.29 | 9.40 | 11 | 282 | 101 | 2.9 |
| 7 | 76.30 | 9.36 | 11 | 950 | 14 | 3.2 |
| 8 | 76.29 | 9.36 | 15 | 54 | 3 | 3.1 |

(a) Pre-monsoon Season

| Station No. | Longitude (°E) | Latitude (°N) | Depth (m) | TLAN (#/g dry Sediment) | TLCN (#/g dry Sediment) | %C _{org} |
|-------------|----------------|---------------|-----------|-------------------------|-------------------------|-------------------|
| 1 | 76.29 | 9.48 | 8 | 100 | 1 | 3.4 |
| 2 | 76.28 | 9.48 | 11 | 58 | 0 | 3.0 |
| 3 | 76.31 | 9.44 | 6 | 16 | 2 | 3.2 |
| 4 | 76.28 | 9.44 | 11 | 25 | 2 | 3.1 |
| 5 | 76.30 | 9.4 | 8 | 192 | 3 | 3.3 |
| 6 | 76.27 | 9.4 | 12 | 318 | 44 | 2.4 |
| 7 | 76.29 | 9.36 | 13 | 59 | 27 | 1.8 |
| 8 | 76.28 | 9.36 | 15 | 1030 | 150 | 1.5 |

(b) Monsoon Season

| Station No. | Longitude (°E) | Latitude (°N) | Depth (m) | TLAN (#/g dry Sediment) | TLCN (#/g dry Sediment) | %C _{org} |
|-------------|----------------|---------------|-----------|-------------------------|-------------------------|-------------------|
| 1 | 76.29 | 9.48 | 9 | 5 | 2 | 2.8 |
| 2 | 76.28 | 9.48 | 12 | 50 | 11 | 2.9 |
| 3 | 76.30 | 9.44 | 8 | 14 | 5 | 3.5 |
| 4 | 76.28 | 9.44 | 13 | 9 | 19 | 2.2 |
| 5 | 76.30 | 9.4 | 8 | 525 | 85 | 3.0 |
| 6 | 76.27 | 9.4 | 14 | 38 | 53 | 3.5 |
| 7 | 76.29 | 9.36 | 13 | 228 | 20 | 2.7 |
| 8 | 76.27 | 9.36 | 16 | 33 | 1214 | 2.9 |

(c) Post-monsoon Season

4.2 Species distribution

The living agglutinated foraminifera belong to 5 genera, namely *Ammoscalaris*, *Ammobaculites*, *Nouria*, *Eggerella*, and *Textularia*. The living calcareous foraminiferal population is more diverse and is represented by 21 genera, namely *Quinqueloculina*, *Bolivina*, *Brizalina*, *Hopkinsinella*, *Bulimina*, *Buliminella*, *Siphogenerina*, *Virgulina*, *Cancris*, *Epnoides*, *Neoconorbina*, *Nonion*, *Nonionella*, *Nonionellina*, *Protelphidium*, *Pararotalia*, *Ammonia*, *Asterorotalia*, *Cribronion*, *Elphidium* and *Florilus*. The specimens belong to a total of 51 species (Table 2). Amongst all of these, genus *Ammobaculites* comprising of two species, namely *Ammobaculites dilatatus* and *Ammobaculites exiguus*, dominate the living benthic foraminifera. Both *A. dilatatus* and *A. exiguus* constitute >5% of the total living benthic foraminiferal population in at least 5 stations in each season (Table 3) (Figs. 3, 4). In the NS, the relative abundance of *A. dilatatus* ranges from 83 to 93% during the pre-monsoon, 78 to 84% during the monsoon and decreases to 53 to 62% in the post-monsoon season. In SS, the relative abundance of *A. dilatatus* ranges from 65 to 86% during pre-monsoon, 57 to 94% in monsoon and 56 to 67% in post-monsoon season. In CMS, the relative abundance of *A. dilatatus* ranges from 72 to 93% during the pre-monsoon, 58 to 74% in monsoon and 23 to 65% in the post-monsoon season (Table 3). The relative abundance of *A. exiguus* in NS, ranges from 4 to 7% in pre-monsoon, 16 to 21% in monsoon and is 0 to 29% during the post-monsoon season. The relative abundance of *A. exiguus* in CMS varies from 0 to 21% in pre-monsoon, increasing to 16 to 26% in monsoon and reducing to 10% in the post-monsoon season. In the SS, the relative abundance of *A. exiguus* ranges from 4 to 23% in pre-monsoon, 5 to 17% in monsoon and 0 to 37% during the post-monsoon season (Table 2).

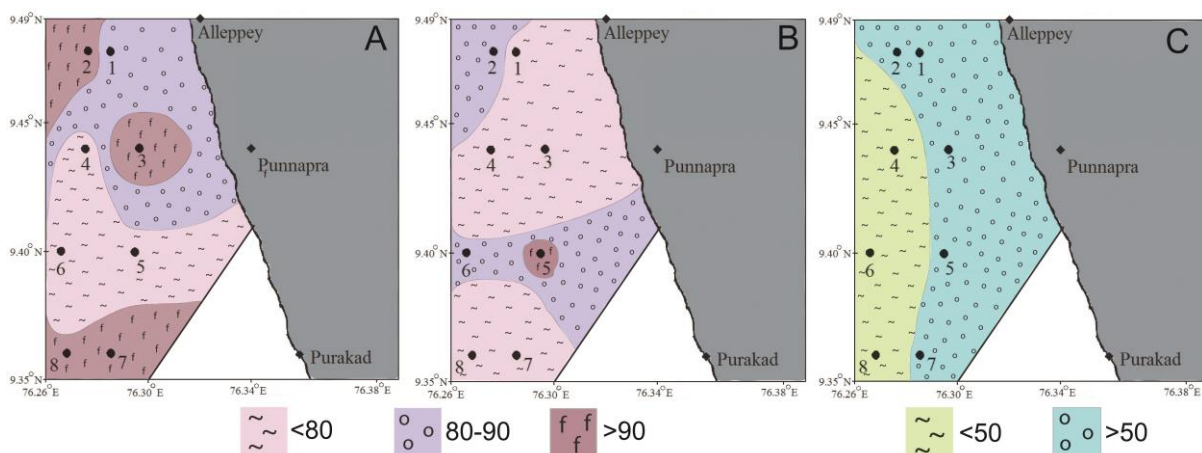


Figure 3. The relative abundance (%) of *Ammobaculites dilatatus* during (A) pre-monsoon, (B) monsoon and (C) post-monsoon season.

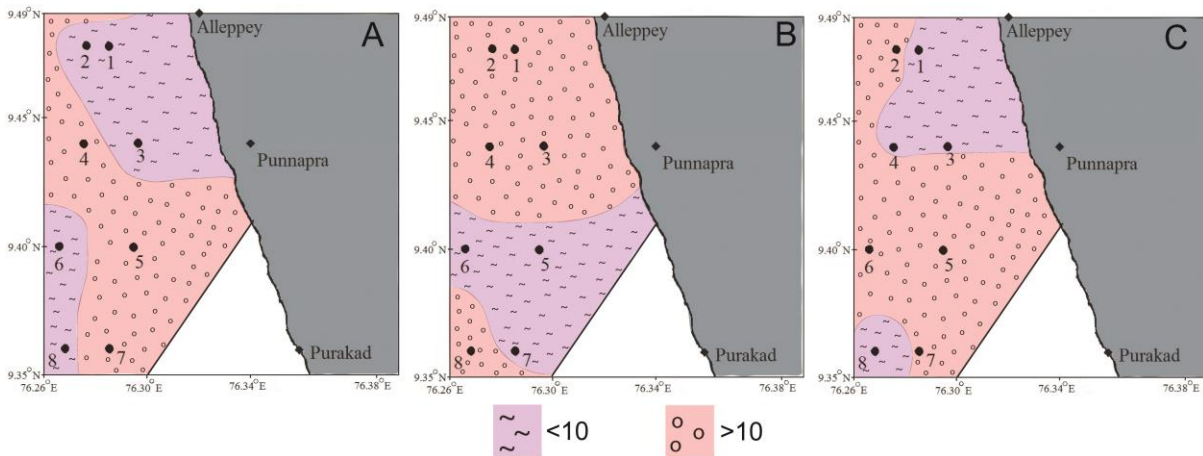


Figure 4. The relative abundance (%) of *Ammobaculites exiguus* during (A) pre-monsoon, (B) monsoon and (C) post-monsoon season.

Table 2. List of benthic foraminifera reported from the mudbank area off Alleppey, Kerala

| S. No. | Species | Presence in Season/Station |
|--------|------------------------------------|--|
| 1 | <i>Ammoscalaris pseudospiralis</i> | Pre-Mon/ St. No. 1; Mon/ St. No. 4, 7 & 8 |
| 2 | <i>Ammobaculites dilatatus</i> | Pre-Mon/ All Sts.; Mon/ All Sts.; Post-Mon/ All Sts. |
| 3 | <i>Ammobaculites exiguus</i> | Pre-Mon/ St. No. 1, 2, 4 to 8; Mon/ All Sts.; Post-Mon/ St. No. 2 to 8 |
| 4 | <i>Nouria polymorphinoides</i> | Pre-Mon/ St. No. 1, 2, 6 & 8; Mon/ St. No. 6 |
| 5 | <i>Eggerella scabra australis</i> | Pre-Mon/ St. No. 4; Mon/ St. No. 6 & 8; Post-Mon/ St. No. 7 & 8 |
| 6 | <i>Textularia earlandi</i> | Pre-Mon/ St. No. 2, 6 & 7; Mon/ St. No. 7 & 8; Post-Mon/ St. No. 1, 6, 7 & 8 |
| 7 | <i>Quinqueloculina laevigata</i> | Pre-Mon/ St. No. 6; Mon/ St. No. 7; Post-Mon/ St. No. 4 & 6 |
| 8 | <i>Quinqueloculina seminulum</i> | Pre-Mon/ St. No. 6; Post-Mon/ St. No. 1 |
| 9 | <i>Bolivina aff. durandii</i> | Mon/ St. No. 7 & 8 |

| | | |
|----|-------------------------------------|---|
| 10 | <i>Bolivina</i> aff. <i>kuriani</i> | Post-Mon/ St. No. 2, 3, 4 & 5 |
| 11 | <i>Bolivina</i> sp. | Mon/ St. No. 7 & 8; Post-Mon/ St. No. 1, 2 & 4 |
| 12 | <i>Brizalina limbata</i> | Pre-Mon/ St. No. 3 |
| 13 | <i>Brizalina ordinaria</i> | Post-Mon/ St. No. 2 |
| 14 | <i>Brizalina semistriata</i> | Mon/ St. No. 8 |
| 15 | <i>Brizalina striatula</i> | Pre-Mon/ St. No. 1, 3, 6-8; Mon/ St. No. 1, 3-7; Post-Mon/ St. No. 2-8 |
| 16 | <i>Hopkinsinella glabra</i> | Pre-Mon/ St. No. 4; Mon/ St. No. 7 |
| 17 | <i>Bulimina exilis</i> | Pre-Mon/ St. No. 8; Post-Mon/ St. No. 4 |
| 18 | <i>Buliminella elegantissima</i> | Post-Mon/ St. No. 4-5 |
| 19 | <i>Siphogenerina virgula</i> | Post-Mon/ St. No. 5 |
| 20 | <i>Virgulina</i> sp. 1 | Post-Mon/ St. No. 6-8 |
| 21 | <i>Virgulina</i> sp. 2 | Post-Mon/ St. No. 6-8 |
| 22 | <i>Virgulina</i> sp. 3 | Post-Mon/ St. No. 6-8 |
| 23 | <i>Virgulina</i> sp. 4 | Mon/ St. No. 8; Post-Mon/ St. No. 2 & 8 |
| 24 | <i>Virgulina</i> sp. 5 | Pre-Mon/ St. No. 2; Post-Mon/ St. No. 5 |
| 25 | <i>Virgulina</i> sp. 6 | Pre-Mon/ St. No. 8; Post-Mon/ St. No. 5 & 8 |
| 26 | <i>Virgulina</i> sp. 7 | Post-Mon/ St. no. 5 |
| 27 | <i>Virgulina</i> sp. 8 | Post-Mon/ St. No. 8 |
| 28 | <i>Cancris auricula</i> | Pre-Mon/ St. No. 6 |
| 29 | <i>Cancris carinatus</i> | Mon/ St. No. 6; Post-Mon/ St. No. 4 & 8 |
| 30 | <i>Eponides regularis</i> | Mon/ St. No. 7 |
| 31 | <i>Neoconorbina</i> sp. | Mon/ St. No. 7; Post-Mon/ St. No. 3, 4, 7 & 8 |
| 32 | <i>Nonion belridgense</i> | Pre-Mon/ St. No. 2; Mon/ St. No. 6-8; Post-Mon/ |

| | | |
|----|-----------------------------------|---|
| | | St. No. 6 & 8 |
| 33 | <i>Nonion boueanum</i> | Post-Mon/ St. No. 8 |
| 34 | <i>Nonion elongatum</i> | Pre-Mon/ St. No. 5 |
| 35 | <i>Nonion scapha</i> | Pre-Mon/ St. No. 4; Mon/ St. No. 8; Post-Mon/ St. No. 4, 6 & 8 |
| 36 | <i>Nonionella cf. monicana</i> | Post-Mon/ St. No. 3 to 8 |
| 37 | <i>Nonionellina labradorica</i> | Post-Mon/ St. No. 2 to 8 |
| 38 | <i>Protelphidium cf. schmitti</i> | Post-Mon/ St. No. 5 |
| 39 | <i>Pararotalia cf. globosa</i> | Post-Mon/ St. No. 4 |
| 40 | <i>Ammonia aff. globosa</i> | Post-Mon/ St. No. 6 |
| 41 | <i>Ammonia sobrina</i> | Mon/ St. No. 6, 7 & 8; Post-Mon/ St. No. 2, 4, 7 & 8 |
| 42 | <i>Ammonia tepida</i> | Pre-Mon/ St. No. 2; Mon/ St. no. 2, 4, 5 & 7; Post-Mon/ St. No. 1, 2, 3, 4, 5, 7 & 8 |
| 43 | <i>Asterorotalia dentata</i> | Pre-Mon/ St. No. 1, 2, 6, 7 & 8; Mon/ St. No. 5, 6, 7 & 8 |
| 44 | <i>Asterorotalia inflata</i> | Mon/ St. No. 5 & 8; Post-Mon/ St. No. 6 & 7 |
| 45 | <i>Cribronion somaense</i> | Post-Mon/ St. No. 4 & 5 |
| 46 | <i>Elphidium excavatum</i> | Pre-Mon/ St. No. 6; |
| 47 | <i>Florilus tobagoensis</i> | Mon/ St. No. 8; Post-Mon/ St. No. 2, 4, 5, 7 & 8 |
| 48 | Unidentified 1 | Post-Mon/ St. No. 1, 4 & 5 |
| 49 | Unidentified 2 | Post-Mon/ St. No. 4 |
| 50 | Unidentified 3 | Post-Mon/ St. No. 4 |
| 51 | Unidentified 4 | Post-Mon/ St. No. 4 |

Table 3. The relative abundance (%) of different benthic foraminifera species in the study area during (a) pre-monsoon, (b) monsoon and (c) post-monsoon season.

| Species | Sampling Stations | | | | | | | |
|------------------------------------|-------------------|-----|-----|-----|-----|-----|-----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| <i>Ammoscalaris pseudospiralis</i> | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Ammobaculites dilatatus</i> | 83 | 93 | 93 | 72 | 77 | 65 | 83 | 86 |
| <i>Ammobaculites exiguus</i> | 6.5 | 4 | 0 | 21 | 23 | 4.3 | 16 | 7.2 |
| <i>Nouria polymorphinoides</i> | 0.6 | 0.6 | 0 | 0 | 0 | 0.7 | 0 | 2.1 |
| <i>Eggerella scabra australis</i> | 0 | 0 | 0 | 2.3 | 0 | 0 | 0 | 0 |
| <i>Textularia earlandi</i> | 0 | 0.6 | 0 | 0 | 0 | 4 | 0.3 | 0 |
| <i>Quinqueloculina laevigata</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |
| <i>Quinqueloculina seminulum</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |
| <i>Brizalina limbata</i> | 0 | 0 | 3.4 | 0 | 0 | 0 | 0 | 0 |
| <i>Brizalina striatula</i> | 0.9 | 0 | 3.4 | 0 | 0 | 17 | 0.9 | 2.1 |
| <i>Hopkinsinella glabra</i> | 0 | 0 | 0 | 2.3 | 0 | 0 | 0 | 0 |
| <i>Bulimina exilis</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| <i>Virgulina</i> sp. 5 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Virgulina</i> sp. 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| <i>Cancris auricula</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |
| <i>Nonion belridgense</i> | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Nonion elongatum</i> | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 |
| <i>Nonion scapha</i> | 0 | 0 | 0 | 2.3 | 0 | 0 | 0 | 0 |
| <i>Ammonia tepida</i> | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Asterorotalia dentata</i> | 8.3 | 0.9 | 0 | 0 | 0 | 7.9 | 0.6 | 1 |
| <i>Elphidium excavatum</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |

(a) Relative Abundance (%) of benthic foraminiferal species during pre-monsoon season

| Species | Sampling Stations | | | | | | | |
|------------------------------------|-------------------|-----|----|-----|-----|-----|-----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| <i>Ammoscalaris pseudospiralis</i> | 0 | 0 | 0 | 1.2 | 0 | 0 | 0.5 | 1.1 |
| <i>Ammobaculites dilatatus</i> | 78 | 84 | 58 | 74 | 94 | 82 | 57 | 66 |
| <i>Ammobaculites exiguus</i> | 21 | 16 | 26 | 16 | 4.6 | 5.1 | 9.8 | 17 |
| <i>Nouria polymorphinoides</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |
| <i>Eggerella scabra australis</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0.4 |
| <i>Textularia earlandi</i> | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 7.5 |
| <i>Quinqueloculina laevigata</i> | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 0 |
| <i>Bolivina aff. durandii</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 |
| <i>Bolivina sp.</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.4 |
| <i>Brizalina semistriata</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 |
| <i>Brizalina striatula</i> | 1.1 | 0 | 16 | 7.4 | 0.5 | 8.8 | 14 | 0 |
| <i>Hopkinsinella glabra</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 |
| <i>Virgulina sp. 4</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 |
| <i>Cancris carinatus</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 |
| <i>Epnoides regularis</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 |
| <i>Neoconorbina sp.</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0 |
| <i>Nonion belridgense</i> | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.5 | 1.5 |
| <i>Nonion scapha</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.2 |
| <i>Ammonia sobrina</i> | 0 | 0 | 0 | 0 | 0 | 1.4 | 1.9 | 0.4 |
| <i>Ammonia tepida</i> | 0 | 0.6 | 0 | 1.2 | 0.5 | 0 | 0.9 | 0 |
| <i>Asterorotalia dentata</i> | 0 | 0 | 0 | 0 | 0.3 | 1.4 | 10 | 1.5 |
| <i>Asterorotalia inflata</i> | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0.4 |
| <i>Florilus tobagoensis</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 |

(b) Relative Abundance (%) of benthic foraminiferal species during monsoon season

| Species | Sampling Stations | | | | | | | |
|-----------------------------------|-------------------|------|------|------|------|------|------|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| <i>Ammobaculites dilatatus</i> | 62.0 | 53.0 | 65.0 | 23.0 | 67.0 | 28.0 | 53.0 | 5.6 |
| <i>Ammobaculites exiguus</i> | 0 | 29 | 10 | 10 | 19 | 13 | 37 | 0.1 |
| <i>Eggerella scabra australis</i> | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1.1 |
| <i>Textularia earlandi</i> | 7.7 | 0 | 0 | 0 | 0 | 0.7 | 0.7 | 1.4 |
| <i>Quinqueloculina laevigata</i> | 0 | 0 | 0 | 0.9 | 0 | 0.7 | 0 | 0 |
| <i>Quinqueloculina seminulum</i> | 7.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Bolivina aff. kuriani</i> | 0 | 2.3 | 2.5 | 3.7 | 0.7 | 0 | 0 | 0 |
| <i>Bolivina sp.</i> | 7.7 | 0.8 | 0 | 0.9 | 0 | 0 | 0 | 0 |
| <i>Brizalina ordinaria</i> | 0 | 0.8 | 0 | 0 | 0 | 0 | 0 | 0 |
| <i>Brizalina striatula</i> | 0 | 2.3 | 7.5 | 6.5 | 8.8 | 28 | 1.4 | 18 |
| <i>Bulimina exilis</i> | 0 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 |
| <i>Buliminella elegantissima</i> | 0 | 0 | 0 | 0.9 | 0.3 | 0 | 0 | 0 |
| <i>Siphogenerina virgula</i> | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 |
| <i>Virgulina sp. 1</i> | 0 | 0 | 0 | 0 | 0 | 1.3 | 0.3 | 2.8 |
| <i>Virgulina sp. 2</i> | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.7 | 5.3 |
| <i>Virgulina sp. 3</i> | 0 | 0 | 0 | 0 | 0 | 3.4 | 0.3 | 3.9 |
| <i>Virgulina sp. 4</i> | 0 | 0.8 | 0 | 0 | 0 | 0 | 0 | 0.4 |
| <i>Virgulina sp. 5</i> | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 |
| <i>Virgulina sp. 6</i> | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 4.2 |
| <i>Virgulina sp. 7</i> | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 |
| <i>Virgulina sp. 8</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 |
| <i>Cancris carinatus</i> | 0 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0.4 |

| | | | | | | | | |
|--|-----|-----|-----|-----|-----|-----|-----|-----|
| <i>Neoconorbina</i> sp. | 0 | 0 | 2.5 | 0.9 | 0 | 0 | 0.3 | 0.4 |
| <i>Nonion belridgense</i> | 0 | 0 | 0 | 0 | 0 | 0.7 | 0 | 1.1 |
| <i>Nonion boueanum</i> | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 |
| <i>Nonion scapha</i> | 0 | 0 | 0 | 0.9 | 0 | 1.3 | 0 | 2.1 |
| <i>Nonionella</i> cf. <i>monicana</i> | 0 | 0 | 5.0 | 3.7 | 0.3 | 15 | 1.4 | 35 |
| <i>Nonionellina labradorica</i> | 0 | 3.1 | 2.5 | 0.9 | 0.7 | 4.7 | 2.1 | 12 |
| <i>Protelphidium</i> cf. <i>schmitti</i> | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 |
| <i>Pararotalia</i> cf. <i>globosa</i> | 0 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 |
| <i>Ammonia</i> aff. <i>globosa</i> | 0 | 0 | 0 | 0 | 0 | 0.7 | 0 | 0 |
| <i>Ammonia sobrina</i> | 0 | 2.3 | 0 | 1.9 | 0 | 0 | 0.3 | 0.4 |
| <i>Ammonia tepida</i> | 7.7 | 3.8 | 5 | 32 | 0.3 | 0 | 0.3 | 0.4 |
| <i>Asterorotalia dentata</i> | 0 | 0 | 0 | 0.9 | 0 | 0.7 | 0 | 0.7 |
| <i>Asterorotalia inflata</i> | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 |
| <i>Cribronion somaense</i> | 0 | 0 | 0 | 0.9 | 0.3 | 0 | 0 | 0 |
| <i>Florilus tobagoensis</i> | 0 | 1.5 | 0 | 1.9 | 0.7 | 0 | 0.3 | 3.9 |
| Unidentified 1 | 7.7 | 0 | 0 | 3.7 | 0.3 | 0 | 0 | 0 |
| Unidentified 2 | 0 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 |
| Unidentified 3 | 0 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 |
| Unidentified 4 | 0 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 |

Relative abundance (%) of benthic foraminiferal species during post-monsoon season

4.3 Species diversity and evenness

From the Margalef's index (d), it is clear that the species richness at CMS, during pre-monsoon (0.6 to 1.1) is similar to that in monsoon season (0.8 to 1.4) (Fig. 5A, Table 4). The species richness, however, increases tremendously and is the highest (varying from 2.6 to 6.0) in the post-monsoon season. The species richness at NS is comparable with that at CMS and ranges from 0.9 to 1.2 in pre-

monsoon and decreases to 0.7 in monsoon season. A large increase in species richness (ranging from 2.4 to 3.0) is reported in this region during the post-monsoon season. In SS, the species richness ranges from 0.3 to 1.6 in pre-monsoon season, 1.5 to 3.8 in monsoon season and 3.8 to 5.1 in post-monsoon season. In CMS, Pielou's Evenness Index (J') ranges from 0.71 to 0.83 in pre-monsoon, increasing to 0.82 to 0.97 in monsoon and 0.91 to 0.93 in post-monsoon (Fig. 5B, Table 4). In NS, J' ranges from 0.67 to 0.76 in pre-monsoon, 0.72 to 0.78 in monsoon and increases to 0.87 to 0.94 in post-monsoon season. In SS, J' ranges from 0.68 to 0.82 in pre-monsoon season, 0.60 to 0.86 during monsoon and increases to 0.79 to 0.92 in post-monsoon season.

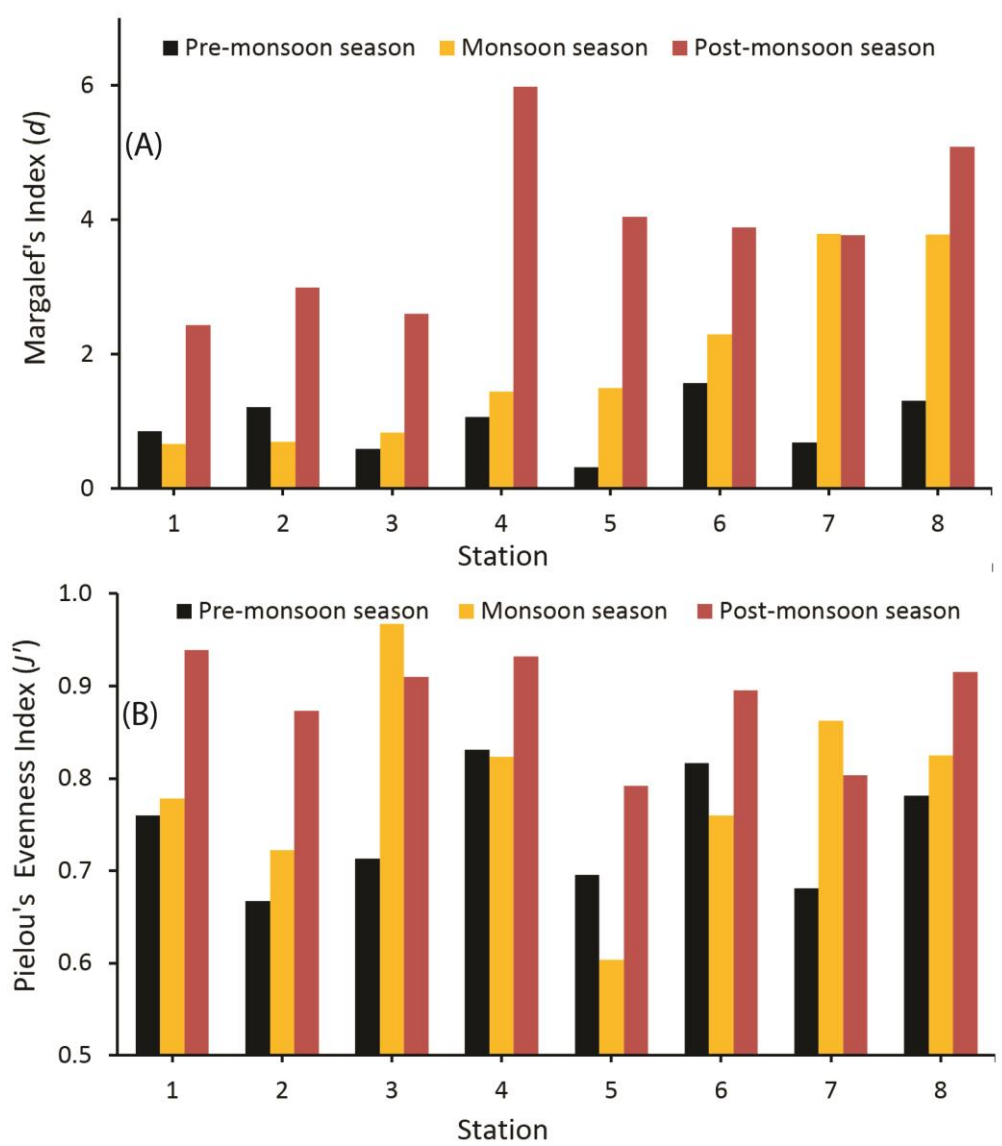


Figure 5. Species diversity represented as (A) Margalef's Index of species richness and (B) Pielou's Evenness Index during all seasons.

Table 4. Number of species (S), number of individuals (N), Margalef's index (*d*), Pielou's Evenness Index (*J'*) and Shannon–Wiener Index (*H'*) during (a) pre-monsoon, (b) monsoon and (c) post-monsoon season.

| Station No. | S | N | <i>d</i> | <i>J'</i> | <i>H'</i> (loge) |
|-------------|----|-----|----------|-----------|------------------|
| 1 | 6 | 336 | 0.9 | 0.76 | 1.36 |
| 2 | 8 | 321 | 1.2 | 0.67 | 1.39 |
| 3 | 3 | 29 | 0.6 | 0.71 | 0.78 |
| 4 | 5 | 43 | 1.1 | 0.83 | 1.34 |
| 5 | 3 | 557 | 0.3 | 0.70 | 0.76 |
| 6 | 10 | 304 | 1.6 | 0.82 | 1.88 |
| 7 | 5 | 349 | 0.7 | 0.68 | 1.10 |
| 8 | 7 | 97 | 1.3 | 0.78 | 1.52 |

(a) Pre-monsoon season

| Station No. | S | N | <i>d</i> | <i>J'</i> | <i>H'</i> (loge) |
|-------------|----|----|----------|-----------|------------------|
| 1 | 3 | 20 | 0.7 | 0.78 | 0.85 |
| 2 | 3 | 18 | 0.7 | 0.72 | 0.79 |
| 3 | 3 | 11 | 0.8 | 0.97 | 1.06 |
| 4 | 5 | 16 | 1.4 | 0.82 | 1.32 |
| 5 | 6 | 28 | 1.5 | 0.60 | 1.08 |
| 6 | 9 | 32 | 2.3 | 0.76 | 1.67 |
| 7 | 15 | 40 | 3.8 | 0.86 | 2.34 |
| 8 | 15 | 41 | 3.8 | 0.82 | 2.23 |

(b) Monsoon season

| Station No. | S | N | <i>d</i> | <i>J'</i> | <i>H'</i> (loge) |
|-------------|----|----|----------|-----------|------------------|
| 1 | 6 | 8 | 2.4 | 0.78 | 0.85 |
| 2 | 11 | 28 | 3.0 | 0.72 | 0.79 |
| 3 | 8 | 15 | 2.6 | 0.97 | 1.06 |
| 4 | 23 | 40 | 6.0 | 0.82 | 1.32 |
| 5 | 16 | 41 | 4.0 | 0.60 | 1.08 |
| 6 | 15 | 37 | 3.9 | 0.76 | 1.67 |
| 7 | 15 | 41 | 3.8 | 0.86 | 2.34 |
| 8 | 22 | 62 | 5.1 | 0.82 | 2.23 |

(c) Post-monsoon season

4.4 Calcium carbonate (%CaCO₃), Organic carbon (%C_{org}) and C_{org}/N

The %CaCO₃ is lower during both the pre-monsoon and monsoon season in the core mudbank and northern peripheral region (Fig. 6A). Interestingly, %CaCO₃ increases at several stations during monsoon season. The lowest %C_{org} (1.5%) is recorded at station 8 during the post-monsoon season, and the highest (3.9%) is at station 5 during pre-monsoon season (Fig. 6B). The %C_{org} varies from 2.9 to 3.9% in the pre-monsoon season. A decrease in %C_{org} is reported during monsoon season (varying from 1.5 to 3.4%). In post-monsoon season, %C_{org} varies from 2.2 to 3.5% (Table 1). In the pre-monsoon and monsoon season, %C_{org} at CMS and NS is closer than that at SS. During the post-monsoon season, however, the entire area does not show appreciable variability in organic carbon concentration. The %C_{org}/N ratio is ~10 at a majority of the stations during all the seasons (Fig. 6C).

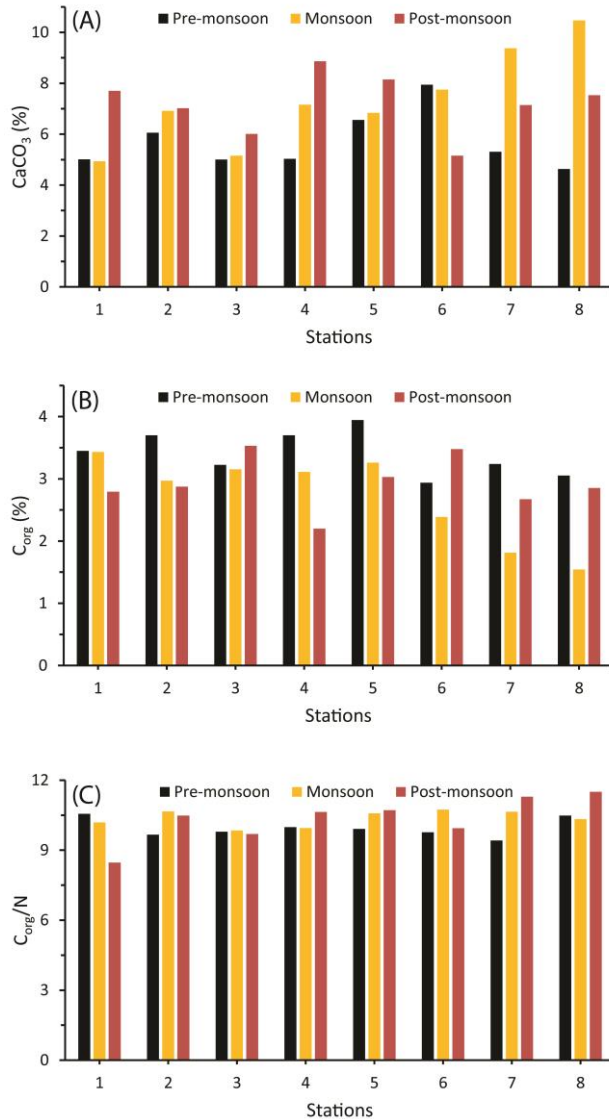


Figure 6. The calcium carbonate (CaCO_3) (A), organic carbon ($\%C_{\text{org}}$) (B) and C_{org}/N (C) in the study area during different seasons.

5. Discussion

5.1 Spatial and seasonal change in living benthic foraminifera

Benthic foraminiferal abundance is low in the monsoon season as the mudbank is very well established during this time. A similar low meiobenthos population with foraminifera being the second largest group after nematodes, has also been reported from the same mudbank (Damodaran, 1972). The agglutinated foraminifera dominate the living benthic foraminifera in both the core mudbank area and its peripheral regions. The presence of agglutinated foraminifera in marine shallow water environment indicates carbonate under-saturation due either to freshwater influence or low pH (Nigam et al., 1979; Setty and Nigam, 1980; Nigam, 1987). The generally high abundance of

living agglutinated benthic foraminifera in the mudbank region is attributed to the low pH. The degradation of high C_{org} content in the mudbank region considerably lowers the ambient seawater pH (Nair and Balchand, 1992). However, we want to point out that even though the high C_{org} induced low pH, considerably modulates the generally high relative abundance of agglutinated benthic foraminifera throughout the year, additional factors control the seasonal changes in benthic foraminiferal population. The % C_{org} is the highest during pre-monsoon season and comparatively lower during the monsoon season when mudbank forms. Therefore, the C_{org} induced lower pH should adversely affect calcareous benthic foraminifera, comparatively more during the pre-monsoon season and not during the monsoon season. We, however, report a higher abundance of calcareous benthic foraminifera during the pre-monsoon season, suggesting additional factors that affect the benthic foraminiferal population in this area. The marginal marine niches as estuaries, river mouths, marshes, lagoons exhibit great variability in their ecological conditions, primarily due to intermixing of a large quantity of freshwater along the shoreline. The field and laboratory culture studies on marginal marine benthic foraminifera suggest that the reduced salinity due to the mixing of freshwater is detrimental to calcareous foraminifera. The low salinity and associated changes cause reduced growth, abnormal reproduction and even dissolution of calcareous benthic foraminifera, thus lowering the benthic foraminiferal population (Nigam et al., 2006; 2008; Kurtarkar et al., 2011; Saraswat et al., 2015). However, the agglutinated foraminifera thrive relatively well in such coastal settings, characterized by low salinity (Boltovskoy and Wright, 1976; Murray, 1991; Sen Gupta, 1999). Thus, the abundance of agglutinated foraminifera in the living benthic foraminiferal population in the core mudbank region, confirms the freshwater influence in the study area. Apart from this, foraminifera being highly sensitive organisms, also exhibit seasonal and spatial variation in its population responding to the formation and withdrawal of mudbank.

The absolute abundance of agglutinated foraminifera decreases marginally in the CMS during the monsoon season (Table 1, Fig. 2), despite the low bottom water salinity (24.4 to 26.9 psu), which otherwise is a positive environmental parameter for agglutinated foraminifera. This decrease in agglutinated benthic foraminiferal abundance during monsoon season occurs due to the disturbance and re-suspension of bottom mud, a phenomenon coherently associated with the formation of mudbank (Mallik et al., 1988; Tatavarti et al., 1999; Narayana et al., 2008). The disturbance of the substrate is expected to affect benthic foraminifera living in a top few centimeters of the sediments (Diz and Frances, 2008; Caille et al., 2013; de Chanvalon et al., 2015; Singh et al., 2017). Such environmental conditions also affect calcareous forms, as its abundance remains consistently very low, due to the combined effect of freshwater influence (in general) and bottom sediment disturbance

(at the time of mudbank formation). The substrate disturbance is evident from the re-suspension of bottom mud resulting in the exceptionally high concentration of suspended particulate matter. The suspended particulate matter concentration in the water column increases from the top to bottom in the mudbank area, that is neither drained by rivers nor affected by wave activity at the time of mudbank formation (Mallik et al., 1988; Shynu et al., 2017). It is important to note that TLCN remains <5 , both in pre-monsoon and monsoon season. Hence, it is difficult to assess the relative weightage of the two factors, namely freshwater influence and bottom sediment disturbance, in controlling the calcareous benthic foraminiferal abundance. As the mudbank withdraws, the faunal population starts rejuvenating in CMS. With the weaning of mudbank in the post-monsoon season, both the freshwater influence and bottom sediment disturbance subdues in CMS. This absence of mudbank in the post-monsoon season is evident in the change in living benthic foraminiferal population, as the TLCN increases and TLAN decreases (Fig. 4). The freshwater influence is further confirmed by the dominance of freshwater diatoms in the mudbank sediments (Thakur et al., 2012). The consistently high %C_{org} in the mudbank region during all the seasons suggests that the food availability is not a factor in low foraminiferal abundance in the mudbank region. The type of food also affects benthic foraminifera. The organic matter in the oceans is either of marine or terrestrial origin. The changes in the relative contribution of marine and terrestrial organic matter sources can be discerned by its C_{org}/N ratio. The protein-rich marine primary producers have a low C_{org}/N, as compared to the generally cellulose-rich terrestrial plants with high C_{org}/N (Burdige, 2007). The possibility of a significant change in the relative contribution of marine or terrestrial source of organic matter in the study area is also ruled out as the C_{org}/N is invariably same at all the stations during all the seasons.

The effect of mudbank is well recorded in the peripheral region. The abundance of both agglutinated (TLAN) and calcareous (TLCN) foraminifera at stations north of the core mudbank region, decreases from pre-monsoon to monsoon season (Fig. 2). Subsequently, the population of both the forms increases again in the post-monsoon season (Fig. 2). The pattern of faunal abundance shows that mudbank affects the northern peripheral region as well. The effect is, however, comparatively marginal, and that NS does not form the mudbank foci, is ascertained by the higher foraminiferal abundance in NS than CMS (Fig. 2). The SS has the highest living foraminiferal abundance, as compared to CMS and NS. This region has invariably high agglutinated and calcareous foraminifera population, both in the pre-monsoon and monsoon season, where the agglutinated forms are more than calcareous benthic foraminifera (Fig. 2). In the post-monsoon season, agglutinated foraminiferal abundance decreases and that of calcareous forms increase in the

southern peripheral region (Fig. 2). Based on the nature of foraminiferal distribution, we are certain that SS does not come under the peripheral effect of mudbank formation.

The low calcareous abundance in the mudbank is expected to affect the resultant carbon sequestration as foraminifera are responsible for a large fraction of carbon burial. The low CaCO_3 in the core mudbank and northern peripheral region is a clear indication of comparatively low foraminifera modulated carbon burial. The low foraminifera modulated carbon burial, however, does not seem to affect overall carbon sequestration, as the $\%C_{\text{org}}$ in the mudbank sediments is very high, possibly due to fine-grained sediments. The fine-grained sediments support better organic carbon preservation (Mayer, 1994). Additionally, the high turbidity is confined to the bottom of the water column and the plankton population in the surface waters is very high even during the peak mudbank formation time (Jyothibabu et al., 2018). The high plankton population results in increased carbon sequestration and its final burial as organic matter in the mudbank region.

5.2 Species richness and evenness

The species richness in CMS does not change significantly, from pre-monsoon to monsoon season. In the post-monsoon season, however, there is a significant increase in the species richness in CMS. The seasonal variation in species richness in NS is similar to CMS, with a significant decrease from the pre-monsoon to monsoon season, but an appreciable increase during the post-monsoon season. The low species richness during both the pre-monsoon and monsoon season in CMS and NS is attributed to stressed conditions including low salinity and very high turbidity. The $\%C_{\text{org}}$ is, however, comparatively higher during the pre-monsoon and monsoon season in both NS and CMS. The high $\%C_{\text{org}}$ implies more food availability and should result in increased benthic foraminiferal population. The change in $\%C_{\text{org}}$ during different seasons is therefore not significant enough to affect species richness. In the SS, species richness remains invariably high compared to CMS and NS. It shows a consistent increase from pre-monsoon to monsoon and from monsoon to the post-monsoon season (Fig. 5A). The high salinity combined and stable substrate allow multiple species to thrive in the southernmost part of the study area.

Species evenness is the highest during the post-monsoon season at all but one station. Surprisingly, an increase in evenness during monsoon season is also evident at several stations, as compared to that in the pre-monsoon season. In other words, dominance decreases during monsoon season and is the least during the post-monsoon season (Clarke et al., 2014). This species response is obvious because with the onset of mudbank in monsoon season only the most tolerant species can survive in mudbank's stressful environment. The evenness improves during the post-monsoon season

as the benthic foraminiferal population is well represented by more number of species (as is also seen with d values) (Fig.5B).

5.3 Species-specific response

Ammobaculites dilatatus dominated the foraminiferal population in the mudbank area. The relative abundance of *Ammobaculites dilatatus* in the core mudbank region decreases from pre-monsoon to monsoon season by 17% (average of the difference in upper and lower values) and further by 22% in the post-monsoon season (Fig. 4A). The decrease in relative abundance from pre-monsoon to monsoon season is attributed to mudbank formation. The very formation of mudbank is associated with a decrease in bottom water salinity and re-suspension of bottom mud. The bottom water salinity in the core mudbank region, at the time of mudbank formation, ranges from 24.4 to 26.9 psu. *Ammobaculites dilatatus* is low salinity (20 – 30 psu) tolerant and thrives in marginal marine environments (Boltovskoy and Wright, 1976). It has an affinity for mud and fine sand, thriving well in 0 - 11 m water depth (Murray, 1991). Additionally, *A. dilatatus* is an epiphytic species (Jones and Charnock, 1985). Since the salinity is well within the tolerance limits of *A. dilatatus*, hence the salinity cannot cause the decrease in its abundance. Another significant environmental parameter that governs faunal population is food. The %C_{org} in the sediment is a good indicator of the food available for benthic foraminifera (Sen Gupta, 1999). There is no significant seasonal change in %C_{org} and hence it does not influence the changes in faunal abundance. The other reason which can cause a decrease in the abundance of *Ammobaculites dilatatus* in monsoon season, is substrate disturbance, due to re-suspension of bottom mud and consequential increase in suspended particulate matter concentration (6.2 to 9.2g/l) especially near the substrate (Shynu et al., 2017). The bottom disturbance during the peak mudbank season will adversely affect the epiphytic *A. dilatatus*. The second phase of a decrease in relative abundance of *Ammobaculites dilatatus* from monsoon to post-monsoon is intriguing. The mudbank no longer exists in the post-monsoon season. The re-suspension of bottom mud subsides as soon as monsoon withdraws as evident from a reduction in the suspended particulate matter concentration (32.9 to 100.9 mg/l) (Shynu et al., 2017). However, the bottom water salinity increases during the post-monsoon season, varying from 26.7 to 31.9 psu. Therefore, the increased salinity is the reason for the post-monsoonal decrease in abundance of *Ammobaculites dilatatus*. With the reduced influence of fresh water, the abundance of agglutinated foraminifera decreases.

In the peripheral regions, the relative abundance of *A. dilatatus* decreases by 7%, in the Northern Stations, during monsoon season, whereas, no significant change is observed at Southern Stations (Fig. 3). Except that, the relative abundance is also low at station number 5 and 6, during

pre-monsoon, and 7 and 8, during monsoon season. The marginal effect of mudbank in the northern region and its total absence from the southern regions is well depicted by the relative abundance of *A. dilatatus* during monsoon. The seasonal change from monsoon to post-monsoon in the peripheral regions is such that the relative abundance of *A. dilatatus* decreases, both in NS and SS, but by different magnitudes. In NS the decrease is 24% while in SS it decreases by 39%. The post-monsoonal decrease in abundance of *A. dilatatus* is primarily due to the decrease in freshwater influence in the area owing to the withdrawal of monsoon, as is also the case in the core mudbank region.

Ammobaculites exiguus is the second most dominant agglutinated benthic foraminifera at all the stations. Its relative abundance is >5% in at least 5 stations, in each season. The response of *A. exiguus* to mudbank formation, however, is different from *A. dilatatus*, and thus outlines the species-specific sensitivity of foraminifera, to the same changes in the common inhabiting environment. At the Core Mudbank Stations, the relative abundance of *A. exiguus* increases by 11% in the monsoon season and decreases by 11% during the post-monsoon season (Fig. 4). This suggests that unlike *A. dilatatus*, *A. exiguus* is more tolerant to environmental changes associated with the formation of mudbank. *A. exiguus* is a characteristic species of brackish water marshes and lagoons in Massachusetts and Mexico, reported over a salinity range of 0 – 25 psu (Ellison and Murray, 1987). It has also been reported from Virginian and Colombian brackish marshes where salinity ranges from 31 – 34 psu (Murray, 1969; Murray, 1991; Woo et al., 1997). *A. exiguus* dominates the Choptank River, Maryland, where salinity ranges from 12 – 15 psu (Murray, 2006). In the Indian Ocean, *A. exiguus* is one of the prominent estuarine taxa along the fresh-water influx dominated eastern margin of India (Rasheed and Ragothaman, 1978). Thus, the change in ambient environment, as a result of mudbank formation, seems to support the population of *A. exiguus*, because of the species' tolerant nature. With the withdrawal of mudbank, when the living conditions become conducive for foraminifera proliferation in general, then relative abundance of *A. exiguus* decreases. At peripheral stations, the relative abundance of *A. exiguus* increases by 13.3% in NS in the monsoon season and in the post-monsoon the abundance decreases by 8% (Fig 4). This pattern of species response is same as was in the CMS, due to the marginal effect of mudbank in the northern peripheral region. As compared to NS, in SS, *A. exiguus* decreases by 22.2% from pre-monsoon to monsoon and increases by 15.5% from monsoon to the post-monsoon season (Fig. 4). Since the southern peripheral region does not experience the marginal influence of mudbank formation, the pattern of faunal change is also different from that of the core mudbank as well as mudbank effected areas.

It is important to note that *Brizalina striatula* sporadically occurs during the post-monsoon season, in representative quantity (Table 2). The genus *Brizalina* has an affinity for muddy sediments and is abundant in marginal marine to bathyal settings (Murray, 1991). From the Pacific Ocean, *Brizalina* has been reported from a salinity range of 32.7 to 35.0 psu, over a depth of 8 to 200 m (Murray, 2006). In the Indian Ocean, *B. striatula* shows an ecological preference for 34 – 40 psu salinity and 6 – 43 m depth. In the Mediterranean Sea, its salinity tolerance limit ranges from 35 – 38 psu, over a depth range of 0 – 100 m, in the muddy substrate (Murray, 2006). In the Gulf of Mexico, *B. striatula* occurs at a depth range of 1 – 46 m over a salinity range of 35 – 40 psu (Murray, 2006). The global distribution of *B. striatula* suggests its ecological preference for relative hypersaline water in the muddy shallow water region. The increase in *B. striatula* is thus attributed to increase in bottom water salinity during the post-monsoon season (34 psu).

Thus, to sum up, it is clear that mudbank environment evokes a well-defined and species-specific response. The dominance of hyposaline agglutinated *A. dilatatus* and *A. exiguus* in the core mudbank region, and increased abundance of calcareous *B. striatula* during the post-monsoon season, clearly suggests a profound influence of freshwater influx in the mudbank. In the absence of rivers, the low salinity and bottom sediment disturbance can well be explained by subterranean flow hypothesis proposed for the formation of mudbank off Alleppey (Loveson et al., 2016).

Conclusions

The living benthic foraminifera in Alleppey mudbank area are dominated by agglutinated forms, indicating carbonate undersaturated conditions. The living foraminiferal population is represented by 51 species belonging to 26 genera in the mudbank area. In response to the formation of mudbank, species richness and evenness remains low during monsoon season in the core mudbank area, suggesting survival of robust benthic foraminiferal species in the stressed benthic environment of mudbank. In the area north of mudbank, species evenness remains unaffected, but species richness increases only in the post-monsoon season, since it comes under the marginal effect of mudbank. The area south of mudbank remains unaffected by the formation of mudbank and has high species richness and evenness in all the seasons. Amongst the foraminiferal species, agglutinated *Ammobaculites dilatatus* and *Ammobaculites exiguus* dominate the mudbank region. These two species can thus be used to identify the previous locations of mudbank and its migratory nature. From the dominance of hyposaline benthic foraminifera, we further conclude that foraminiferal response to mudbank formation is influenced by a combination of low bottom water salinity, low pH and re-suspension of bottom sediments. Interestingly, the low calcareous benthic foraminiferal

abundance does not significantly change the carbon burial as the organic carbon content is high, as a result of better preservation in fine sediments.

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