The Study of Marsh Foraminifera in the East Coast of India

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CERTIFICATE FROM THE SUPERVISOR

This is to certify that the thesis entitled **"The Study of Marsh Foraminifera in the East Coast of India"** submitted by **Ms. Ishita Das** who got her name registered on **28.07.2015** for the award of **Ph.D. (Science) degree** of **Jadavpur University**, is absolutely based upon her own work under the supervision of **Dr. Anupam Ghosh** and that neither this thesis nor any part of it has been submitted for either any degree/diploma or any other academic award anywhere before.

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- Dutta, D., **Das, I.**, Buragohain, D. and Ghosh, A. 2021. A study of marsh foraminifera microhabitat in Harshad, Gujarat. Journal of the Palaeontological Society of India; v. 66(2), pp. 346-356.
- **Das, I.**, Ghosh, A. and Buragohain, D., 2019. A study of microhabitat of intertidal foraminifera from Chandipur coast, Odisha. Journal of the Palaeontological Society of India; v. 64(1), pp. 49-60.
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- Ghosh, A., **Das, I.** and Buragohain, D. (2020). Distribution trends of foraminiferal assemblages from the world's largest mangrove ecoregion, the Sunderbans, West Bengal. Deep Time Biodiversity of Bengal, Geological Studies Unit, Indian Statistical Institute; 25-27pp (Abstract volume).

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Abstract

Mangroves or vegetated intertidal wetlands are stressed ecosystems situated within 30 degrees north and south of the Equator. These are sites of rich biodiversity, anchoring huge populations of flora and fauna. Foraminifera are marine microfauna found abundantly in these marshlands, many of which still lie undocumented. Foraminifera are a vital organism in studying climate changes in the Quaternary. The present work aims to compare foraminiferal assemblages along three marsh areas along the northern part of the east coast of India; namely, the Sunderban mangroves in the north, Bakkhali marshes in between and Chandipur marshes in the south.

Surface sediment samples were collected from various stations in Sunderbans, Bakkhali marshes and intertidal flats and Chandipur swamp and intertidal flats. Physical parameters such as pH, temperature and salinity were measured along with foraminiferal distribution. The Total foraminiferal number (TFN) varies from few thousands to tens. There is an abundance of agglutinated forms in the high marsh areas such as *Trochammina inflata*, *Haplophragmoides wilberti*, H. *canariensis*, *Miliammina fusca* and M. *petila*. Low marsh regions show abundance of calcareous hyaline forms like *Ammonia tepida*, *Ammonia parkinsoniana*, *Cribroelphidium poeynum*, *Haynesina depressula*, H. *germanica, Elphidium advenum* and *Cocoarota madrasensis*. Calcareous porcelaneous forms are mostly absent except for the occurrence of *Quinqueloculina seminulum* and *Triloculina trigonula* at certain stations. A new agglutinated species, *Srinivasania sundarbanensis,* has been discovered from the Sunderban marshes.

Thirty-one species of benthic foraminifera have been identified from the northern Sunderbans, sixteen species from the Bakkhali marsh region and fourteen species from the Chandipur marshlands. A lot of different forms have been recorded but diversity of foraminifera is less than 5. The small size of the organisms, high abundance and lower diversity along with the unstable environmental conditions indicate an r-selective population pattern of marsh foraminifera. Agglutinated and calcareous taxa and species richness decrease in abundance from the northern part of the study area towards the southern part of the area. The total foraminiferal number is directly proportional to the moisture content and inversely proportional to the sand content of the sediment. Optimum salinity for benthic foraminifera is found to be around 22 to 23 PSU, pH conditions slightly alkaline (7.8 – 8) and temperatures around 25º C for the marsh foraminifera along the northern part of the east coast of India.

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1.1 General Introduction

Micropalaeontology is the study of microfossils systematically including their morphology, classification and environmental and stratigraphic significance. A microfossil can be defined as any fossil, usually tiny, whose distinguishing characteristics has to be studied under the microscope. It encompasses both heterogeneous groups of fossils of microorganisms like foraminifera, ostracoda and radiolaria; and detached skeletal elements of large-sized organisms that are difficult to identify without a microscope, e.g., sponge spicules and echinoderm spines.

Foraminifera are unicellular protists with a perforated chalky shell through which thin protrusions of the protoplasm extends. They are mostly marine and form thick ocean floor sediments when they die. They have the distinction of being the most important group of microfossils due to their stratigraphic significance and their value as indicators of palaeoenvironment. Their ability to be extremely sensitive towards subtle environmental changes makes them perfect proxies for environmental monitoring. Benthic foraminifera are a major constituent of shallow-water carbonates, including the well-known Fusulinid limestone and Nummulitic limestone of the Permocarboniferous and Eocene ages, respectively. Foraminifera, as a group, exhibit broad ecological tolerance to salinity, depths and temperature of the ambient waters. Typical mangrove foraminiferal assemblages help to identify ancient tidal beds. Studies on foraminifera have also proved to be very useful for hydrocarbon exploration, past oceanic and climatic conditions, Quaternary sea-level changes and monitoring environmental pollution in coastal areas. Recent foraminiferal assemblages from different environments contributes in gathering knowledge on microhabitats of the group and also help in understanding the controlling biotic and abiotic factors for its growth and survival in the environment.

1.2 Origin of the research work

The Indian subcontinent has a long coastline stretching over 7500 km. Coastal areas comprises of diverse, complex and productive ecosystems where the fauna are extremely sensitive to slight environmental changes. Coastal areas show varied morphology consisting of estuaries, bays, deltas, lagoons, coastal marshes, mudflats and also sandy and rocky shores. They are the dynamic junction of ocean, atmosphere and land that continuously undergoes geomorphologic changes from natural and anthropogenic activities (Bruun, 1962). Vegetated intertidal sediments or marshes are stressed environments which are mostly restricted to tropical zones between 32 °N and 32 °S. Marshes grow where the monthly minimum air temperature is 20 °C and their poleward limit is the winter seawater 20 °C isotherm. Marshes are formed in low energy areas sheltered from wave attacks and floating ice. These are highly dynamic environments that accrete and prograde but are also subject to localised erosion from waves, currents and floating ice. The highest marshes are flooded less regularly than low marshes and consequently, the high marsh sediments are often more oxygenated as the water has more time to drain away. During the last few decades, environmental change in estuarine and coastal areas has increased, and foraminiferal assemblages in many places of the world have markedly changed (Yanko et al., 1999). Marsh foraminifera may be infaunal or epifaunal, the latter mainly free-living but sometimes clinging to algal filaments. They are a mixture of detritivores and herbivores feeding on smaller plants and animals. Understanding the coastal ecosystem is vital for its management, and foraminifera are one of the biological proxies to capture the response of the ecosystem to the changes in the environmental changes. Characteristic feature of marsh foraminifera is the abundance of typical agglutinated and calcareous taxa. The marsh foraminifera taxonomy of the east coast is mostly unexplored. Before studying palaeoenvironment with the help of foraminiferal shells, it is essential to document the taxonomy of foraminifera of a region. Some works of foraminifera from the east coast of India comprises of Dey et al. 2012, Ghosh et al. 2014, Sen and Bhadury, 2016, Tripathi et al. 2018 and Das et al. 2019. Since studies on foraminiferal taxonomy are scarce on the east coast of India, this research work aims at providing a record of foraminifera from the east coast of India. This work also aims at comparing the foraminiferal assemblage from the different marsh regions of the northern Sunderbans, Bakkhali and Chandipur in order to understand the impact of the environment on the microfaunal content.

1.3 Aims and Objectives

The present study aims to prepare a foraminiferal biofacies map of the marshlands along the east coast of India along with the following objectives:

(a) To study the systematics of the foraminifera in the marsh regions of the eastern coast of India, namely, Northern Sunderbans, Bakkhali and Chandipur.
(b) To understand the relationship of marsh foraminifera with different abiotic factors.
(c) To compare the foraminiferal assemblages from northern Sunderbans with that of the Bakkhali and Chandipur marshes.

1.4 Sunderban marshes

1.4.1 Geomorphological set-up of the Sunderban marshes of West Bengal

The Sunderban mangrove is the largest mangrove forest in the world. It lies on the confluence of the Ganges, Brahmaputra and Meghna rivers on the Bay of Bengal shared by the two countries, India (40%) and Bangladesh (60%). Mangroves are unique forest ecosystems found at the junction of land and sea, usually prevalent in tropical and subtropical regions. These ecosystems are characterised by some distinct floral and faunal assemblages, one of them being foraminifera.

The tectonic evolution of the Bengal Basin is essentially related to the collision pattern of the Indian plate with Burma and Tibetan plates. The oblique subduction of the oceanic crust beneath the Burma plate resulted in the development of accretionary wedges, which after undergoing deformation has subsequently uplifted the Indo-Burman Ranges. The Bengal basin is one of the world’s widest, deepest and tectonically active basins and it represents a classical asymmetric pericratonic basin that originated through different phases of the Tertiary Himalayan orogeny. The basin has a relatively stable shallow shelf part (1-8 km thick) in the west and north-west facing the Indian shield and a tectonically active southern and eastern foredeep part centered below the present Ganga-Brahmaputra river mouths. These two parts are separated by a hinge zone marked by high gravity and magnetic anomalies.

The Bengal Basin was filled up through Tertiary marine geosynclines and shelf sedimentation (<16 km thick) followed by gradual progradation of the Quaternary Ganga-Brahmaputra delta fronts towards the southern sea producing the Bengal Delta complex, the mangrove vegetated recent-sub recent part of the Sunderbans delta complex. This delta complex is characterized by the prolific growth of rich and diverse mangrove vegetation and forms an integral down drift coastal part of the Bengal delta complex that overlies a massive thickness of Tertiary marine sediments of the actively subsiding Bengal basin.

The Sunderban delta complex extends geographically between the sea and plains of Bengal along the easternmost coast of India. The development of the Sunderban began probably from the early Pleistocene and the delta formation started from the Tertiary period. This delta complex began forming near the mouth of the Ganges, the Brahmaputra and Meghna later emerged out of the sea with the extension southwards. Enormous quantities of sand, silt and other debris drained by these three rivers are the primary sources of sediment in this region. The present-day drainage pattern of this coastal area results from two distinct factors (a regional southerly slope of the Bengal basin and the increasing rate of southerly tilt of West Bengal to a relatively greater rate of subsidence of the south-western part) noticeable to date through the Tertiary history of Bengal basin (Biswas 1963; Sengupta 1966). All the important river systems, of Sunderbans, maintain a north to south trend and are actually surface manifestations of the subsurface southerly tilt of the Bengal basin. This southerly tilt, however, has been supposed to be more effective right from the late seventeenth century (Sengupta 1966).

The temporal as well as geographical distribution of mangrove plants are largely controlled by continental drift, dynamics of land and sea, along with environmental and physiographic changes over time since the advent of mangrove ecosystems on the earth in the tropical-subtropical coastal land masses after the break down of Gondwanaland. The present Sunderbans mangroves have their widespread ancient counterparts buried under deltaic sediment cover further inland. As it is situated on the delta of the Ganga River, the accretion erosion behaviour of the rivers are primarily controlled by the regional geology of delta formation involving both fluvial and coastal processes. The deltaic zone represents a downwarped basin flanked by successively occurring older rocks from Tertiary and older sediments to younger Pleistocene Terraces into which the major river valleys have been incised (Morgan 1970). Strong tidal currents (4.6–5.5 tide gauge in spring tide) on the coast result in the formation of a network of deeply scoured (>30 m) tidal rivers and inlets and the formation of an overlapping tidal plain across the intermittently subsiding Bengal delta (Morgan 1970).

The Sunderbans is a complex network of tidal channels, extensive tidal flats, mangrove swamps, low salt marshes and islands. The process of erosion and deposition, morphologic variability and sediment transport determine the geomorphology of this estuarine river system.

1.4.2 Climate in the Sunderban marshy regions of West Bengal

The Sunderbans has a tropical oceanic climate. There are three seasons, viz. summer (March to June), monsoon (July to October) and winter (November to February), which are easily recognizable. The summer temperatures range between 28 to 36 °C and winter temperatures between 10 to 25 °C. The annual rainfall ranges between 1,900 to 2,100 mm. the coastal water salinity ranges from 19 to 31 per mil. The pH of coastal water ranges from 7.5 to 8.5. The generally mesotidal coast (tidal amplitude – 4 m) is macrotidal (tidal amplitude >4 m) at the funnel mouths of estuaries and big rivers. The tides are semi-diurnal with slight diurnal inequality. The heavy rainfall during the monsoon includes the tidal interactions in almost all the rivers of Sunderbans and flood and ebb tidal currents fluctuate with seasons. The maximum wind velocity is 16.7–20 km/h (April–June) and the minimum wind velocity is 10.7–11.8 km/h (December–February). The Sunderban area is cyclone prone. A number of severe cyclones may even be 3–4 in a year. The wind velocity during cyclones often ranges from 80 to 140 km/h. Cyclones also initiate large-scale littoral drift and lead to devastating coastal modifications. Wave height goes much above 2.5 m during cyclonic storms. The south-southwest to southwest wind direction of pre-monsoon and monsoon changes to the north-northeast to northeast during the post–monsoon times. The mean water temperature decreases with the channel length from the source point towards the river mouth. As the amount of suspended solids decreases and the depth of the channel increases, water is observed to retain a lesser amount of heat. The shallow depth estuarine brackish water temperature is always a few degrees higher than the adjacent coastal waters.

1.4.3 Sedimentation in the Sunderban marshy region of West Bengal

The Sunderban region is drained by three mighty rivers, namely, the Ganges, Brahmaputra and Meghna. The Ganges – Brahmaputra – Meghna (GBM) river system while draining through the deltaic alluvial plain on their course to the Bay of Bengal, carries an estimated annual sediment load of 2–4 billion tons (Coleman 1969). This sediment load comprises of sand, silt and clay. Sands settle at the confluence of rivers and the Bay of Bengal, creating a river mouth bar. Silts in suspension come back to the rivers again due to tidal force at the mouth and ultimately settle down at riverbanks, leading to the formation of mud flats. There is an obstruction to the carried sediment load at sea: 'Swatch of No Ground' located at the abyssal plain of Bengal basin and tidal bore at most of the river mouths. Therefore, the sediments come back from the Bay of Bengal and the depositional processes are continued along the course of the rivers and help in the formation of islands. In this way, tidal shoal, crescentic or linear point bars are formed. Vegetation consequently modifies the bar into the islands, which are isolated by either the creeks or tidal inlets. River Hugli changed its course several times due to tectonic rise and for this reason, the rivers of Sunderbans are no more connected at their heads with Hugli River and the fresh water supply is stopped there on.

1.4.4 River System in the Sunderban marshy region of West Bengal

A network of thirty-one tidal rivers; or large tidal creeks, encompasses the Indian Sunderban in this low-lying coastal deltaic plain. During the process of to-and-fro movement of tidal water on a gently sloping plain these rivers are joined by many other creeks of lesser and lesser magnitude, variously called locally as khal, gang etc. The orientation, geomorphic setting and materials of the river deposits are resultant products of the complex interaction of several factors like the tectonic framework of the Bengal basin, geological, climatological, physical, chemical and biological processes. The geographic location of the rivers also acts as important parameter as all other factors are subjected to change depending on its variability. The morphodynamic changes of the coastline are supposed to be the outcome of (i) long-term events like tectonic and geological processes and (ii) Short term events like tides and waves. Both these events collaborate in this highly dynamic macrotidal coastline. The river mouth widens into a funnel as the river approaches the Bay of Bengal. This riverine feature characterises this coast of West Bengal to be designated as a deltaic estuarine coast. There are in all thirty-one major tidal rivers and estuaries and many minor inlets and creeks, which have given rise to a much-indented nature of this coast. From the Indo-Bangladesh border in the east to the further west, the crucial rivers and creeks are Raimangal, Haribhanga, Jhilla, Guasuba, Bangaduni, Matla, Thakuran, Jagadal, Saptamukhi, Mridangabhanga, Gobadia, Edward's creek, Chenair, Murigangaor Bartala and Hooghly. An asymmetric distribution of flow velocity over transverse profiles of these meandering rivers facilitates erosion on the outer concave side and deposition on the inner concave side of the meander bends. Point bars, thus, are the products of lateral accretion and are resultant of the combination of helicoidal and sinuous tidal flows (flood and ebb) of the rivers. A large number of meandering creeks emerge at right angles to the periphery. The surface of the mid-channel bar that emerged on the river bed is characterised by several sedimentary structures ripple marks, megaripple marks of various kinds and magnitudes. All these bedforms suggest that from the lower part to the upper part of the lower flow regime of the rivers (Simons and Richardson 1962) are characteristics of this area.

1.4.5 Flora and Fauna in the Sunderban marshy region of West Bengal

Sunderbans forest comprises of a wide variety of halophytic mangrove species, salt marshes and sea shrubs, constituting of a unique Biosphere Reserve in the coastal Bay of Bengal. Point bars and mid-channel bars of the rivers of Sunderbans primarily support mangrove vegetation, whereas marsh vegetation is confined to upper intertidal to supratidal zones of levees and river flood plain. Species diversity of mangrove depends on the preferred salinity of individual species, availability of nutrients, organic carbon, soil texture, water retention and capacity of the soil. *Excoecaria – Avicennia – Phoenix* combination occurs mainly in the upper stretch of Sunderbans rivers, whereas *Avicennia – Aegialitis – Ceriops – Rhizophora* assemblages are seen in the middle and lowest stretch of the rivers. The mangrove cover acts as a protector of the shoreline as well as agricultural land. Yet, it is a serious concern that the local population often does not realize the importance of mangrove forest and exploits it profusely in an unplanned way. To save this, a unique Biosphere Reserve that exhibits various generic and species diversity, a massive awareness program is most essential.

The Sunderban mangroves are the home to endangered wild species like estuarine crocodiles, otters, fishing cats, dolphins, pythons and cobra and other species. The mangroves fauna are unique and depend upon the mangrove habitats, like the crown of trees including trunks, branches, leaves and flowers that provide a niche essentially to terrestrial fauna. The conceptual model of the mangrove ecosystem diagram shows the interactions and the interconnection among fresh water inflow, nutrient uptakes, tidal flows, consumers, physico-chemical parameters and the animal sediment relationship (Das, 2015).

1.5 Bakkhali marshes

1.5.1 Geomorphological set-up of the Bakkhali marshes

Bakkhali region is a constituent of the southern Sunderbans, comprising of both marshy and intertidal regions. The island is bordered by river Hooghly in the west and river Muriganga in the east, which drains a considerable amount of terrestrial sediments into the Bay of Bengal, especially after the southeast monsoons. The western part of Bakkhali Island hosts a narrow strip of mangroves called the Patibhunia mangroves, whereas the eastern part has thick mangrove vegetation in Henry's island region. Bakkhali is situated on the southern part of the Sunderbans of Bengal deltaic plain in the Bengal Basin, lying on the Bay of Bengal. It has a coastal length of about 1.2 km and is located in the lower reaches of the South 24-Parganas district along the coastal tract of West Bengal. It is a highly dynamic beach and keeps changing characters every year after the monsoons. This sea beach represents a wide range of diversity in terms of coastal processes, geomorphology and environment. This coastal stretch lay beyond the paleo-shoreline during Holocene times, indicating that maximum sea-level transgression occurred about 6500 years before the present when the shoreline was low to 300 km inland of the present shoreline. This area experienced shoreline progradation and basin infilling by the Ganges-Brahmaputra Rivers, which accounted for 30,000 square kilometres of its growth.

The fluctuation of tides in the form of rise and fall of water level causes migration of energy zones (De Boer et al. 1989), which results in characteristic surface sedimentary structures dependent on factors like beach slope, local morphology, depth of water, flow direction, flow velocity and textural attributes of sediments. Tides in the Bay of Bengal near Bakkhali are primarily semi diurnal in nature, with the maximum velocity of current reaching up to 3.8 metres per second. The Hooghly-Matla estuary has a funnel-type shape that causes tides to be highest along the northeastern coast, where ranges can be as high as 6 metres near the river mouths. The low tidal height varied from 0.74 to 4.17 m and the high tide from 1.67 to 5.46 m along this coast (Das 2009b, 2010).

Coastal sand dunes form the ultimate border of the shore along the coastline. The important morphotypes of Bakkhali beach are coastal dunes, runnels and inlets, mud flats and mangrove patches and sand flats. The shoreline from its east wing to the west provides an example of a dynamic morphological domain and is presently under the threat of severe erosion. It is evident from the narrow lying Fraserganj beach at the southeastern proximity of the island. The severity of the erosion can be judged by the underlying clayey sediment often exposed in upper and idle foreshores of the sandy coast because of storm surges.

1.5.2 Climate in the Bakkhali marshes

Bakkhali temperatures are highest on average in May, at around 29.8 °C. In January, the average temperature is 20.5 °C, the lowest average temperature of the whole year. The variation in the precipitation between the driest and wettest months is 488 mm. The average temperatures vary during the year by 9.3 °C. The month with the highest relative humidity is August (86.29 %). The month with the lowest relative humidity is December (67.31 %). The maximum wind velocity of coastal Bakkhali ranges between 35 to 55 km in summer and 2 to 4 km during the post-monsoon time. The dominant wind direction is towards south and south-west during the pre-monsoon period and towards north to north-west during winter seasons. The least amount of rainfall occurs in December. The average in this month is 9 mm. Most precipitation falls in July, with an average of 497 mm.

1.5.3 Sedimentation in the Bakkhali marshes

The Bakkhali shoreline has shifted position during different periods showing landward shifting of the high water line by ∼325m - 400m and low water line by ∼100m - 175m since 1969, barring the western sector, where the shifting is much less. The coast has been more or less stable since 2001. Some catastrophic events during the seventies/eighties might have caused landward shifting of the coast. Massive erosion in the western part of Bakkhali River mouth may be due to divergence of littoral current caused by the perpendicularly oriented shoreline and presence of shore-parallel sand bar off the river mouth (Saha et al. 2011). Rootlets, palaeo-mud and clay balls on the inter-tidal zone are some of the prominent erosional features in the Bakkhali area. The gently sloping (0.5° to 1.3°) wide beach is veneered by fine to very fine sand, with occasional silt and clay. The inner shelf up to 12 km is shallow, with a maximum water depth of ∼10m. There is an abrupt change in water depth at a few sectors, due to the presence of shoals and submarine erosion of the sea floor by strong tidal current. Increased bottom friction caused by a strong tidal current in the constricted passage is responsible for steepening of the eastern flank of the 'Sagar Sand Range'. Submarine erosion resulted in the extension of Lacams Channel further south. The seabed is veneered mostly by fine to very fine sand, with patchy occurrences of admixed varieties of sand, silt and clay. Clay balls are found at a few locations in relatively deeper parts. The heavy mineral of the sediments collected from the beach areas of Bakkhali indicates that the sediments are mostly derived from the crystalline, metamorphic and sedimentary rocks (Das 2004). Zircon, tourmaline, rutile, topaz, barite, hornblende, olivine, apatite, magnetite and ilmenite indicate derivation of sediments from crystalline rocks, whereas epidote, zoisite, garnet, kyanite, sillimanite and biotite are typical mineral of metamorphic origin.

1.5.4 River System in the Bakkhali marshes

Instead of the tidal creek network that is seen in the northern Sunderbans, Bakkhali is an island bound by three rivers; river Hatania Doania in the north that separates it from the mainland of Namkhana, river Hooghly runs along the western margin of Bakkhali whereas river Saptamukhi runs along its eastern margin. On the southern fringe of this island lies the Bay of Bengal. Due to a difference in the type of river network, the northern Sunderbans and the Bakkhali region experience different types of energy. The northern Sunderbans experiences more tidal energy than wave energy, but since Bakkhali has a direct connection with the ocean, this region experiences more wave energy than tidal energy.

1.5.5 Flora and Fauna in the Bakkhali marshes

The entire length of the Bakkhali beach is lined with casuarinas trees. On both sides of the creeks, mangrove vegetation is commonly seen. In the southeast portion and western portion open mixed and dense mixed jungle are noticeable.

Mangroves like Sundari (*Heritiera fomes*), Gewa (*Excoecaria agallocha*), Goran (*Ceriops decandra*) and Keora (*Sonneratia apetala*) occur dominantly throughout the area. Apart from this, there is an abundance of Dhundul or Passur (*Xylocarpus granatum*) and Kankra (*Bruguiera gymnorhiza*). Among palms, *Poresia coaractata*, *Myriostachya wightiana* and Golpata (*Nypa fruticans*), and among grasses, spear grass (*Imperata cylindrica*) and Khagra (*Phragmites karka*) are well distributed. Bain (*Avicennia* spp.) trees extensively line the Patibhunia area.

The Sunderban provides a unique ecosystem and a rich wildlife habitat. Besides the forest, there are extensive areas of brackish water and freshwater marshes, intertidal mud flats, sand flats, sand dunes with typical dune vegetation, open grassland on sandy soils and raised areas supporting a variety of terrestrial shrubs and trees. Crabs, shrimps and other crustaceans like barnacles that adapt to feed, shelter and reproduce among the tangled mass of roots, known as pneumatophores, which grow upward from the anaerobic mud to get the supply of oxygen, are spotted in the study area. Macaques, wild boars, common grey mongooses, foxes and jungle cats are seen on Henry's island.

1.6 Chandipur marshes

1.6.1 Geomorphological set-up of the Chandipur marshy region

Chandipur is a beach in Balasore district, Odisha. Chandipur has a wide intertidal area spanning over 3 km and has a sand bar on the southeastern side of the coastline. The sheltered area behind the bar has given rise to a swampy region where some mangrove vegetation has developed.

Chandipur coast in Balasore district of Orissa can be described as a wide tidal or marshy flat that emerges during low tide and submerges during high tide. There is a narrow beach in the northwestern part of the coastline. The beach is abutted by aeolian dunes and recent alluvium can be found towards the inland. River Buribalam is situated at the eastern side along with its emerged terrace covered with some marshlands. In the southward direction beyond the tidal flat, the shoreface of the Balasore shelf is almost planar. This area experiences severe coastal erosion due to the infringement of the sea. The shoreline here inclines in a NE-SW direction. The tidal flat has two distinct morphometric facets: a sandy sloping shoreward zone and a wide silty flat matted with a wide variety of ripples having an average width of 1.5 km. The upper sandy part of the Chandipur tidal flat is composed mostly of fine sand, whereas in the wide silty flat more than 80% of the sediments are even finer. In the Chandipur tidal flat, manifestations of wave energy in the form of a swash/backwash system dominate over tidal energy as seen from the intertidal surface that is intensely matted with ripples.

Chandipur beach is unique in the sense that the water level recedes up to 5 kilometres during the ebb tide. So, it can be described as an endless tidal flat with marshy characteristics in between that emerges during low tide and submerges during high tide. Geomorphology and physiography of this part of the east coast of India are influenced by the dominant action of waves, micro and macro-tidal cycles, along with typical longshore currents. The Chandipur coast is a part of the coastal plain that extends from the River Buribalam to the north, forming an extensive alluvial tract. Interplay of fluvial, fluvio-marine, marine and aeolian processes give rise to a variety of geomorphic features like the beach, tidal flat, coastal dunes, swamps and the bar. The Buribalam River, which forms an estuary in this region, drains this area and its emerged terrace, is covered with marsh. Here, the groundwater is generally saline and the freshwater occurs in discontinuous patches.

The coast includes a narrow beach (~100 m) bordering the land and a vast expanse of extremely low gradient intertidal flat (~4-5 m) on its front. The beach is divided into two distinct parts – the foreshore and the backshore. The foreshore extends from the lower limit of the backshore to the contact of the beach-tidal flat. It has a very low dip of less than 3.5º; filled with wet, firm sand material. The backshore extends from the foot of the berm to the uppermost limit of the water during high tide and is characterized by dry fluffy sand (Sur et al., 2006). The tidal flat is comprised of various types of ripples of varying characteristics. The contact between the beach and the tidal flat is sharp and continuous. Swamps are found behind the aeolian dune field and in the interbar areas. Near the mouth of the Buribalam River, a back swamp has developed behind the bar. The bar is crescent-shaped and its palaeo portion coalesces with the beach. The river Buribalam forms a meander near the sea. The two different banks of the river, one has a greater slope (corresponding to the erosional bank) and another has a lower slope (refers to the depositional bank). The river flows by cutting the lateral bar and there is evidence of lateral migration of the river as confirmed by abandoned palaeo-channels.

The coastal region undergoes both gradual and sudden changes with physical processes on the earth's surface. Changes occur over both short terms and long terms and often involve various factors like hydrodynamic, geomorphic, climatic and tectonic forces. The major cause of coastal erosion is the rise of the mean sea level. Researchers suggest that from 1990 to 2005, accretion has been occurring in the northern part of the coastline, whereas the middle and the southern part of the coastline are prone to erosion. This characteristic changed from 2005 to 2010, when it has been observed that the entire coastline experiences erosion. It is also found that the sea surface height is increasing from 1993 to 2011, which is possibly the primary cause of coastal erosion (Mukhopadhyay et al., 2006). Analysis of the rate of erosion and sea surface height anomaly suggest the rate of erosion is increasing and the rate of accretion is becoming lower along the Chandipur coast; of which, the primary cause is sea-level rise. The last two decades show many dynamic changes along the stretch of the Chandipur coast. It is quite alarming that the rate of erosion is increasing as this implies many losses to the coastal people. Necessary action should be taken to address this particular problem.

1.6.2 Climate in the Chandipur marshy regions

The state of Orissa experiences a subtropical, monsoon climate with three different seasons: monsoon, winter and summer. The monsoon lasts from June to September, during which the area experiences quite a heavy precipitation rate. Freshwater discharge during this period alters the salinity conditions of the marine waters. Winter extends from November to February, when the temperature ranges from 5ºC to 25ºC. Summers are sweltering, extending from April to May, where the temperature varies from 30ºC to as high as 45ºC. The annual average temperature of the Balasore district is around 22°-30°C and the yearly rainfall is about 120-250cm.

1.6.3 Sedimentation in the Chandipur marshy regions

The tidal flat is a vast monotonous rippled flat extending for about 4 km seaward from the beach. Contact between the beach and the tidal flat is sharp and stepped (Sarkar et al., 1991). The gradient of the rippled flat is lower than that of the beach and the slope is south-west. Sediment in the tidal flat is fine silt to clay, which becomes coarser towards the bar. In general, the sediment becomes coarser landward and on the beach, the size grade varies from silt to fine sand to coarse sand. A shore parallel tidal channel intervenes between the beach and the rippled flat for about 1.85 km starting about 300 m from the PWD bungalow, towards the bar. The landward limit of the beach is demarcated by dunes that were earlier stabilized by vegetation. Different types of bars are encountered as one travels towards the mouth of the river Buribalam along the beach. After about 3 km from the PWD bungalow, the beach merges with the ancient barrier bar. This has turned into a spit bar further southeast. It runs sub-parallel to the coast and tends to migrate shoreward under the influence of the tide, which enters at a low angle to the shore from the south-western side. The distal bar, however, tends to migrate seaward. The drowned channel of the river Buribalam gets exposed twice a day during ebb tide. Point bars and levee bars have developed in this region with their axes parallel to the axis of the drowned channel. The levee bars are characterized by dunes which are rippled and which tend to migrate shoreward. Swamps are found behind the Aeolian dune fields and in the interbar areas. Near the mouth of the river Buribalam a back swamp has developed behind the bar. Fresh water occurs near the surface and freshwater ponds are found in the marshy area behind the dune field.

1.6.4 River System in the Chandipur marshy regions

The river system in this part of the study area is widely different from the other two parts. Chandipur lies on the Bay of Bengal and there is only one river, Buribalam, draining into the sea just northeast of Chandipur beach. The typical tidal creek network of Sunderbans is absent in this part of the study area. Due to the absence of numerous creeks, the main energy experienced by this coast is wave energy. The area of marshland on this coast is much lesser than the two earlier study areas.

1.6.5 Flora and Fauna in the Chandipur marshy regions

Few different types of vegetation has been observed in the Chandipur coast, although the diversity is not much high. The aeolian dune fields behind the beach are dotted with trees like casuarinas, coconuts, screw pines, cashews & firs. Two series of windbreaker tree have been planted on the dune field. There were both natural and artificial plantations of these trees as a measure to stop coastal erosion. They grow well in regions where seawater does not enter. Some mangrove vegetation was observed mainly in the inter-tidal areas of Chandipur, mainly near the river mouth. Pneumatophores of mangrove trees were observed in the inter-tidal areas near the river mouth. The mangroves are inundated by salt water during high tides, so they adapt to these adverse situations by developing negatively geotropic breathing roots, or the pneumatophores. Some long grasses were found in the tidal creeks and swamp areas as well as near the river mouth region. Algal material was also prevalent in some regions of the beach, mostly near the river mouth area. Although the area has little floral diversity, it is blessed with a huge diversity and abundance of marine fauna. Different types of bivalves, mainly *Mactra* sp., *Anadara* sp., *Arca* sp., *Mytilus* sp., *Mya* sp., *Meretrix* sp., *Ostrea* sp., *Solen* sp., *Chlamys* sp., *Cardium* sp., *Pecten* sp., *Donax* sp., *Sanguinolaria* sp. and others were found on the coast. Gastropods like *Natica* sp., *Telescopium* sp., *Turritella* sp., *Tonna* sp., *Polinices* sp., *Murex* sp., *Nassarius* sp., *Cypraea* sp., *Oliva* sp., *Amalda* sp. and some Cerithids and Murithids were encountered and crabs (red crabs, fiddler crabs and hermit crabs) were found on the coast. Some other faunas that were observed were squids, jellyfish, sea urchins, the horseshoe crab *Limulus* sp., polychaetes, barnacles, hydrozoa and sea anemones.

1.7 Organisation of the Thesis

The thesis is organised into six chapters. The current chapter gives an introduction about the three areas of the research work; Sunderbans, Bakkhali and Chandipur and outlines the objectives of the present research. Chapter 2 deals with the materials and methodology followed in this thesis work. Chapter 3 is a detailed systematics of the foraminifer and an understanding of their relationship with abiotic factors in the northern Sunderbans. Chapter 4 discusses the foraminiferal distribution and relation with physical attributes in the Bakkhali region. Chapter 5 documents the foraminifera from the southernmost study area, Chandipur and their relation with physical factors. Chapter 6 compares the marshes of these three regions and proposes a biofacies model for the marshlands on the east coast of India.

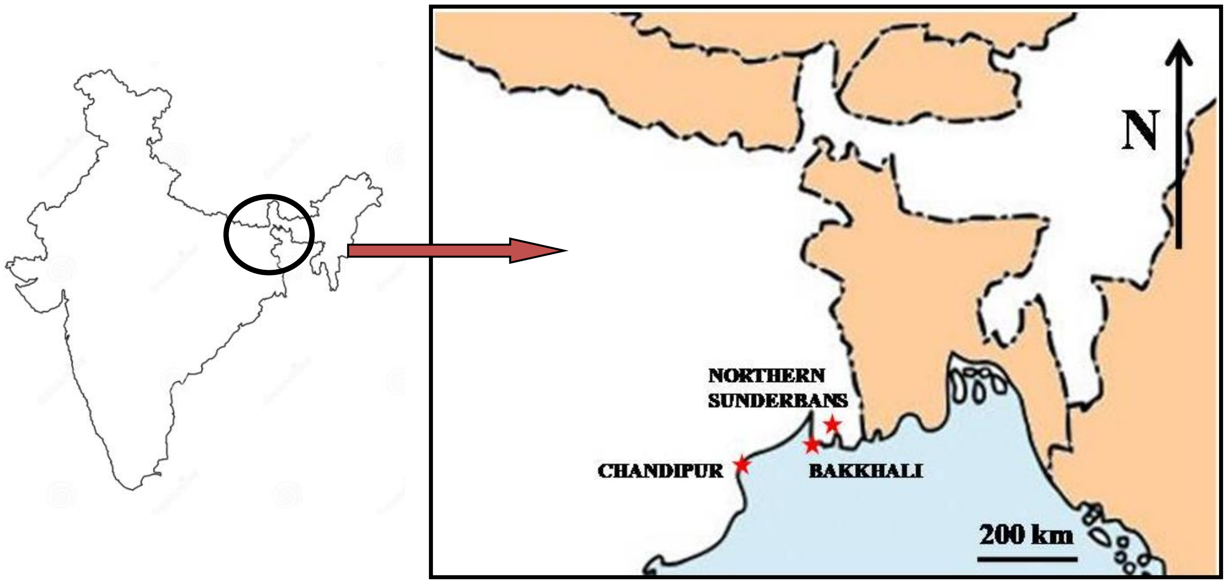


Figure 1: Map of the east coast of India showing the three sampling regions

2.1 Sample Collection

Surface sediment samples of 100 cc (10 cm x 10 cm x 1 cm) were collected from forty sampling stations from the Sunderbans, seasonally, with the help of a trowel. Samplings were done in the months of January, April, July, September and November in the year 2018. Due to different tidal conditions, which led to varying water levels, all the stations were not accessible in all the five seasons; hence, the twenty-four stations which could be accessed in all the five seasons have been chosen. Samples were collected from high marsh areas and low marsh areas based on different environmental conditions. The GPS reading was noted in each station and the lithology, vegetation, sedimentary structures and fauna were noted accordingly. Sediment samples were transferred to wide-mouthed plastic containers for preservation and rose Bengal solution was added to the samples so that the live samples could be identified. This solution is prepared by dissolving 2 grams of Rose Bengal powder (4, 5, 6, 7-tetrachloro-2’, 4’, 5’, 7’ – tetraiodofluorescein) in one litre of ethanol. Rose Bengal solution helps in identifying live samples by staining their protoplasm pink.

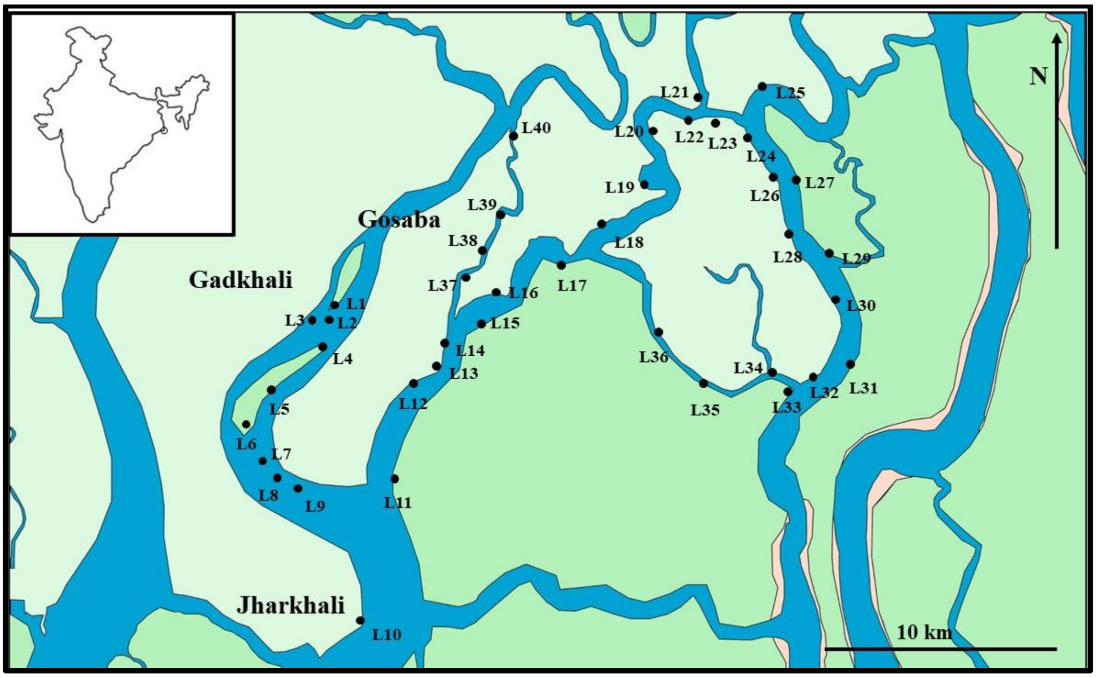


Figure 2.1: Sampling stations from the northern Sunderbans

Each of the containers was adequately labeled and carefully brought back to the laboratory and stored at room temperature prior to processing. For the micropalaeontological analysis, the standard methodology described by the FOBIMO technique was followed.

Figure 2.2: Sample collection from low and high marshes from the northern Sunderbans

For sample collection from the Bakkhali marshes, seasonal sampling was done twice: September 2017 (post-monsoon) and February 2018 (pre-monsoon). Surface sediment samples of 100 cc were collected from twelve stations spread across the southern coast of the island. Both high marsh and low marsh samples were collected. Two core samples were also collected, one from the Henry’s island marshes (eastern side) and the other from the Patibhunia marshes (western side). Standard procedures of sample collections and staining were carried out for all the Bakkhali samples.

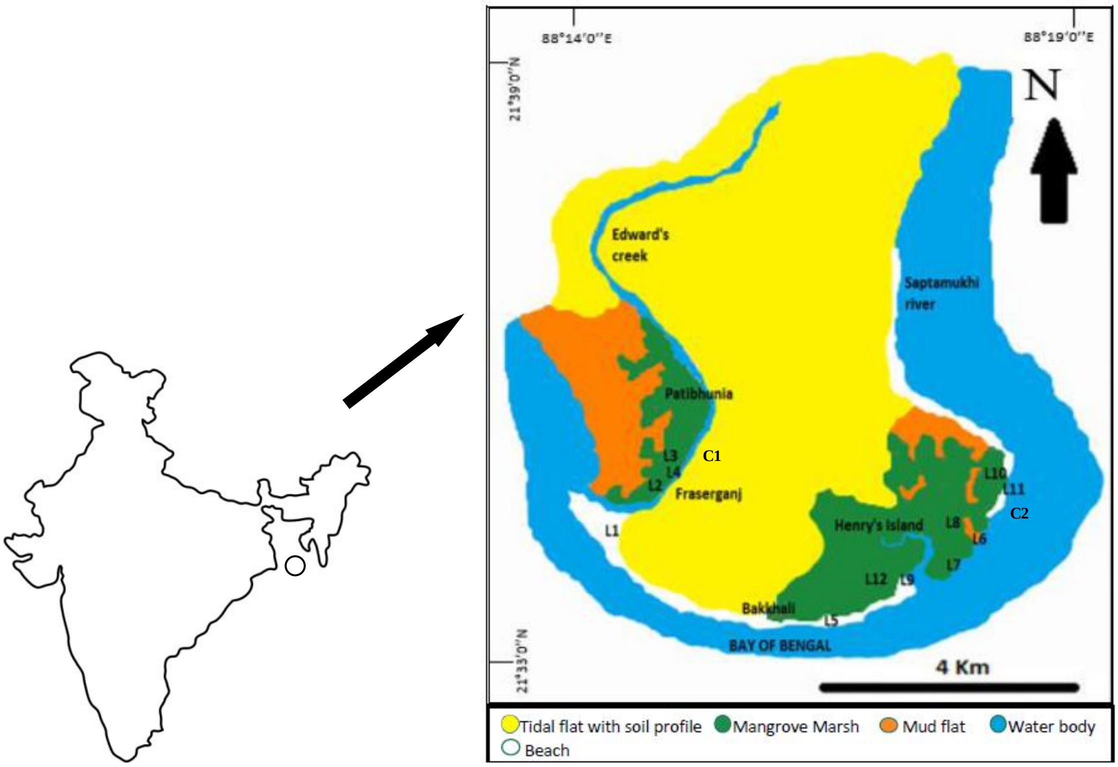


Figure 2.3: Sampling stations from Bakkhali area

Figure 2.4: Sample collection from the Bakkhali marshes

In the third study area, Chandipur, seasonal surface sampling was done in the months of September 2016 (post monsoon) and February 2017 (pre monsoon). Standard procedures of sample collection were maintained during sample collection from this region. Both surface sediment samples (eight stations) and core samples (three stations) were collected from this area.

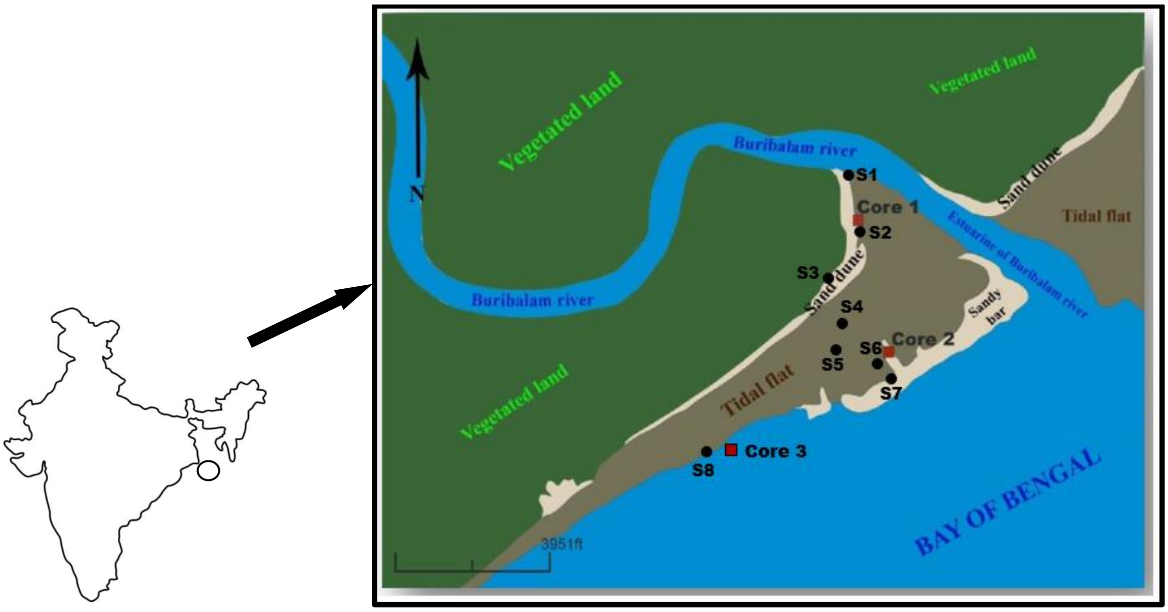


Figure 2.5: Sampling stations from Chandipur area

Figure 2.6: Sample collection from Chandipur area

2.2 Sample Processing Technique

Sediment samples brought to the laboratory were measured and the wet weights of the samples were recorded. After documenting the wet weights of all the samples, they were dried in an oven under 50 °C. Once thoroughly dried, the dry weights of these samples were noted down. Hence, the moisture content of the samples could be measured. After that, the samples were submerged under water again for about twelve hours and then they were washed on a 63-µm sieve. This sieve size helps in eliminating all the unwanted silt and finer clay particles but obstructs the sand and larger fraction of sediments, which includes the size range of most foraminifera. They were again oven-dried under 50 °C and then weighed to find out the dry weight of the processed samples. The difference between the dry weight of the untreated sample and the dry weight of the processed sample gives the sand weight of the sediment samples. After drying, the sample bowls containing the residues were taken out of the oven and the samples were transferred into Tarson plastic tubes for further analysis. The excess samples were kept in ziplock pouches for future reference. Foraminiferal assemblages within the size fraction in between 63 µm and 125 µm were both quantitatively and qualitatively analyzed, showing high amounts of foraminiferal species greater than 63 µm.

2.3 Sorting and Identification

A micro-splitter was used to separate the greater than 63 µm fraction of the selected samples into smaller portions. Sediment from the plastic tubes was transferred on a black picking tray that was gridded with golden lines. The samples were spread thinly over it. One gram of dry sediment was studied under the microscope for each sample (except for the surface samples from Bakkhali). Sediments weighing less than one gram were studied entirely and then the foraminiferal number was normalized. For the Bakkhali surface samples, due to scarce occurrence of foraminifera, 10 gram of sample was studied. Separation of the microorganisms from the processed sediments were done by using certain accessories like finest stable hairbrush (#000), micropalaeontological slides (twelve and twenty-four chambered) made up of a glass slide with cardboard cover and aluminium case and micropalaeontological tray (marked by grids). Foraminifera were collected with the aid of a moist brush under the stereo zoom microscope (Nikon SMZ 1000). The picked foraminifera were placed on twenty chambered slides and specimen of each species in double punched slide for further identification. Different types of faunal slides were available for this purpose. Twenty-four chambered slides were used to store all the foraminifera from one sampling location and double punched slides were used to store tests of specimens from the same species, which was further used, for SEM analysis.

The taxa are identified with the help of the works of Loeblich and Tappan (1964), Barker (1960), Horton and Edwards (2006), Nomura and Seto (1992, 2002), Kathal (2002), Akimoto et al. (2002), Ghosh (2012) and Ghosh et al. (2014). The classification given by Loeblich and Tappan (1987) is followed in the present study. Photomicrographs of selected taxa, including the most abundant ones, were obtained using a Scanning Electron Microscope (Carl Zeiss EVO-18) at Jadavpur University, India. Analyzed samples of the Sunderban marshes, Bakkhali Island and Chandipur region are housed in the Department of Geological Sciences, Jadavpur University respectively and illustrated specimens are stored in the micropalaeontology laboratory at Jadavpur University.

2.4 Statistical Analysis

The Total Foraminiferal Number (TFN) from 1 gram of dry sample was calculated for each sampling location. The living foraminifera were counted separately (identified by stained protoplasm) and the live/dead ratio of the assemblages were found out. The three different wall structures (calcareous hyaline, calcareous porcelaneous and agglutinated) were studied for foraminifera from all sampling locations and studied for determining the environmental conditions based on foraminiferal wall types. The data was plotted on ternary plots in order to visualize the similarities and differences between assemblages (Murray, 2006) from different environments. The older distinction among suborders Rotaliina, Miliolina and Textulariina (Loeblich and Tappan, 1987) is not regarded anymore, due to the taxonomic advances derived from combined morphometric and genetic studies that raised Miliolida, Rotaliida and Textulariida at the order rank and introduced minor modifications in the definition of orders (Pawlowski et al., 2013; Holzmann and Pawlowski, 2017). The ecological attribution of taxa to the epifaunal or infaunal mode of life was obtained in accordance with Murray, 2006. In order to track palaeoenvironmental changes potentially reflected by shifts in the community structure of benthic foraminiferal assemblages, several diversity indices were calculated for the studied samples: Species richness (S), Shannon-Wiener (H) and Fisher‘s α. The Fisher α index (Fisher et al., 1943; Murray, 1973) gives the relationship between the number of species and the number of specimens in the locations of the study area. The species richness gives the count of the total number of species present in the locations of the study area. Shannon-Wiener index (Shannon & Weaver, 1949) used both the number of individuals as well as the number of taxa to give an idea on the diversity of foraminiferal assemblages in the locations under study. The former indices are standardized based on the number of individuals and were therefore preferred. The bivariate cross-plot of Fisher‘s α-diversity and H was applied to examine any changes that occurred in the ecological habitat.

Cluster analysis is a method that uses a matrix of similarity coefficients computed between every pair of samples to construct a dendrogram. This method is appropriate where the samples are expected to fall into natural groups. Where the faunal pattern responds to a more continuous environmental gradient, ordination is more appropriate (Clarke and Warwick, 1994). A dendrogram always produces clusters whether or not any natural groupings occur in the data.

Q-mode cluster analyses were performed on the core samples from Bakkhali and Chandipur region in order to obtain meaningful groups of samples according to the ecological significance of some selected variables. In this context, cluster analysis revealed fauna having similar ecological niches.

3.1 INTRODUCTION

The Indian Sunderbans is a part of the world's largest fluvio-marine delta, which is situated at the confluence of the Indo-Bangladesh mainland with the Bay of Bengal. It is the largest single block of tidal halophytic mangrove forest in the world. It is rich in diverse families of flora and fauna. This rich biodiversity is at stake because of the rapid climate changes. Sunderbans is a target area for numerous storms. Researchers suggest that the rising sea levels due to global warming could destroy over 75% of the mangrove cover. The area of Indian Sunderbans is 9,630 km^2 out of the total area of 25,500 km^2 and the remaining part covers the area of Bangladesh Sunderbans. This region, being a part of the Bengal Basin, represents coalesced multi-generation deltas that have prograded in phases during the positive interglacial eustatic sea-level changes that occurred during the Plio-Pleistocene time towards the Bay of Bengal. The area of Sunderbans can be characterized as a low flat alluvial plain covered with mangrove swamps and marshes; and is intersected by a large number of tidal rivers, estuaries, creeks and saltwater courses. This large block of halophytic mangrove ecosystem is highly productive, which provides large quantities of organic detritus which is considered as the primary food for the natural habitats of this ecosystem. The relationship between microbes and nutrients acts as a mechanism to recycle and conserve nutrients in the mangrove ecosystem. The mangrove ecosystem of Sunderbans is highly disturbed due to the over-exploitation of mangrove forests and unplanned land use pattern.

3.2 FORAMINIFERAL ASSEMBLAGES

Thirty-one species have been identified from the study area. The most common agglutinated forms observed from the study area are *Haplophragmoides canariensis*, *Haplophragmoides wilberti*, *Trochammina inflata*, *Miliammina fusca* and *Miliammina petila*, with minor occurrences of *Reophax agglutinatus*, *Ammotium salsum*, *Ammobaculites agglutinans*, *Ammodiscus evolutus* and *Textularia agglutinans*. One new species, *Srinivasania sundarbanensis* has been discovered from the low marsh regions of Rangabelia, Dayapur, Satjelia, Kankmari and Lahiripur (Kaushik et al., 2021). The most common hyaline forms are *Ammonia tepida*, *Ammonia beccarii*, *Ammonia parkinsoniana*, *Cribroelphidium poeynum*, *Cribroelphidium decipiens*, *Haynesina germanica*, *Haynesina depressula*, *Elphidium advenum*, *Elphidium excavatum*, *Elphidium crispum*, *Nonion commune*, *Nonionella turgida*, *Cocoarota madrasensis*, with minor occurrences of *Asterorotalia trispinosa*, *Bolivina advena*, *Brizalina singhi*, *Rotalidium annectens* and *Pararotalia nipponica*. Only one porcelaneous species, *Quinqueloculina seminulum* is the most prevalent with minor occurrences of *Triloculina trigonula*.

3.3 SYSTEMATICS

Phylum: Foraminifera d'Orbigny, 1826

Class: Globothalamea Pawlowski, Holzmann & Tyszka, 2013

Subclass: Textulariana Mikhalevich, 1980

Order: Lituolida

Suborder: Lituolina Lankester, 1885

Family: Lituolidae Blainville, 1827

Genus: *Ammobaculites* Cushman, 1910

Ammobaculites agglutinans d'Orbigny, 1846

(Plate 3A, Figure 1)

Remarks: This species occurs mostly in the high marsh regions of Bally Island, Datta Forest and Rangabelia.

Genus: *Ammotium* Loeblich & Tappan, 1953

Ammotium salsum Cushman & Brönnimann, 1948

(Plate 3A, Figure 3)

Remarks: This species is reported from the high marsh regions of Bally 6, Bally Island, Bally Amlamethy and Dayapur.

Family: Haplophragmoididae Maync, 1952

Genus: *Haplophragmoides* Cushman, 1910

Haplophragmoides canariensis d'Orbigny, 1839

(Plate 3A, Figure 4)

Remarks: This species occurs throughout the study area, that is, northern Sunderbans. It is reported mostly from the high marsh samples but is reported from some low marsh assemblages too.

Haplophragmoides wilberti Andersen, 1953

(Plate 3A, Figure 5)

Remarks: This species is reported from all over the study area throughout northern Sunderbans in the high marsh samples.

Suborder: Trochamminina Saidova, 1981

Superfamily: Trochamminoidea Schwager, 1877

Family: Trochamminidae Schwager, 1877

Genus: *Trochammina* Parker & Jones, 1859

Trochammina inflata Montagu, 1808

(Plate 3A, Figures 12 and 13)

Remarks: This agglutinated form is quite common throughout the study area and has been found in almost all the stations in the high marsh samples.

Order: Textulariida Pawlowski et al., 2013

Genus: *Srinivasania* Kaushik & Ghosh, 2021

Srinivasania sundarbanensis Kaushik & Ghosh, 2021

(Plate 3A, Figures 9 and 10)

Remarks: This form has been first described from the Indian Sunderbans. It is reported from the high marsh regions of Rangabelia, Bally Island and Bally 6.

Suborder: Textulariina Delage & Hérouard, 1896

Superfamily: Textularioidea Ehrenberg, 1838

Family: Textulariidae Ehrenberg, 1838

Subfamily: Textulariinae Ehrenberg, 1838

Genus: *Textularia* Defrance, 1824

Textularia agglutinans d'Orbigny, 1839

(Plate 3A, Figure 11)

Remarks: This form occurs in the high marsh regions of Pakhiralay and Jatirampur.

Class: Tubothalamea Pawlowski, Holzmann & Tyszka, 2013

Order: Spirillinida Hohenegger & Piller, 1975

Suborder: Ammodiscina Mikhalevich, 1980

Family: Ammodiscidae Reuss, 1862

Genus: *Ammodiscus* Reuss, 1862

Ammodiscus evolutus Zheng, 1988

(Plate 3A, Figure 2)

Remarks: This form has been reported from the marshy regions of Jharkhali and Pirkhali.

Order: Miliolida Delage & Hérouard, 1896

Family: Miliamminidae Saidova, 1981

Genus: *Miliammina* Heron-Allen & Earland, 1930

Miliammina fusca Brady, 1870

(Plate 3A, Figure 2)

Remarks: This agglutinated species is widely prevalent throughout the study area and is found from almost all the sampling stations of the high marsh regions.

Miliammina petila Saunders, 1958

(Plate 3A, Figure 7)

Remarks: This foraminifera is recorded from the high marsh regions of Dulki, Sonargaon, Kaalir Chor and Dayapur.

Family: Hauerinidae Schwager, 1876

Subfamily: Haueríninae Schwager, 1876

Genus: *Quinqueloculina* d'Orbigny, 1826

Quinqueloculina seminulum Linnaeus, 1758

(Plate 3A, Figure 14)

Remarks: This is the most common porcelaneous form reported from the study area. It is quite abundant and has been found from almost all the sampling stations.

Subfamily: Miliolinellinae Vella, 1957

Genus: *Triloculina* d'Orbigny, 1826

Triloculina trigonula Lamarck, 1804

(Plate 3A, Figure 15)

Remarks: This is another porcelaneous form reported from Lahiripur, Dayapur, Morichjhapi and Datta Forest.

Class: Nodosariata Mikhalevich, 1992 emend. Rigaud et al., 2015

Subclass: Hormosinana Mikhalevich, 1992

Superfamily: Hormosinoidea Haeckel, 1894

Family: Reophacidae Cushman, 1927

Genus: *Reophax* Montfort, 1808

Reophax agglutinatus Cushman, 1913

(Plate 3A, Figure 8)

Remarks: This form is reported from the high marsh regions of Bally Amlamethy, Bally 6, Dulki and Rangabelia.

Class: Globothalamea Pawlowski, Holzmann & Tyszka, 2013

Subclass: Rotaliana Mikhalevich, 1980

Order: Rotaliida Delage & Hérouard, 1896

Superfamily: Rotalioidea Ehrenberg, 1839

Family: Ammoniidae Saidova, 1981

Subfamily: Ammoniinae Saidova, 1981

Genus: *Ammonia* Brünnich, 1771

Ammonia beccarii Linnaeus, 1758

(Plate 3B, Figures 1 and 2)

Remarks: This is a quite common form and is reported from Bally Island, Sonargaon, Pirkhali and Jatirampur, mostly from the low marsh samples.

Ammonia parkinsoniana d'Orbigny, 1839

(Plate 3B, Figure 3 and 4)

Remarks: This calcareous form is found from Datta Forest, Kankmari, Morichjhapi and Lahiripur.

Ammonia tepida Cushman, 1926

(Plate 3B, Figures 5 and 6)

Remarks: This is the most common calcareous form found in the study area. It has been reported from almost all the sampling stations in the northern Sunderbans.

Genus: *Asterorotalia* Hofker, 1950

Asterorotalia trispinosa Thalmann, 1933

(Plate 3B, Figures 7 and 8)

Remarks: This unique form reported only from the east coast of India has been reported from a few southernmost stations like Lahiripur and Panchamukhani.

Genus: *Rotalidium* Asano, 1936

Rotalidium annectens Parker & Jones, 1865

(Plate 3C, Figure 10)

Remarks: This form is reported from Rangabelia and Gobindopur.

Family: Elphidiidae Galloway, 1933

Subfamily: Elphidiinae Galloway, 1933

Genus: *Cribroelphidium* Cushman and Brönnimann, 1948

Cribroelphidium decipiens Costa, 1856

(Plate 3C, Figure 1)

Remarks: This hyaline form has been reported from Jharkhali, Pakhiralay, Gobindopur and Lahiripur.

Cribroelphidium poeynum

(*Polystomella poeyana* d'Orbigny, 1839)

(Plate 3C, Figure 2)

Remarks: This is a common form widely found in the study area. It has been collected from almost all the sampling stations from both high marsh and low marsh samples.

Genus: *Elphidium* Montfort, 1808

Elphidium advenum Cushman, 1922

(Plate 3C, Figure 3)

Remarks: This form is found from certain areas of the study area like Rangabelia, Gobindopur and Morichjhapi.

Elphidium crispum Linnaeus, 1758

(Plate 3C, Figure 4)

Remarks: This form has been observed from Rangabelia, Kankmari and Datta Forest.

Elphidium excavatum Terquem, 1875

(Plate 3C, Figure 5)

Remarks: This form is reported from Bally Island, Bally 6, Dulki and Oxpol Dayapur region

Family: Haynesinidae Mikhalevich, 2013

Genus: *Haynesina* Banner & Culver, 1978

Haynesina depressula Walker & Jacob, 1798

(Plate 3C, Figure 6)

Remarks: This is a common form and has been found from almost all sampling stations of the study area of northern Sunderbans.

Haynesina germanica Ehrenberg, 1840

(Plate 3C, Figure 7)

Remarks: This is an abundant form and has been reported from almost all the stations of the study area, both from the middle marsh and the low marsh assemblages.

Superfamily: Nonionoidea Schultze, 1854

Family: Nonionidae Schultze, 1854

Subfamily: Nonioninae Schultze, 1854

Genus: *Nonion* Montfort, 1808

Nonion commune d'Orbigny, 1846

(Plate 3C, Figure 8)

Remarks: This form is quite common and found almost all throughout the study area, mostly in the low marsh samples.

Genus: *Nonionella* Cushman, 1926

Nonionella turgida Williamson, 1858

(Plate 3C, Figure 9)

Remarks: This form is found from the marshy regions of Dulki, Sonragaon, Pakhiralay, Jatirampur, Oxpol Dayapur, Rangabelia and Bally Island.

Superfamily: Chilostomelloidea Brady, 1881

Family: Gavelinellidae Hofker, 1956

Subfamily: Gavelinellinae Hofker, 1956

Genus: *Cocoarota* Loeblich & Tappan, 1986

Cocoarota madrasensis Rao & Revets, 2001

(Plate 3B, Figure 11)

Remarks: This form has been reported from Bally Island, Bally 6, Dulki and Rangabelia

Superfamily: Cassidulinoidea d' Orbigny, 1839

Family: Bolivinitidae Cushman, 1927

Subfamily: Bolivinitinae Cushman, 1927

Genus: *Bolivina* d'Orbigny, 1839

Bolivina advena Cushman, 1925

(Plate 3B, Figure 9)

Remarks: This form is found from areas of Datta Forest and Kankmari.

Genus: *Brizalina* Costa, 1856

Brizalina singhi Singh, Jauhari & Vimal, 1976

(Plate 3B, Figure 10)

Remarks: This form has been reported from Jatirampur, Dayapur and Sonargaon.

Superfamily: Calcarinoidea Schwager, 1976

Family: Calcarinidae d'Orbigny, 1826

Subfamily: Pararotaliinae Reiss, 1963

Genus: *Pararotalia* Le Calvez, 1949

Pararotalia nipponica Asano, 1936

(Plate 3C, Figure 11)

Remarks: This form is recorded from Rangabelia and Jharkhali.

3.4 MODERN SURFICIAL DISTRIBUTION OF FORAMINIFERA

Surface sediment samples were collected from forty locations from the Sunderban mangrove region, encompassing high marsh, middle marsh and low marsh regions. The high marsh regions were identified by those stations where the water level reached only during the high tide and the low marsh regions were identified by those stations which remained submerged under water all throughout the day. In stations where there was a large space in between these two regions, a third region, the middle marsh region, has been documented. The blue colour code in the sampling seasons (Table 3.1) depicts the months in which sampling has been done. All the stations could not be covered during all the sampling seasons because it was not accessible due to tidal conditions.

Serial No.	Station code	Location name	GPS reading	Sampling seasons (year 2018)				
				January	April	July	September	November
1	L1/HM	North Bally Dweep	N 22° 07’ 22” E 88° 44’ 08”					
2	L2/MM	Mid Bally Dweep	N 22° 06’ 41” E 88° 43’ 43”					
3	L2/LM	Mid Bally	N 22° 06’ 41”					

		Dweep	E 88° 43’ 43”					
4	L3/HM	South Bally Dweep	N 22° 06’ 34” E 88° 43’ 32”					
5	L4/HM	Bally Amlamethy	N 22° 05’ 56” E 88° 43’ 15”					
6	L4/MM	Bally Amlamethy	N 22° 05’ 56” E 88° 43’ 15”					
7	L5/HM	Mid Bally Amlamethy	N 22° 05’ 23” E 88° 42’ 22”					
8	L6/HM	South Bally Amlamethy	N 22° 04’ 18” E 88° 41’ 33”					
9	L7/HM	Bally Amlamethy 2	N 22° 03’ 01” E 88° 43’ 10”					
10	L8/HM	Mid Bally Amlamethy 2	N 22° 02’ 49” E 88° 43’ 26”					
11	L9/HM	South Bally Amlamethy 2	N 22° 02’ 34” E 88° 43’ 55”					
12	L10/HM	Jharkhali	N 22° 01’ 09” E 88° 44’ 22”					
13	L10/MM	Jharkhali	N 22° 01’ 09” E 88° 44’ 22”					
14	L10/LM	Jharkhali	N 22° 01’ 09” E 88° 44’ 22”					
15	L11/HM	Pirkhali	N 22° 03’ 20” E 88° 44’ 55”					

16	L12/HM	Bally 9	N 22° 05' 06" E 88° 45' 17"					
17	L12/MM	Bally 9	N 22° 05' 06" E 88° 45' 17"					
18	L12/LM	Bally 9	N 22° 05' 06" E 88° 45' 17"					
19	L13/HM	Sonargaon	N 22° 06' 52" E 88° 47' 21"					
20	L13/MM	Sonargaon	N 22° 06' 52" E 88° 47' 21"					
21	L13/LM	Sonargaon	N 22° 06' 52" E 88° 47' 21"					
22	L14/HM	Dulki	N 22° 07' 55" E 88° 48' 28"					
23	L14/MM	Dulki	N 22° 07' 55" E 88° 48' 28"					
24	L14/LM	Dulki	N 22° 07' 55" E 88° 48' 28"					
25	L15/HM	Pirkhali	N 22° 07' 33" E 88° 48' 27"					
26	L16/HM	Oxpol Dayapur	N 22° 07' 42" E 88° 50' 39"					
27	L17/HM	Pakhiralay	N 22° 08' 37" E 88° 51' 09"					
28	L17/MM	Pakhiralay	N 22° 08' 37"					

			E 88° 51’ 09”					
29	L17/LM	Pakhiralay	N 22° 08’ 37” E 88° 51’ 09”					
30	L18/HM	Jatirampur	N 22° 09’ 11” E 88° 50’ 54”					
31	L18/MM	Jatirampur	N 22° 09’ 11” E 88° 50’ 54”					
32	L18/LM	Jatirampur	N 22° 09’ 11” E 88° 50’ 54”					
33	L19/HM	Satjelia Sardarpara	N 22° 09’ 19” E 88° 50’ 54”					
34	L19/MM	Satjelia Sardarpara	N 22° 09’ 19” E 88° 50’ 54”					
35	L19/LM	Satjelia Sardarpara	N 22° 09’ 19” E 88° 50’ 54”					
36	L20/HM	Rangabelia	N 22° 10’ 33” E 88° 52’ 54”					
37	L20/MM	Rangabelia	N 22° 10’ 33” E 88° 52’ 54”					
38	L20/LM	Rangabelia	N 22° 10’ 33” E 88° 52’ 54”					
39	L21/HM	Mollakhali Gobindopur	N 22° 10’ 11” E 88° 53’ 45”					
40	L21/MM	Mollakhali Gobindopur	N 22° 10’ 11” E 88° 53’ 45”					

41	L21/LM	Mollakhali Gobindopur	N 22° 10’ 11” E 88° 53’ 45”					
42	L22/HM	Satjelia	N 22° 10’ 04” E 88° 52’ 32”					
43	L22/MM	Satjelia	N 22° 10’ 04” E 88° 52’ 32”					
44	L22/LM	Satjelia	N 22° 10’ 04” E 88° 52’ 32”					
45	L23/HM	Pancharam Mollakhali	N 22° 09’ 43” E 88° 53’ 42”					
46	L23/MM	Pancharam Mollakhali	N 22° 09’ 43” E 88° 53’ 42”					
47	L23/LM	Pancharam Mollakhali	N 22° 09’ 43” E 88° 53’ 42”					
48	L24/HM	Satjelia Jemspur	N 22° 09’ 52” E 88° 53’ 12”					
49	L25/HM	Morichjhapi	N 22° 09’ 29” E 88° 54’ 00”					
50	L26/HM	Kankmari	N 22° 09’ 00” E 88° 53’ 51”					
51	L27/HM	Datta Forest	N 22° 08’ 23” E 88° 54’ 32”					
52	L28/HM	Kankmari Asram	N 22° 06’ 59” E 88° 55’ 05”					
53	L29/HM	Opposite bank	N 22° 06’ 45”					

		of Kankmari	E 88° 55’ 47”					
54	L30/HM	Lahiripur	N 22° 05’ 52” E 88° 55’ 18”					
55	L31/HM	Hamilton Island-Morichjhapi	N 22° 05’ 17” E 88° 55’ 11”					
56	L32/LM	RW Block	N 22° 05’ 17” E 88° 54’ 23”					
57	L33/HM	Kaalir chor	N 22° 05’ 14” E 88° 54’ 10”					
58	L34/HM	Sadhupur	N 22° 05’ 27” E 88° 53’ 39”					
59	L35/HM	Dayapur-Rajakjuli	N 22° 05’ 14” E 88° 52’ 25”					
60	L36/HM	Panchamukhani	N 22° 05’ 10” E 88° 52’ 21”					
61	L37/HM	Dayapur	N 22° 06’ 02” E 88° 51’ 15”					
62	L38/HM	Sonaga-within Durgadowani	N 22° 06’ 30” E 88° 46’ 21”					
63	L39/HM	Dulki 3	N 22° 07’ 49” E 88° 47’ 15”					
64	L40/HM	Bally 6	N 22° 08’ 29” E 88° 47’ 30”					
65	L40/MM	Bally 6	N 22° 08’ 29”					

			E 88° 47’ 30”					
66	L40/LM	Bally 6	N 22° 08’ 29” E 88° 47’ 30”					

Table 3.1: Details of the sampling stations from the Sunderban mangroves

3.5 RESULTS FROM THE SUNDERBAN MANGROVES

In the pre-monsoonal samples, mostly during January, the Total Foraminiferal Number (TFN) of the different stations is quite abundant (Figure 3.1). In most of the sampling stations, the TFN count is more than 100 in 1 gram of dry sediment. The maximum TFN is observed in Bally Dweep (L1), which measures 5656 in 1 gram of dry sediment. No foraminiferal tests are observed in Pirkhali (L11) in July, September and November. Living foraminifera is also abundant (Figure 3.2) and reaches a high of 970 in 1 gram of dry sediment in the high marsh regions in Dulki (L14). Figure 3.3 shows the variation of TFN across the sampling stations for the month of April. The foraminiferal count of the month of April is lower than that of the month of January. The maximum TFN for the month of April is 291, recorded from the high marsh regions of Rangabelia (L20). The living foraminiferal number is quite scanty in the month of April (Figure 3.4). The highest living foraminiferal number is only 26, recorded from the same location (L20).

TFN from monsoon sampling (July) is represented in Figure 3.5. The maximum TFN recorded is 4120 from the high marsh regions of Bally 6 (L40). Maximum number of living foraminifera is also from the same location and amounts to 180 (Figure 3.6).

Figure 3.7 shows the TFN variation in the post-monsoonal month of September. Maximum TFN reaches an astonishingly high value of 8273 in Bally Dweep (L1). The highest living foraminiferal number is 141, recorded from Datta Forest (L27) (Figure 3.8). The Total Foraminiferal Number of the post-monsoonal month of November has been plotted in Figure 3.9. The maximum TFN recorded in 1074 from Dulki (L14). Maximum living foraminifera (86) is recorded from Rangabelia (L20) (Figure 3.10).

Murray's ternary (Figure 3.11) plot has been plotted by taking pre-monsoon (January), monsoon (July) and post-monsoon (September) samples. Pre-monsoonal samples are indicated with blue dots, monsoonal samples with red dots and post-monsoonal samples with green dots. Most of the assemblages are clustered towards the calcareous hyaline corner of the plot; however pre-monsoon and monsoonal samples show a significant number of agglutinated populations, too. Fisher's alpha plot (Figure 3.12) shows the foraminiferal diversity varies in between 1 and 3; however, the pre-monsoonal samples show slightly greater diversity than the monsoonal or the post-monsoonal samples. Here, the pre-monsoonal samples are indicated by blue dots, monsoonal samples by red dots and post-monsoonal samples by green dots.

Seasonal variation of the dominant high marsh assemblages have been plotted; such as *Haplophragmoides canariensis* (Figure 3.13), *Haplophragmoides wilberti* (Figure 3.14), *Trochammina inflata* (Figure 3.15), *Miliammina fusca* (Figure 3.16) and *Miliammina petila* (Figure 3.17). The two most prevalent middle marsh species are *Cribroelphidium poeynum* and *Cribroelphidium decipiens,* whose seasonal variations have been plotted in Figure 3.18 and Figure 3.19, respectively. Calcareous hyaline forms dominate the low marsh assemblages like *Ammonia tepida*, *Ammonia beccarii*, *Haynesina depressula*, *Haynesina germanica* and *Quinqueloculina seminulum,* shown in Figures 3.20, 3.21, 3.22, 3.23 and 3.24 respectively. Pre-monsoonal months (January and April) are found out to be most productive in terms of foraminiferal assemblages. The month of July (monsoon samples) shows the lowest abundance of foraminifera.

Agglutinated species like *Trochammina inflata*, *Haplophragmoides wilberti*, *Haplophragmoides canariensis*, *Miliammina fusca* and *Miliammina petila* has dominant populations in all the high marsh stations round the year. *Cribroelphidium poeynum* and *Cribroelphidium decipiens* are the most encountered species in the middle marsh region. Low marsh stations are mostly inhabited by the calcareous hyaline species of *Ammonia tepida, Ammonia beccarii*, *Haynesina germanica* and *Haynesina depressula* throughout the year. The calcareous porcelaneous species *Quinqueloculina seminulum* is also abundant in the low marsh regions.

In the high marsh area, the westernmost region shows abundance of *Trochammina inflata* and *Haplophragmoides wilberti,* followed by the *Haplophragmoides wilberti* and *Haplophragmoides canariensis* in the middle and the *Haplophragmoides canariensis* and

Srinivasania sundarbanensis in the easternmost part of the study area. For the low marsh area, the western part consists of the *Ammonia tepida*, *Ammonia parkinsoniana*, *Cocoarota madrasensis*, *Haynesina depressula* and *Haynesina germanica* whereas the eastern part comprises of *Haynesina germanica*, *Haynesina depressula*, *Cribroelphidium poeynum*, *Ammonia tepida* and *Nonionella turgida*.

Figure 3.25 shows the variation of Total Foraminiferal Number with sand content and moisture content. The Foraminiferal number is inversely proportional to the sand content and directly proportional to the moisture content of the sediment samples. Therefore, it can be established that marsh foraminifera prefers finer substrate than coarser substrate as their habitat. The nutrients derived for the metabolism of the organisms come from the organic matter generally associated with fine-grained sediments.

Figure 3.26 shows the seasonal variation (July and November) of pH recorded in some selected sampling stations (representing all the different environmental conditions). The pH for July lies in between 7.6 to 7.8 whereas it ranges from 7.8 to 8 for the month of November. The overall pH of November is higher than that of the pH in July because of the greater influence of river water during this monsoon period. If compared with the Total Foraminiferal Number, it has been observed that the TFN of the November sampling stations is comparatively higher than that of the July samples. So, it can be inferred that foraminifera prefers an alkaline medium habitat in its growing stage. This data is corroborated by Saraswat et al. 2011.

Figure 3.27 shows the variation of temperature in some selective stations in the months of July and November. Although the difference in temperatures is not very high, it is evident that the July temperatures are a little higher (ranging at around 30 °C), whereas November temperatures ranges around 26 °C. As we have noticed that the TFN of November is comparatively higher, it can be deduced that the optimum temperature for foraminifera to live in is around 25 to 26 °C.

Figure 3.28 shows the foraminiferal variation with salinity in some selective stations for the months of July (32 to 35 PSU) and November (30 to 32 PSU). From the graph, it is evident that the favourable salinities for foraminifera lie in the range of 30 to 32 PSU and higher abundance of foraminifera is recorded from November samples. The month of July has lower salinity due to the influx of enormous amounts of freshwater from the terrestrial domain. This is also corroborated by Saraswat et al., 2011.

3.5.1 RESULTS FROM PRE-MONSOON (JANUARY, 2018)

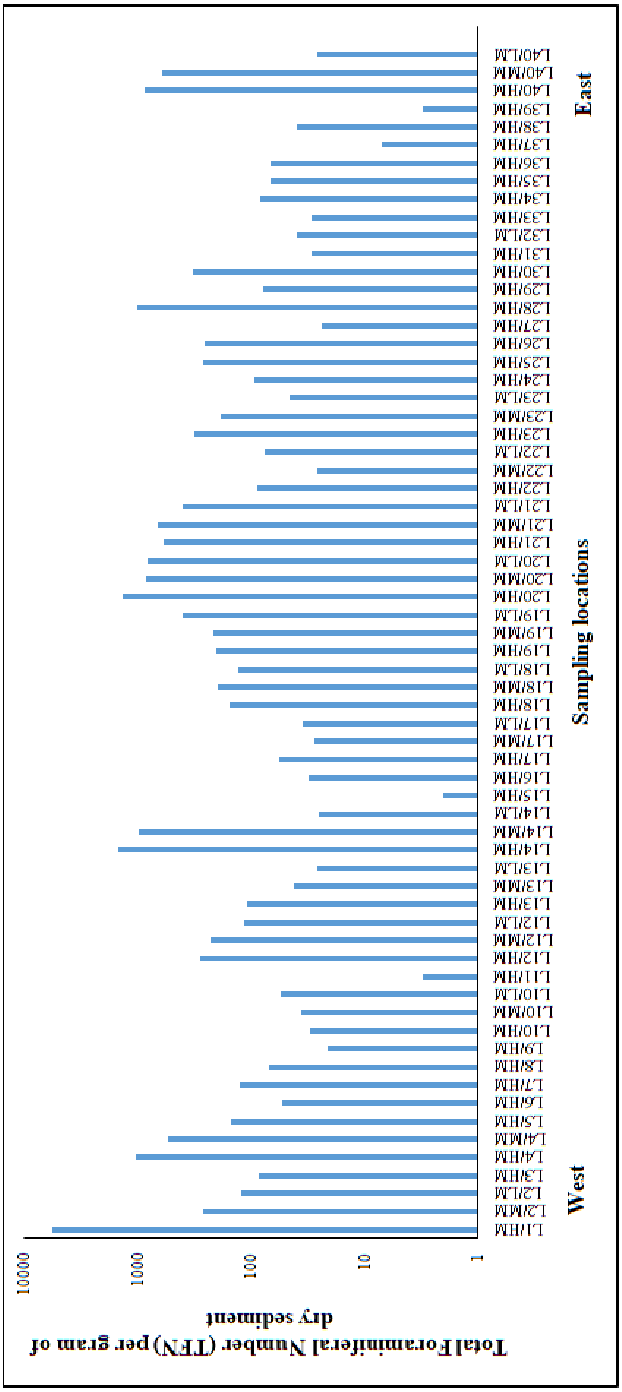


Figure 3.1: Variation of the Total Foraminiferal Number (live + dead) across the sampling locations in the month of January

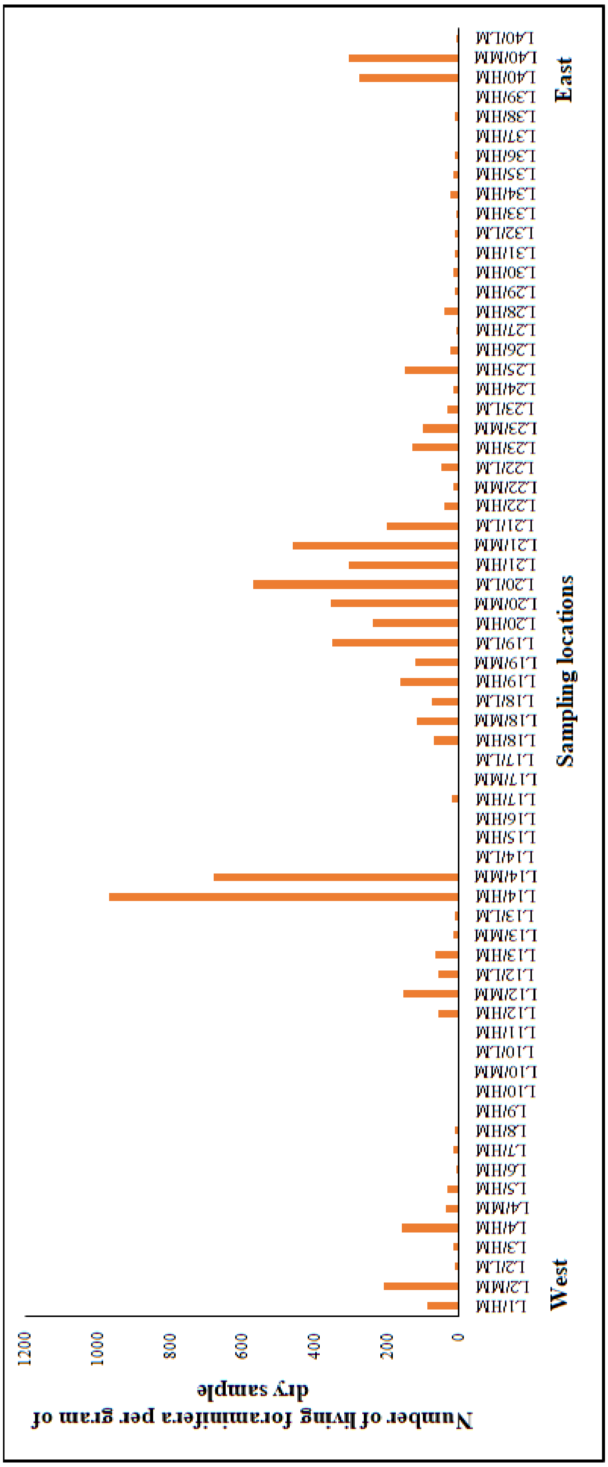


Figure 3.2: Variation of the living foraminifera across the sampling locations in the month of January

3.5.2 RESULTS FROM PRE-MONSOON (APRIL, 2018)

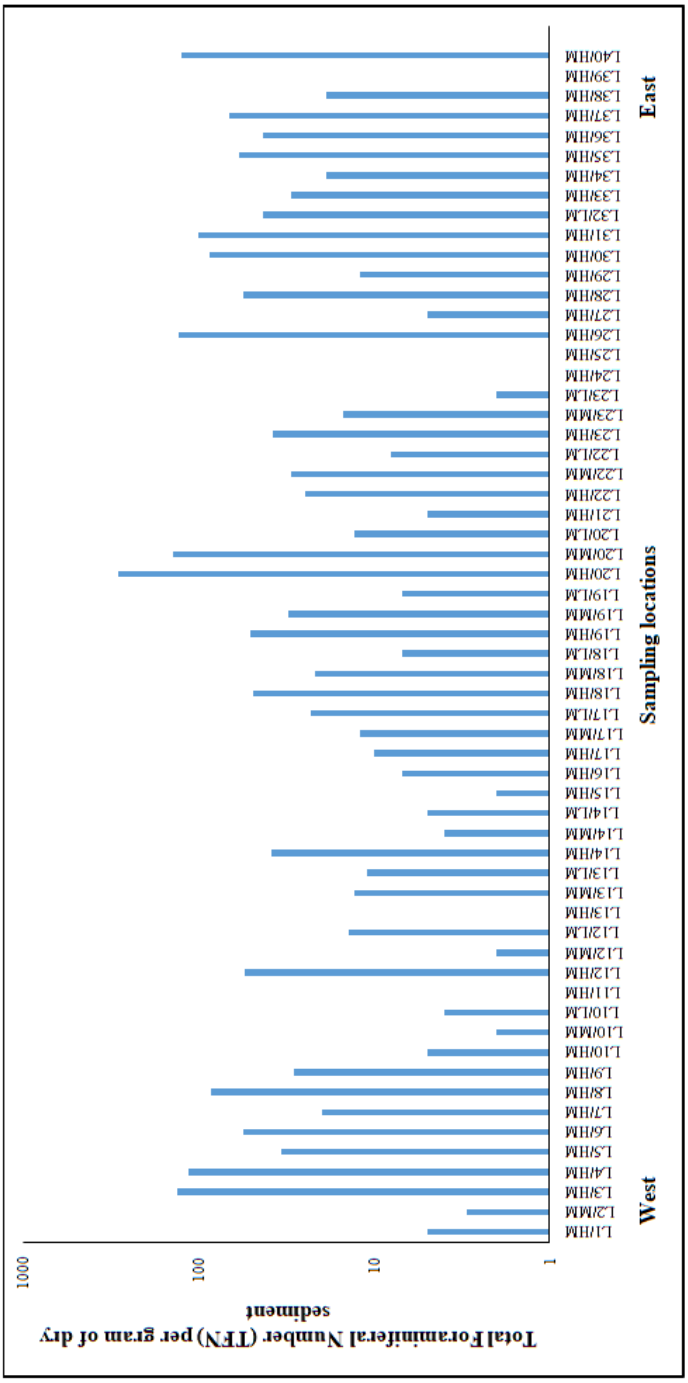


Figure 3.3: Variation of the Total Foraminiferal Number (live + dead) across the sampling locations in the month of April

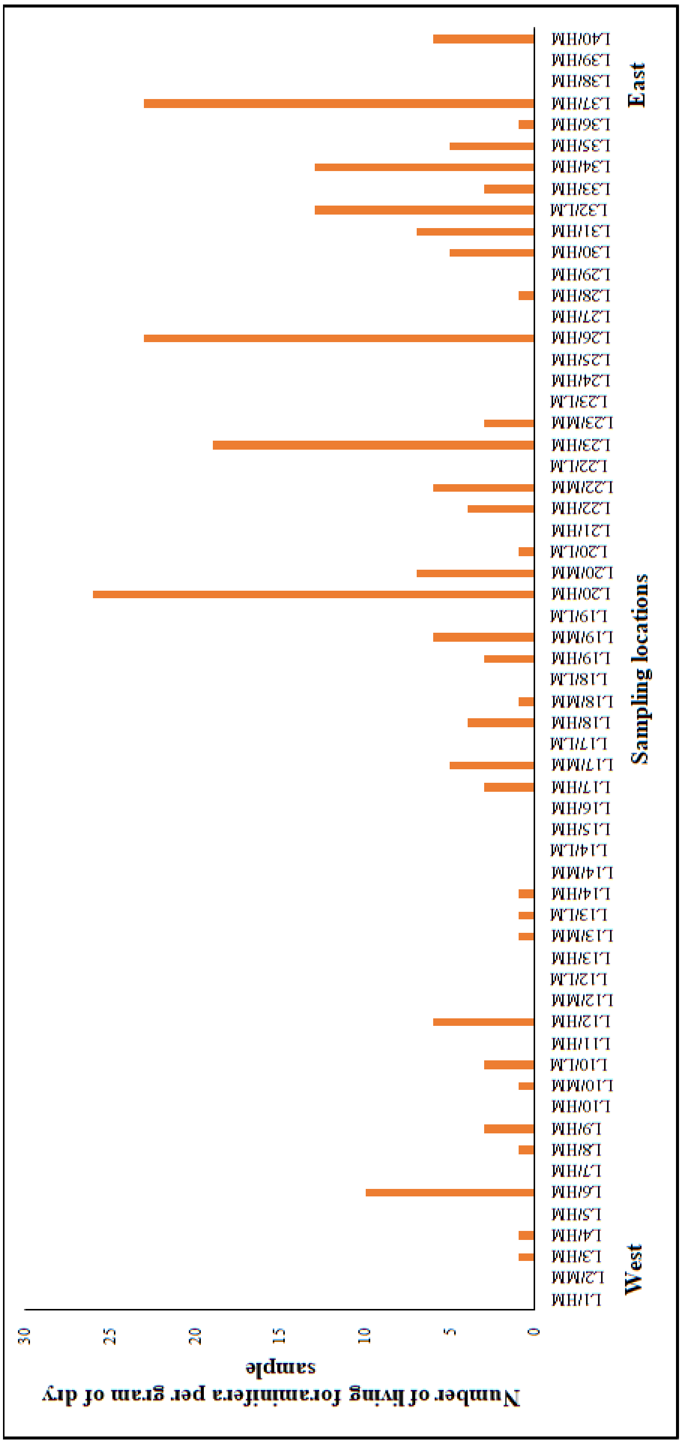


Figure 3.4: Variation of the living foraminifera across the sampling locations in the month of April

3.5.3 RESULTS FROM MONSOON (JULY, 2018)

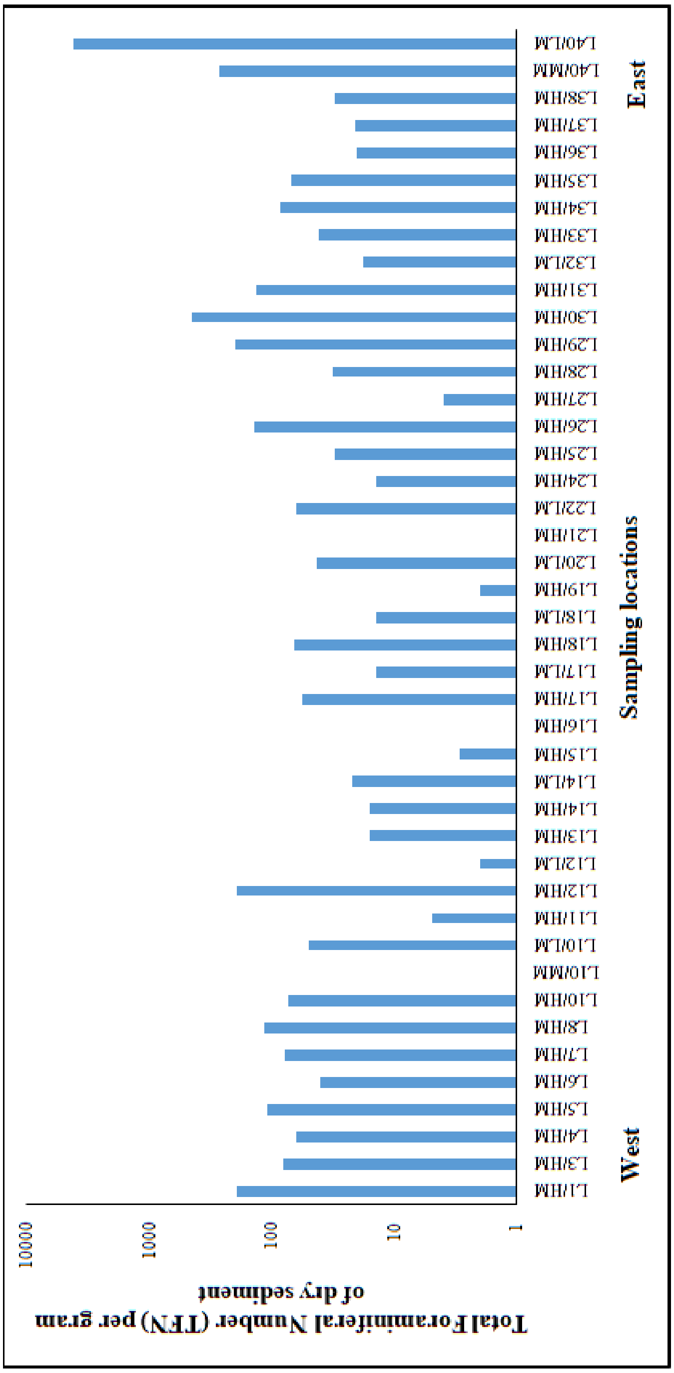


Figure 3.5: Variation of the Total Foraminiferal Number (live + dead) across the sampling locations in the month of July

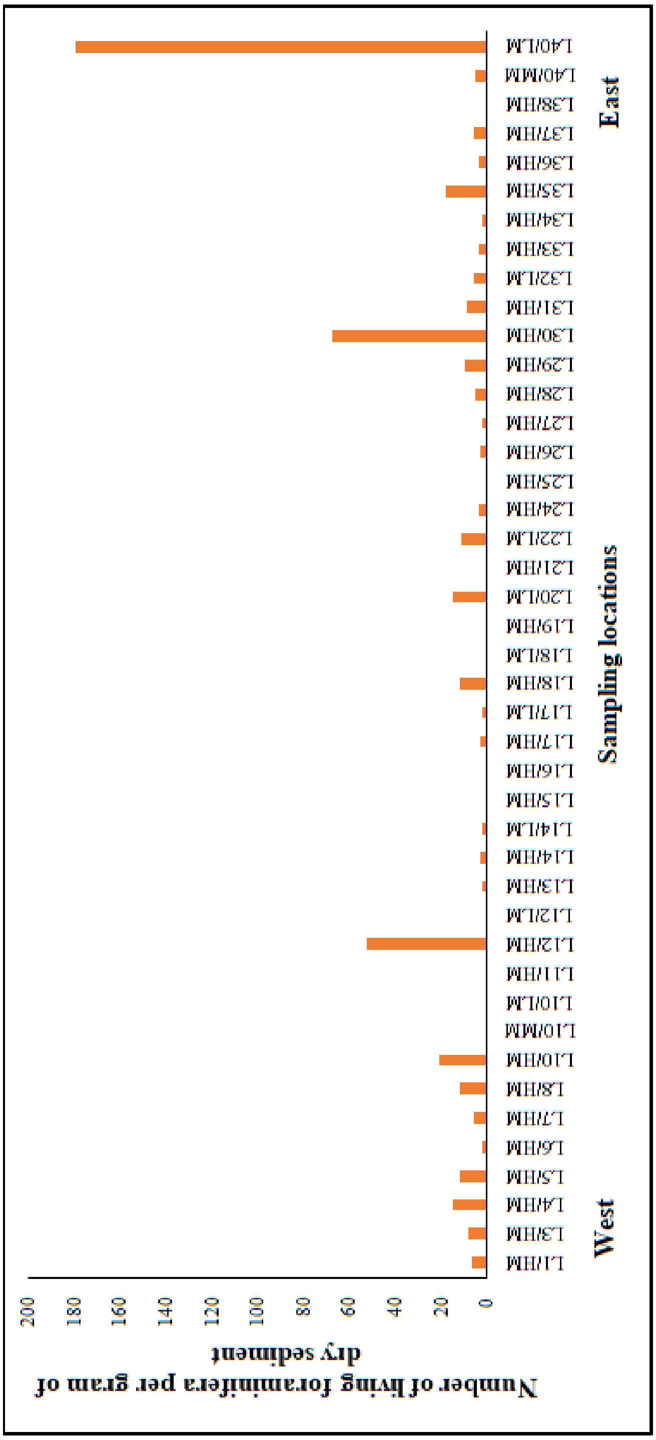


Figure 3.6: Variation of the living foraminifera across the sampling locations in the month of July

3.5.4 RESULTS FROM POST-MONSOON (SEPTEMBER, 2018)

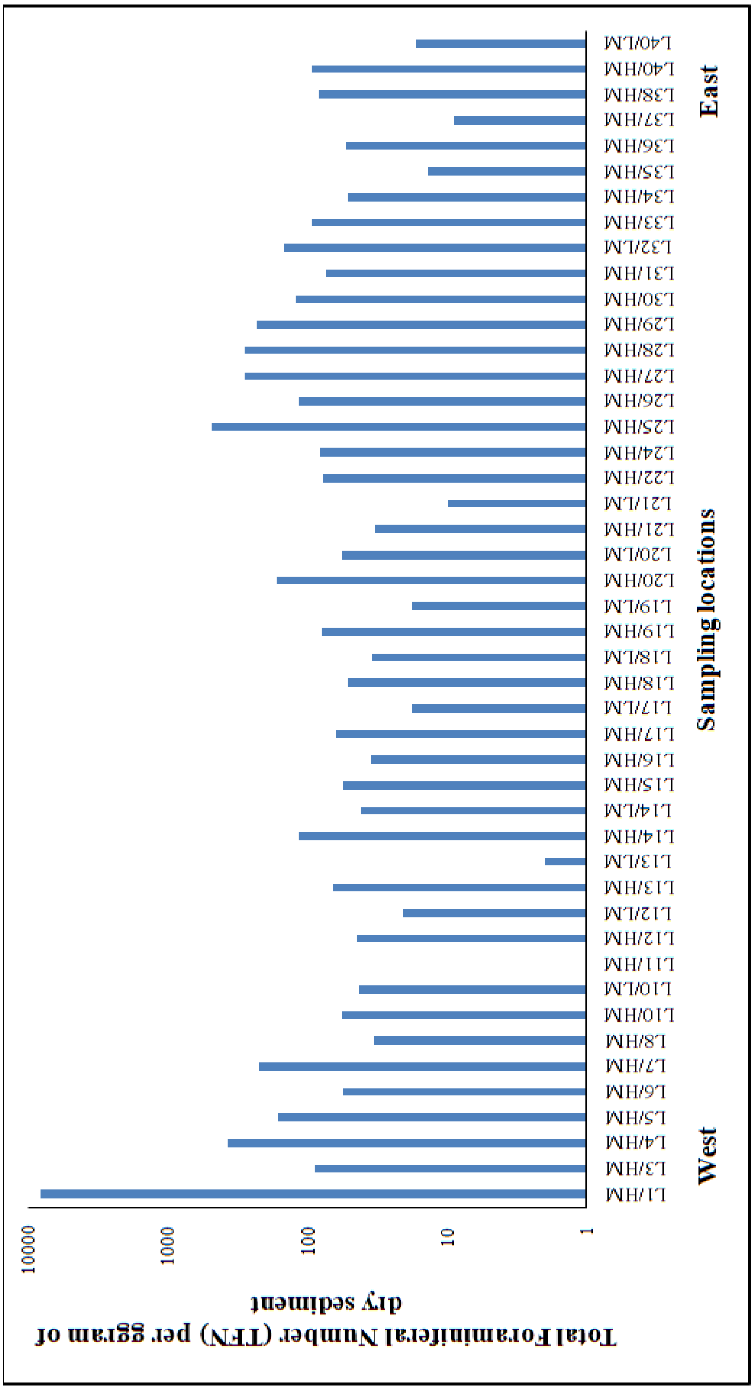


Figure 3.7: Variation of the Total Foraminiferal Number (live + dead) across the sampling locations in the month of September

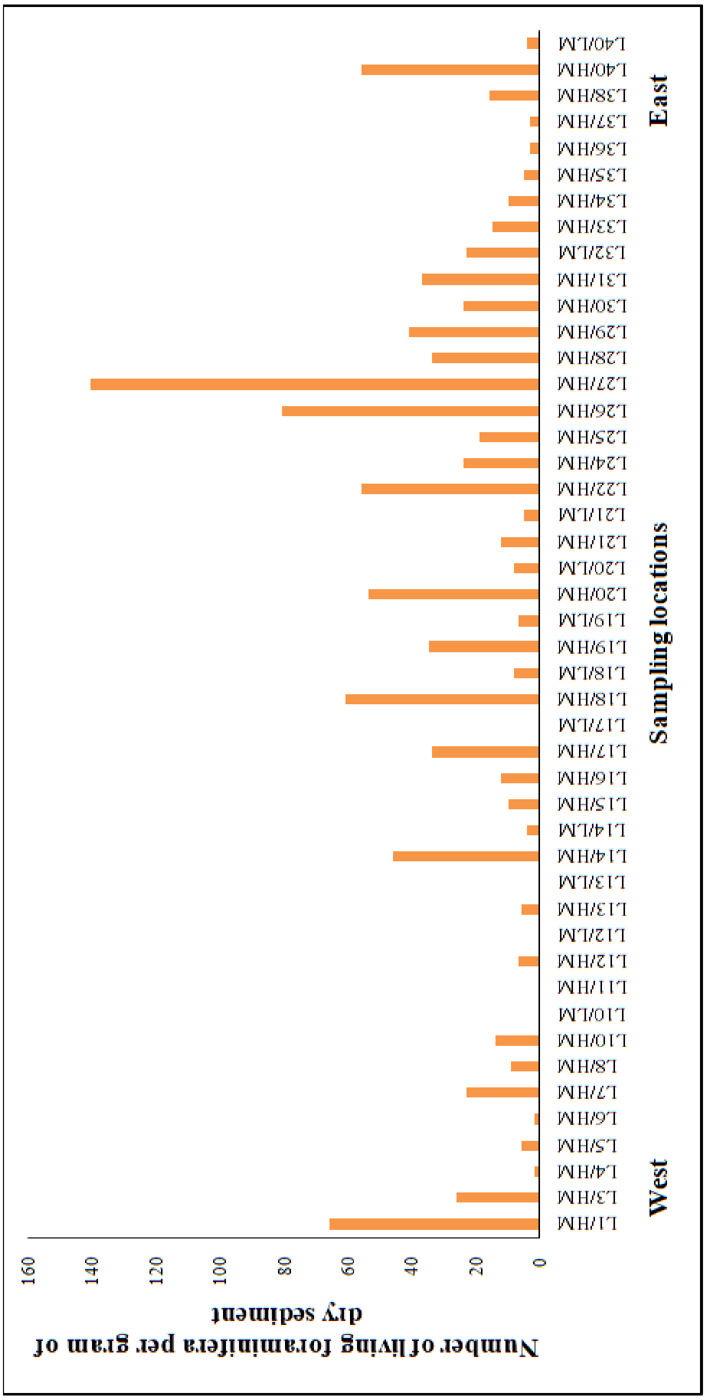


Figure 3.8: Variation of the living foraminifera across the sampling locations in the month of September

3.5.5 RESULTS FROM POST-MONSOON (NOVEMBER, 2018)

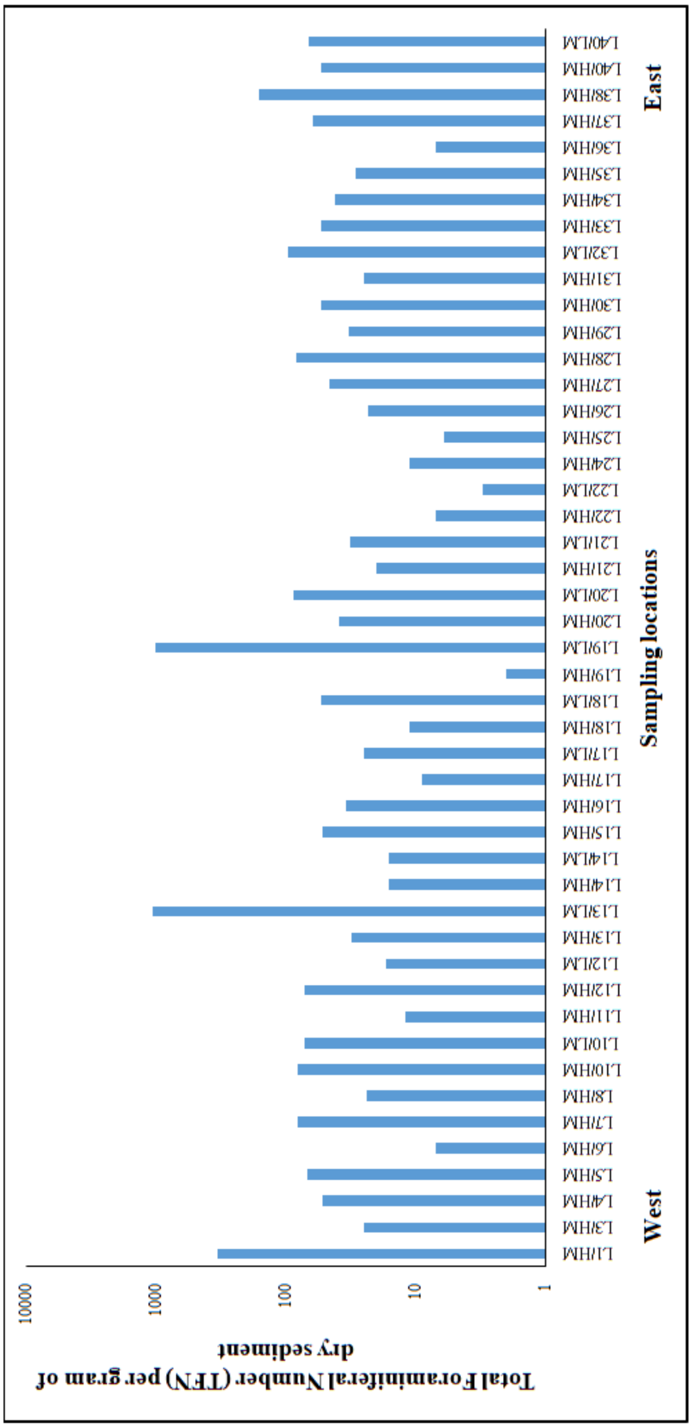


Figure 3.9: Variation of the Total Foraminiferal Number (live + dead) across the sampling locations in the month of November

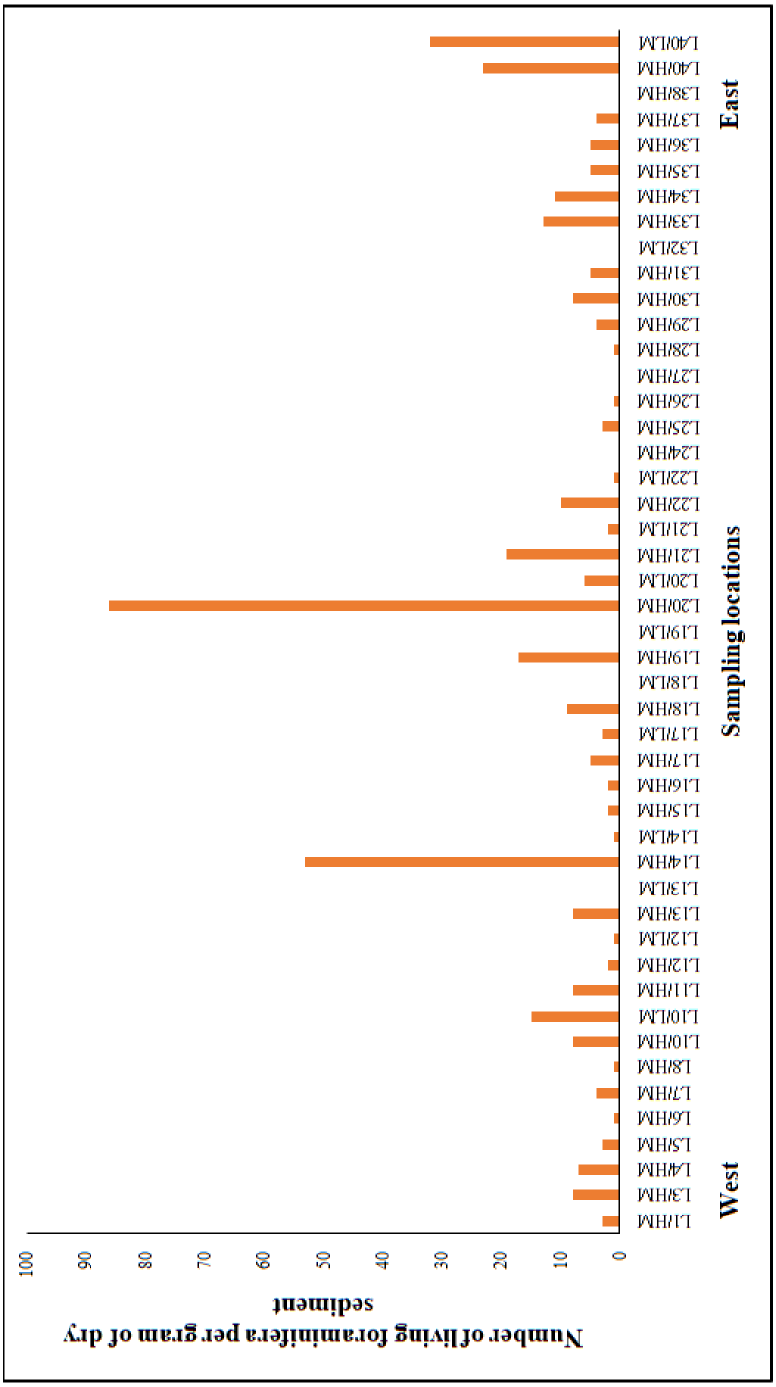


Figure 3.10: Variation of the living foraminifera across the sampling locations in the month of November

3.6 CUMULATIVE RESULTS FROM THE WHOLE STUDY

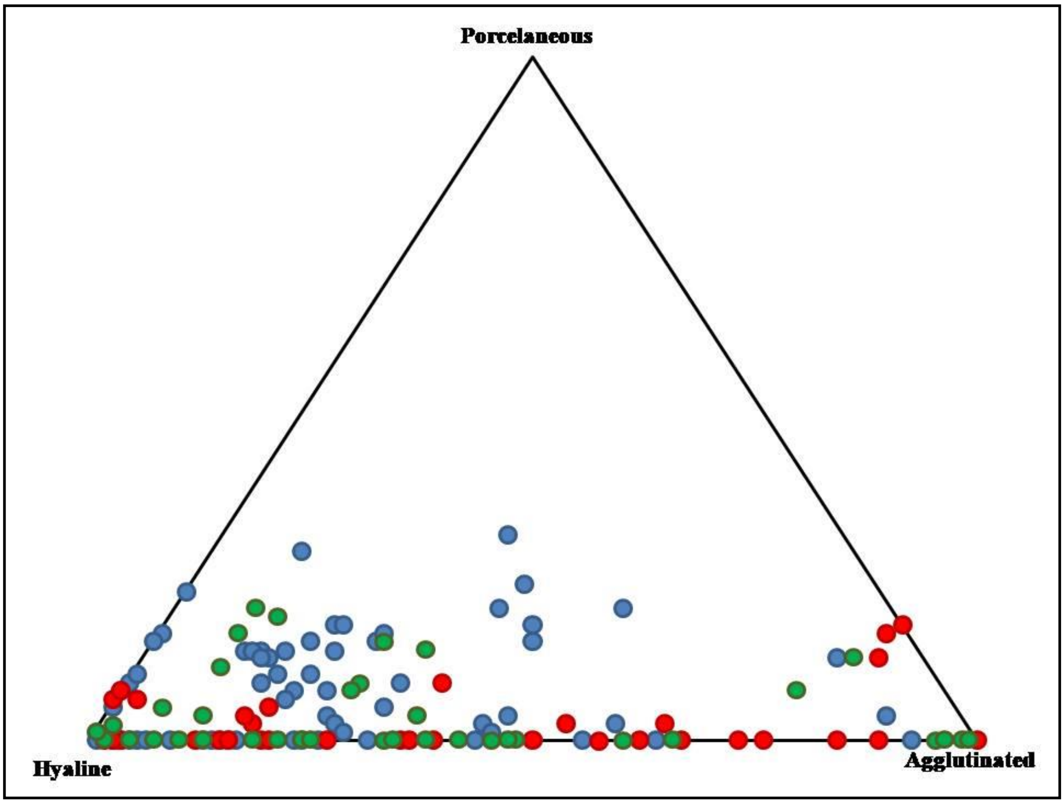


Figure 3.11: Murray's ternary plot showing pre-monsoonal (blue), monsoonal (red) and post-monsoonal (green) samples

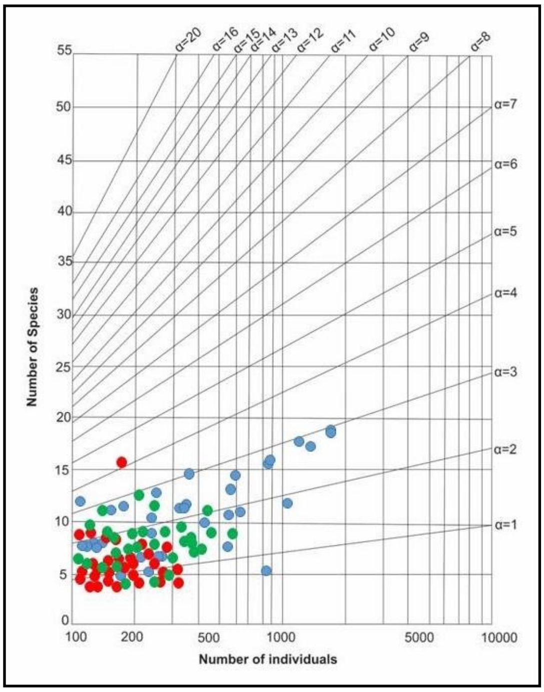


Figure 3.12: Fisher's alpha diagram showing pre-monsoonal (blue), monsoonal (red) and post-monsoonal (green) samples

3.6.1 CHARACTERISTIC SPECIES OF THE HIGH MARSH AREAS

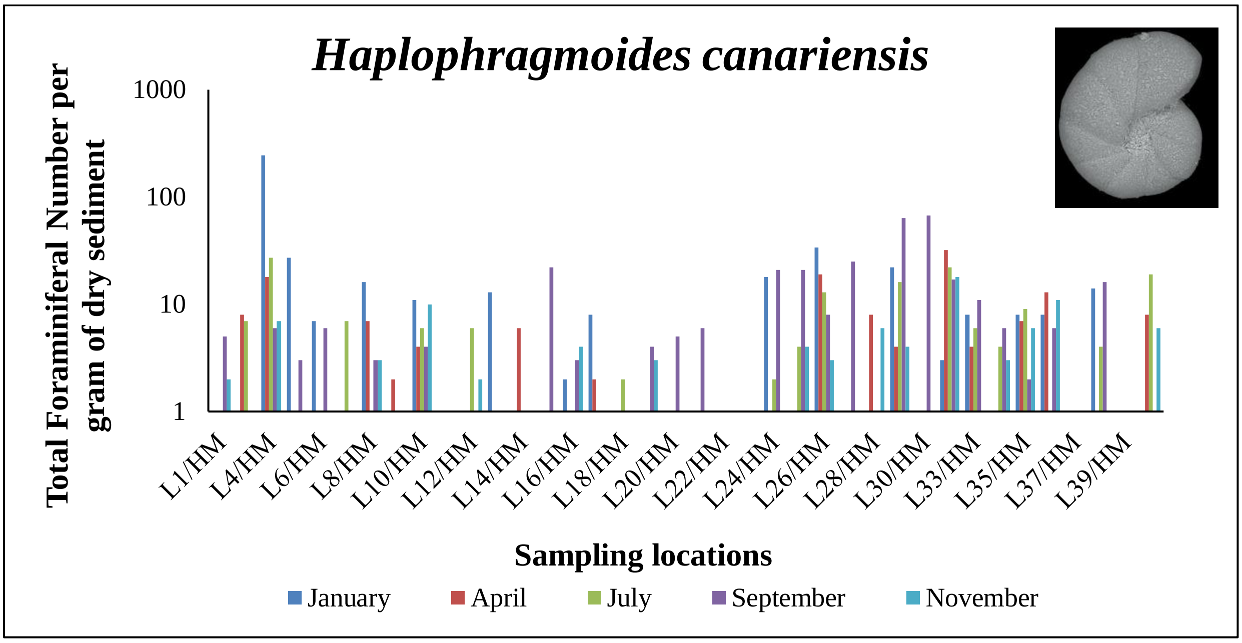


Figure 3.13: Seasonal variation of Haplophragmoides canariensis

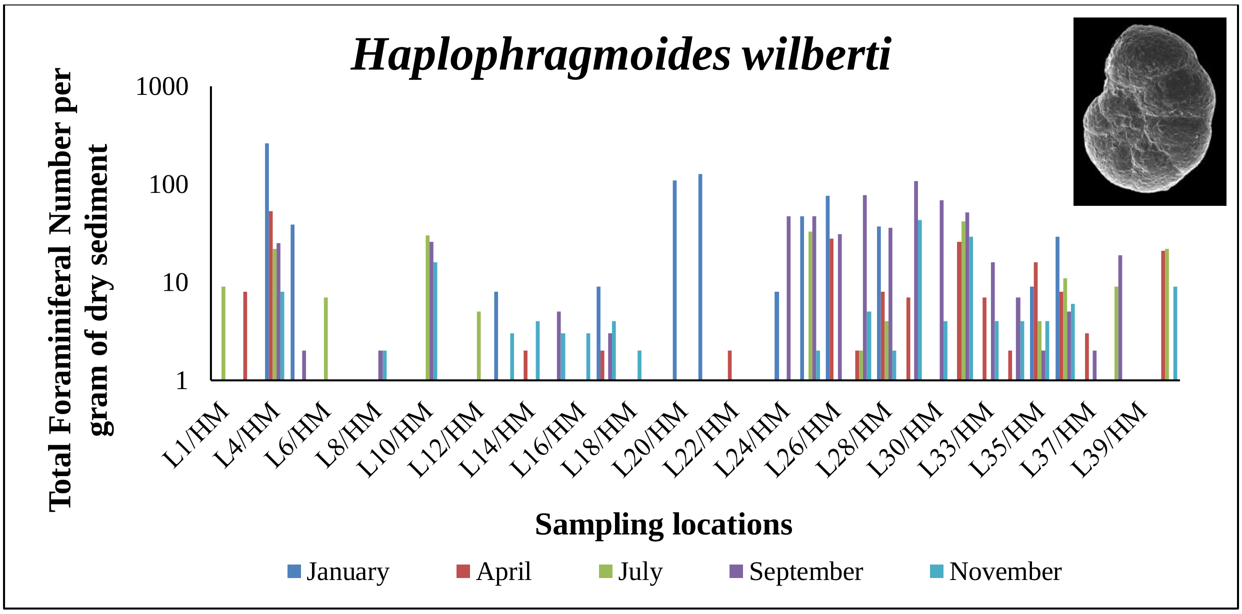


Figure 3.14: Seasonal variation of Haplophragmoides wilberti

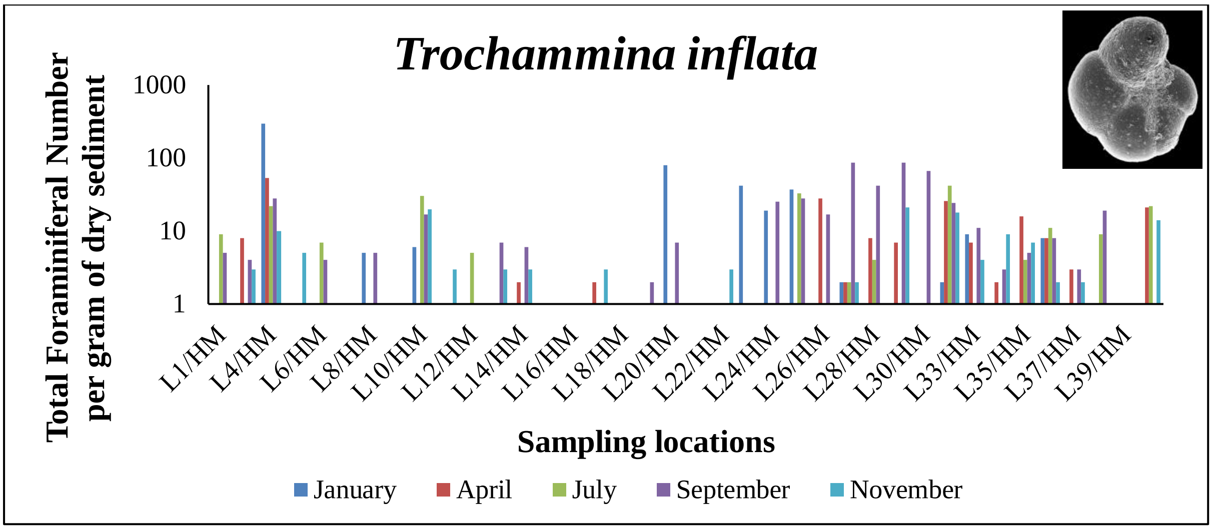


Figure 3.15: Seasonal variation of Trochammina inflata

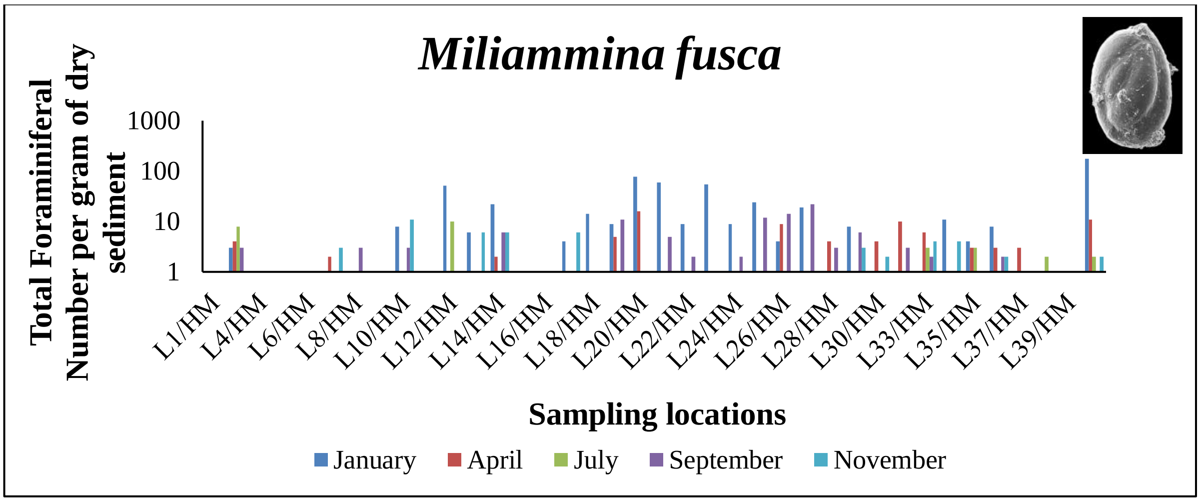


Figure 3.16: Seasonal variation of Miliammina fusca

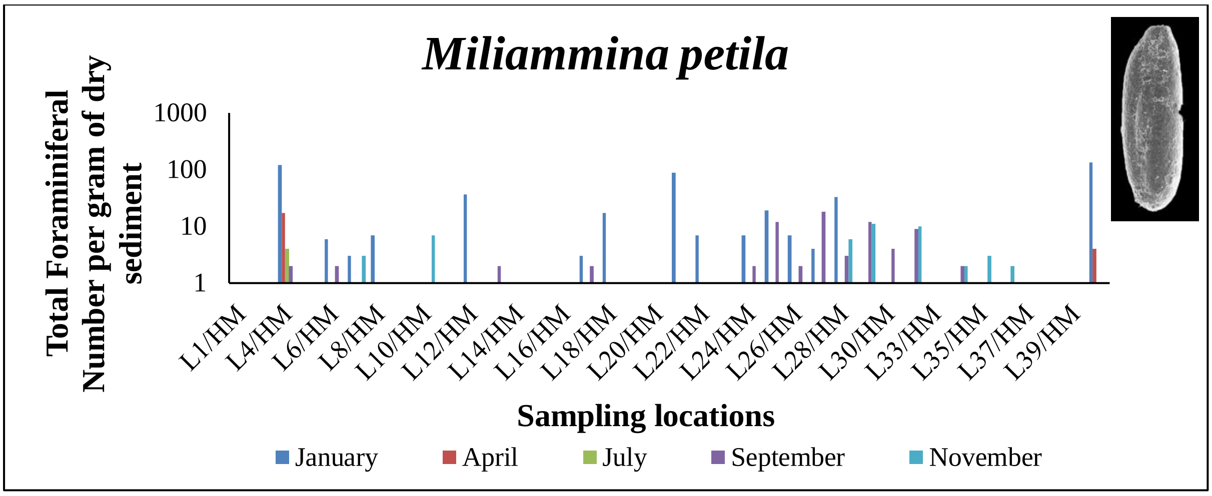


Figure 3.17: Seasonal variation of Miliammina petila

3.6.2 CHARACTERISTIC SPECIES OF THE MIDDLE MARSH AREAS

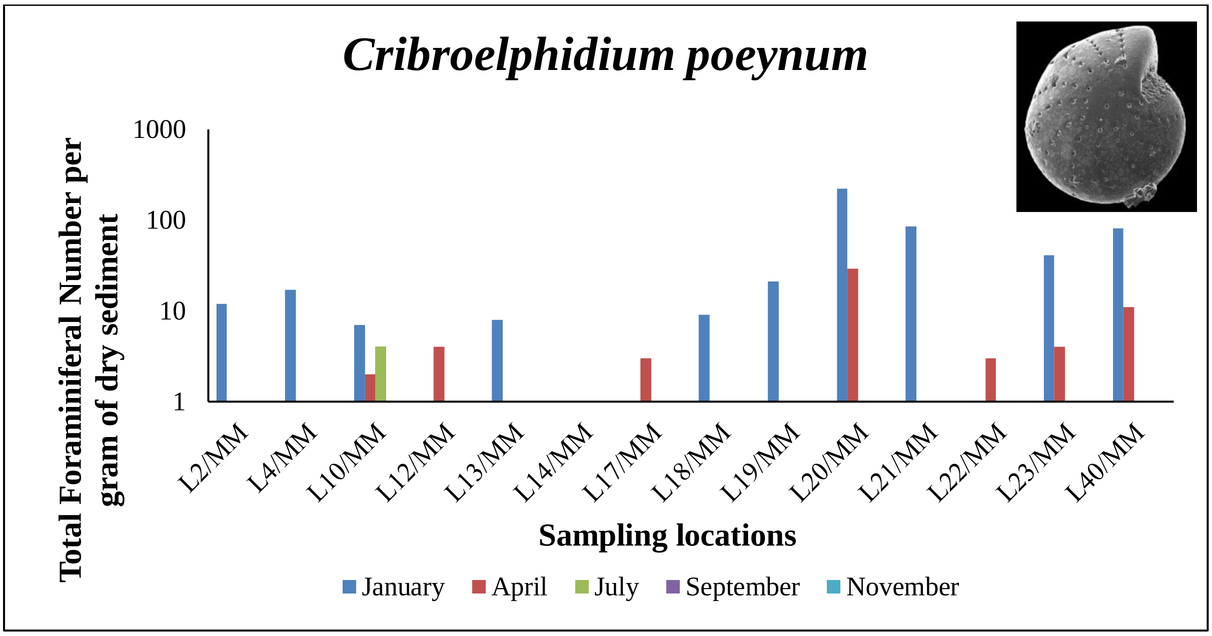


Figure 3.18: Seasonal variation of Cribroelphidium poeynum

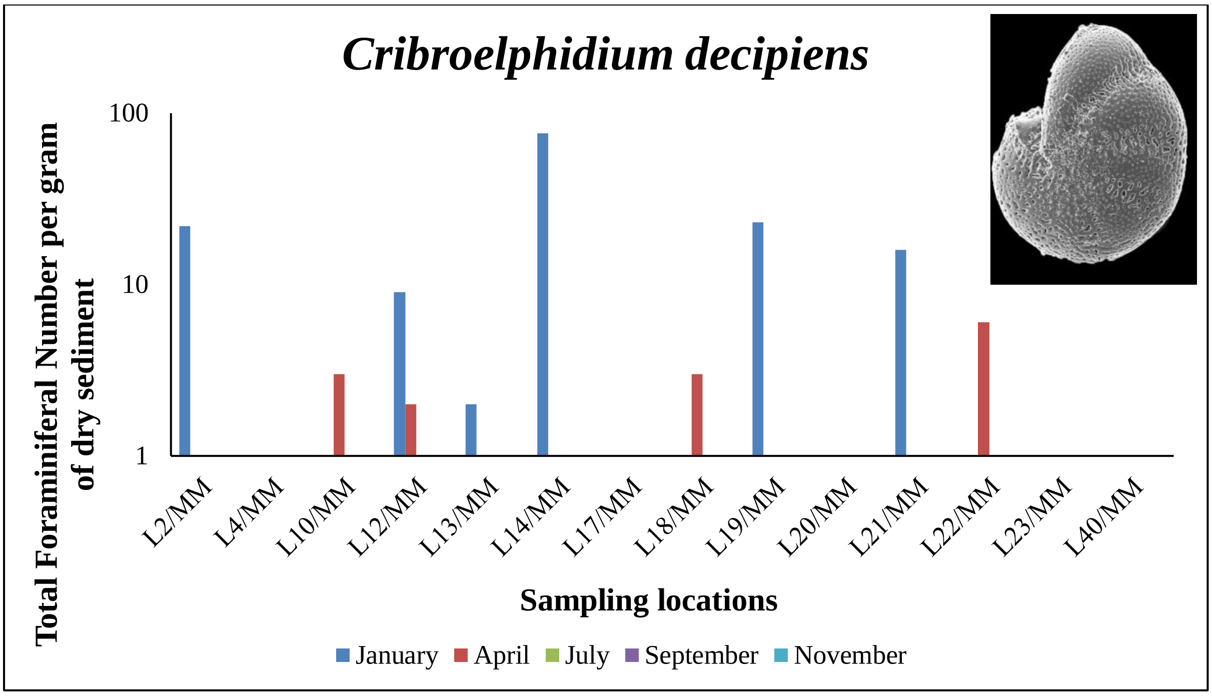


Figure 3.19: Seasonal variation of Cribroelphidium decipiens

3.6.3 CHARACTERISTIC SPECIES OF THE LOW MARSH AREAS

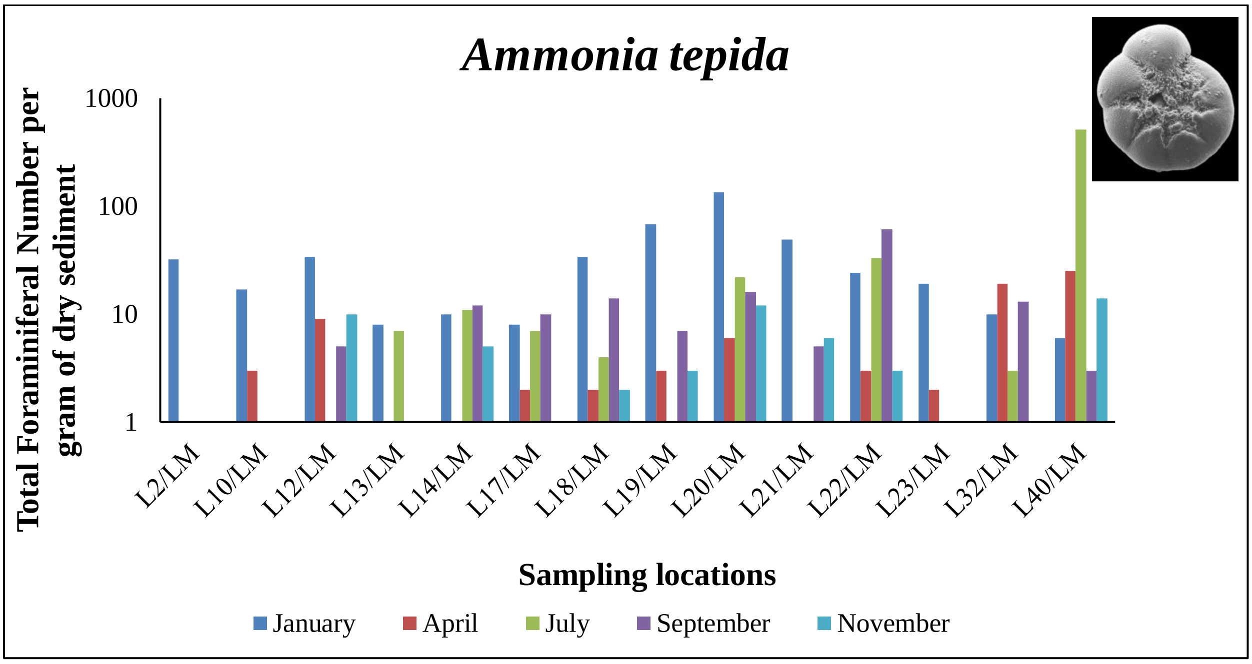


Figure 3.20: Seasonal variation of Ammonia tepida

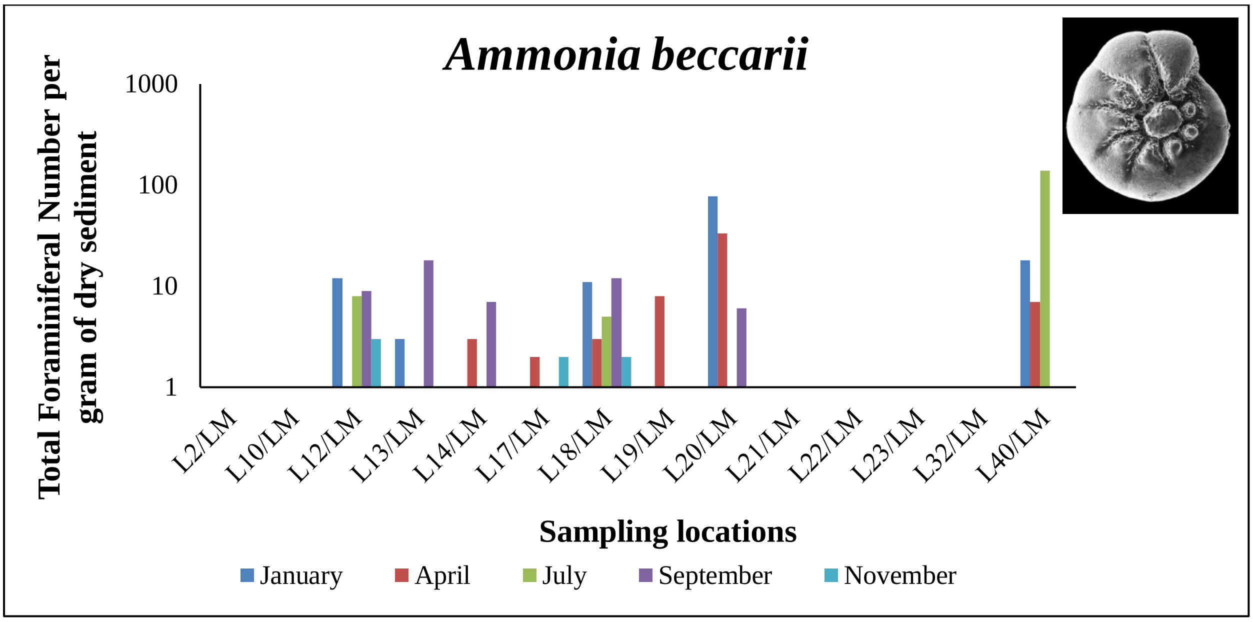


Figure 3.21: Seasonal variation of Ammonia beccarii

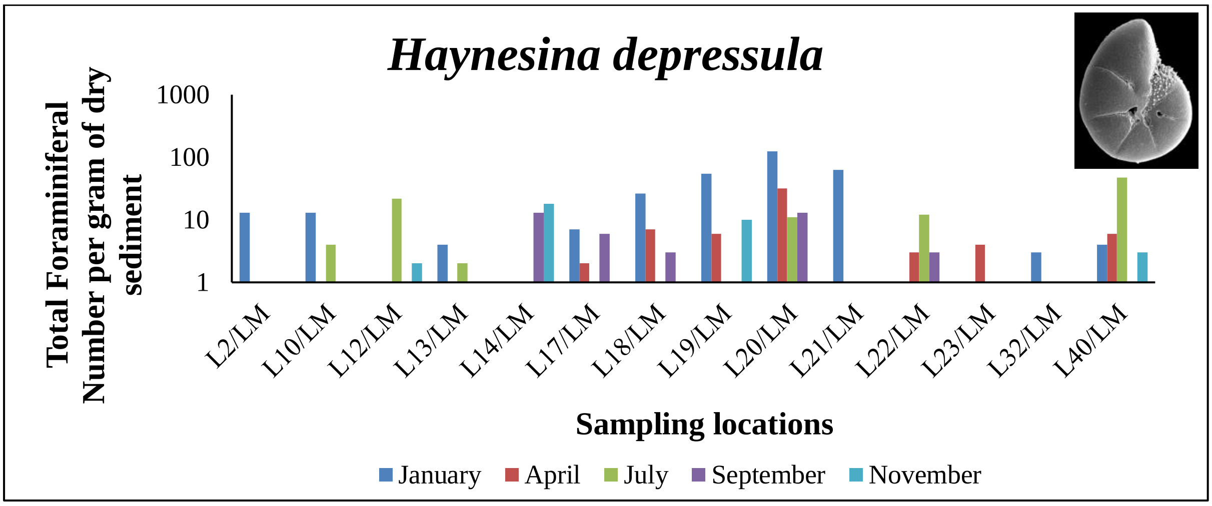


Figure 3.22: Seasonal variation of Haynesina depressula

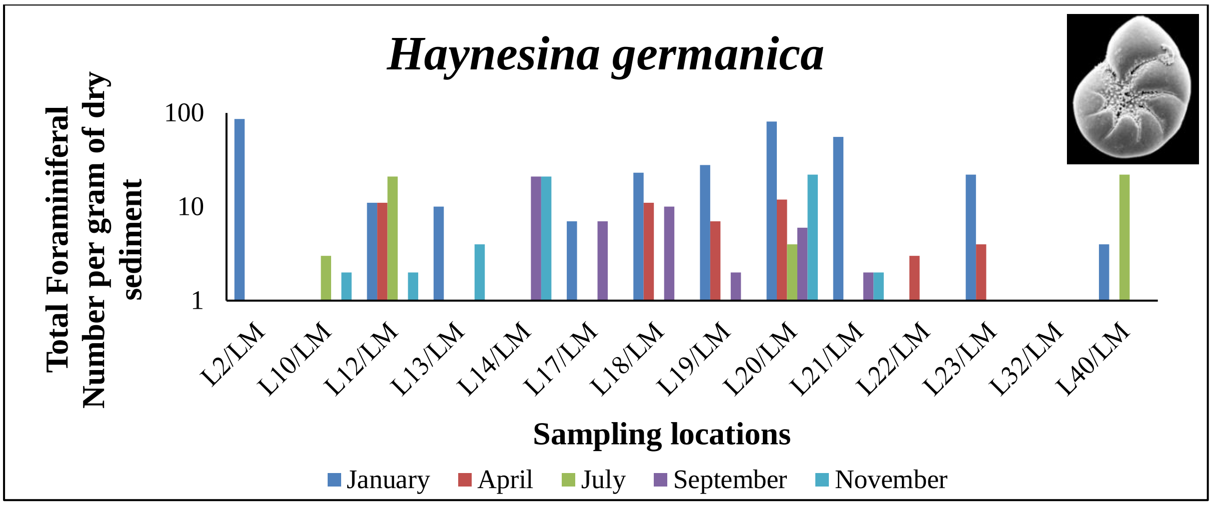


Figure 3.23: Seasonal variation of Haynesina germanica

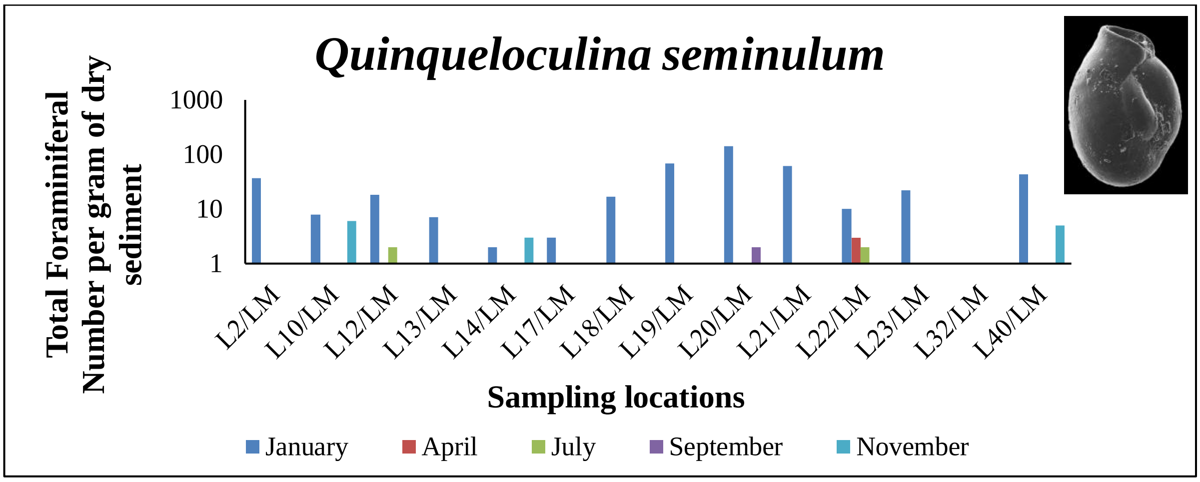


Figure 3.24: Seasonal variation of Quinqueloculina seminulum

3.7 FORAMINIFERAL RELATIONSHIP WITH PHYSICAL PARAMETERS

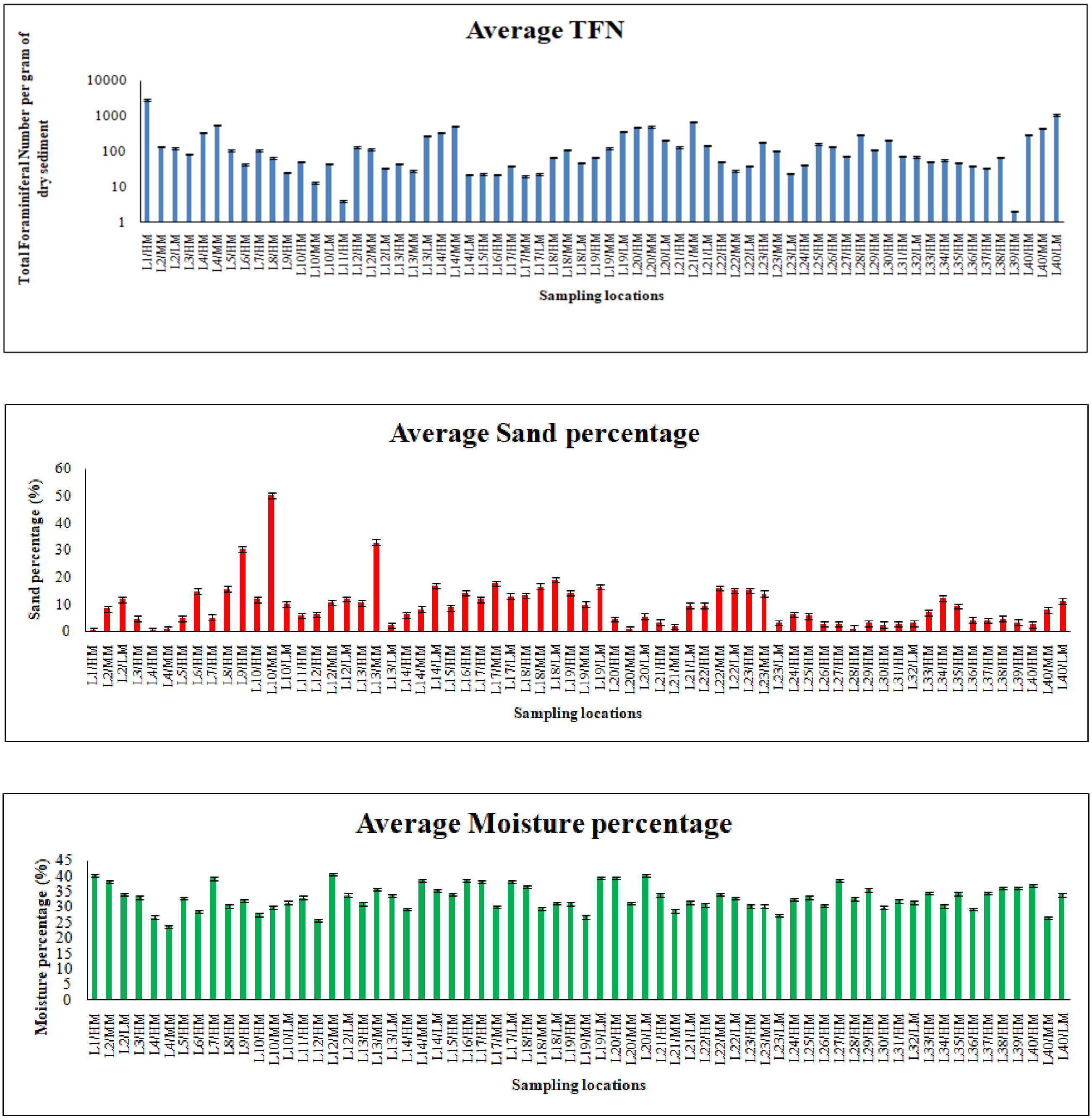


Figure 3.25: Variation of foraminifera with physical parameters: sand content and moisture content

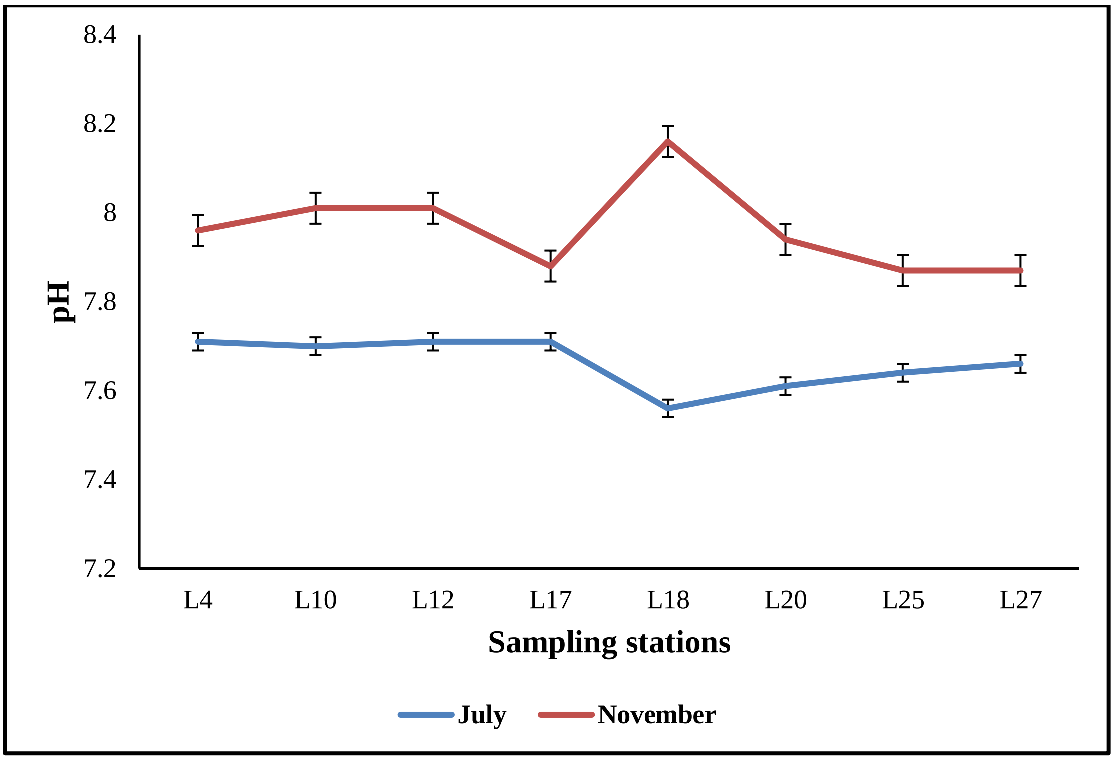


Figure 3.26: Seasonal variation in pH

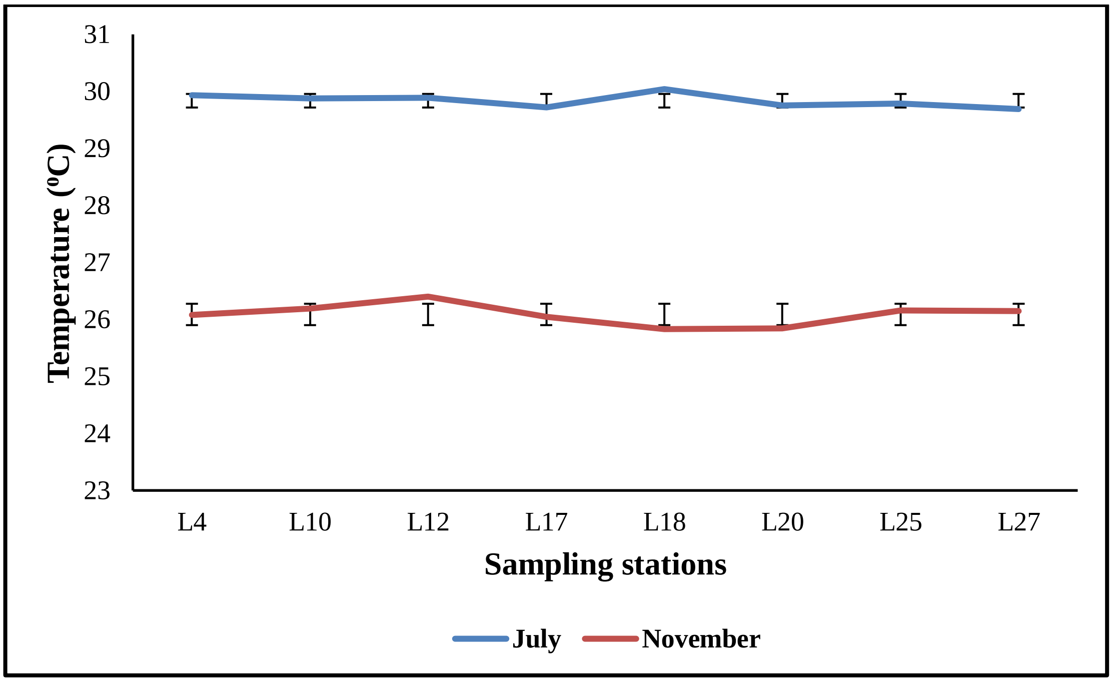


Figure 3.27: Seasonal variation in temperature

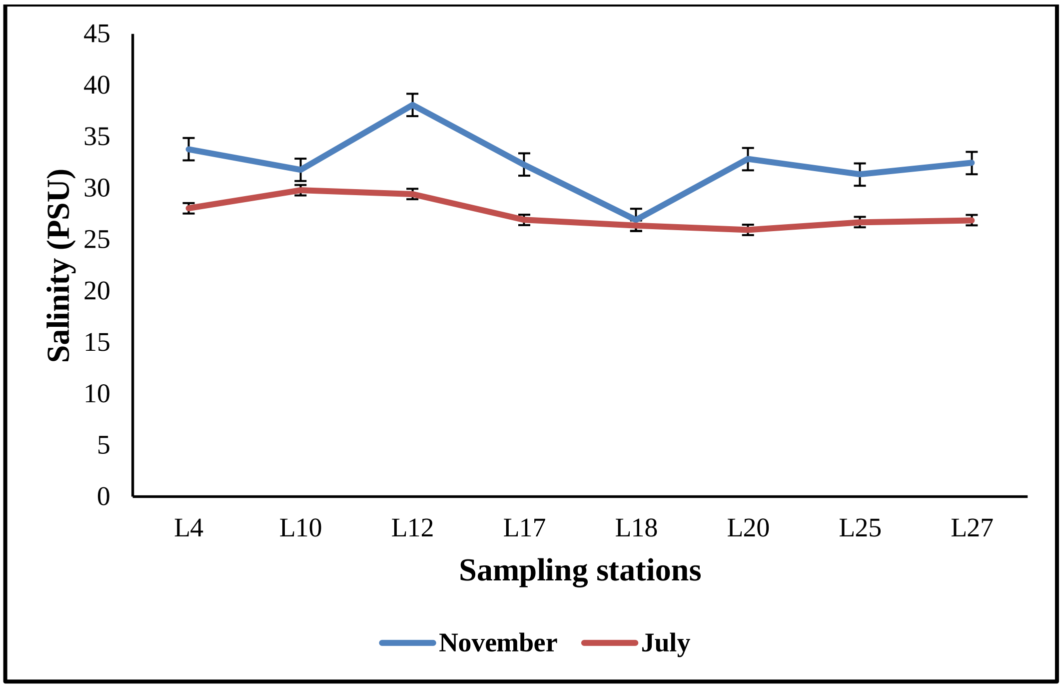


Figure 3.28: Seasonal variation in salinity

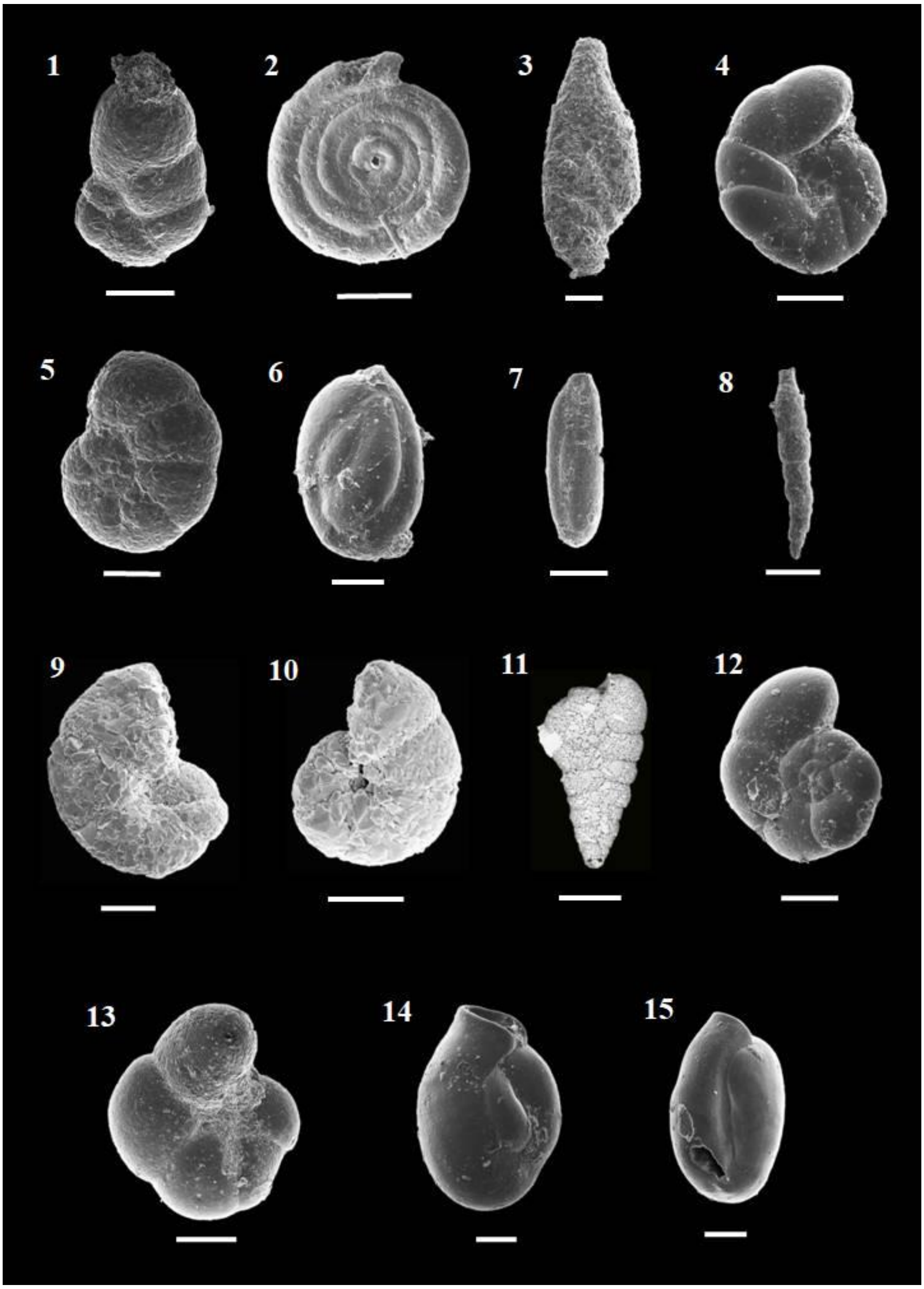


Plate 3.1: 1 – *Ammobaculites agglutinans* (Si); 2 – *Ammodiscus evolutus* (U); 3 – *Ammotium salsum* (Si); 4 – *Haplophragmoides canariensis* (U); 5 – *Haplophragmoides wilberti* (U); 6 – *Miliammina fusca* (Si); 7 – *Miliammina petila* (Si); 8 – *Reophax agglutinatus* (Si); 9 – *Srinivasania sundarbanensis* (S); 10 – *Srinivasania sundarbanensis* (U); 11 – *Textularia agglutinans* (Si); 12 – *Trochammina inflata* (S); 13 – *Trochammina inflata* (U); 14 – *Quinqueloculina seminulum* (Si); 15 – *Triloculina trigonula* (Si).

Legends: Si – Side view, U – Umbilical view, S – Spiral view. All scale bars represent 100 µm.

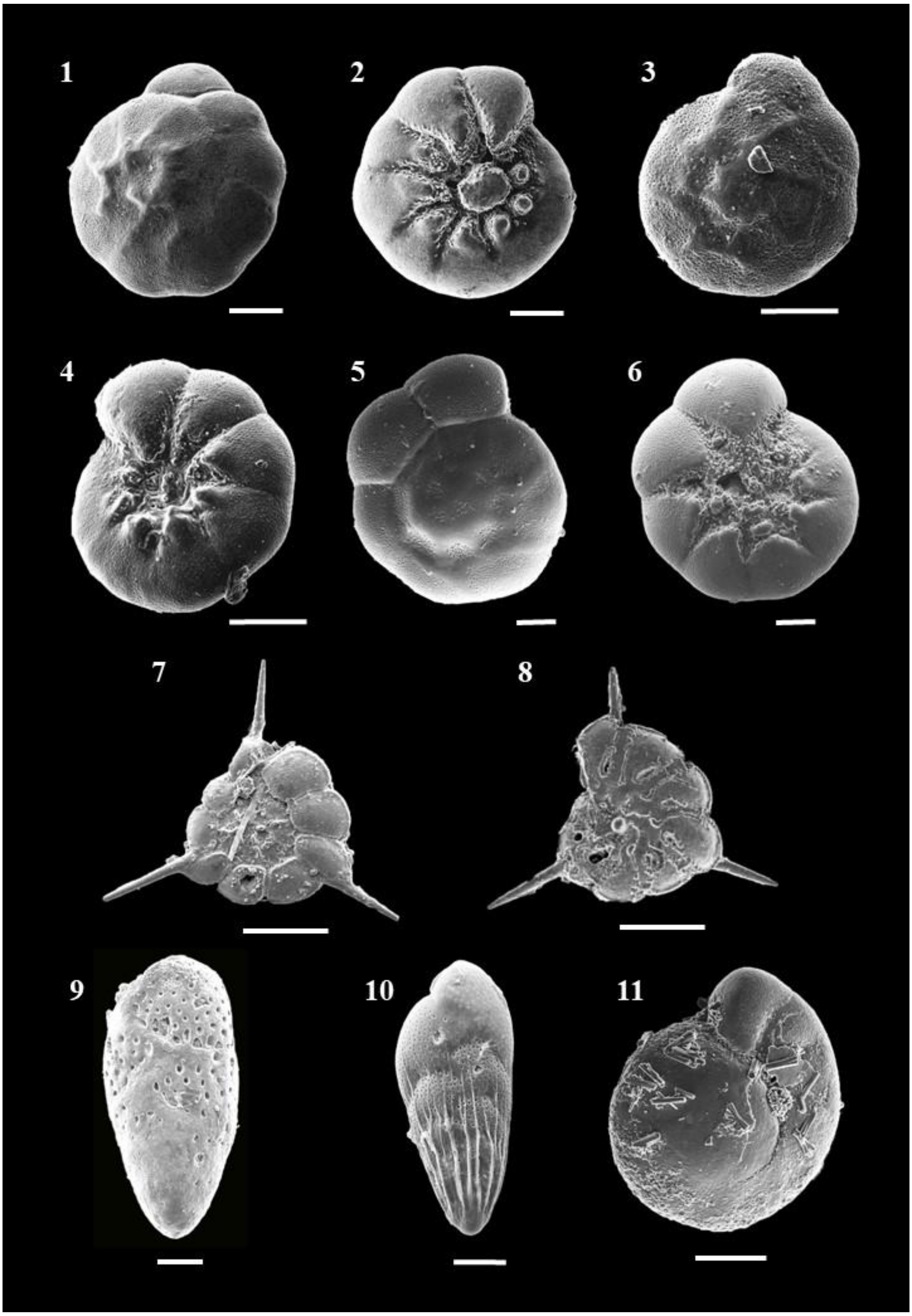


Plate 3.2: 1 – *Ammonia beccarii* (S); 2 – *Ammonia beccarii* (U); 3 – *Ammonia parkinsoniana* (S); 4 – *Ammonia parkinsoniana* (U); 5 – *Ammonia tepida* (S); 6 – *Ammonia tepida* (U); 7 – *Asterorotalia trispinosa* (S); 8 – *Asterorotalia trispinosa* (U); 9 – *Bolivina advena* (Si); 10 – *Brizalina singhi* (Si); 11 – *Cocoarota madrasensis* (U).

Legends: Si – Side view, U – Umbilical view, S – Spiral view. All scale bars represent 100 μm.

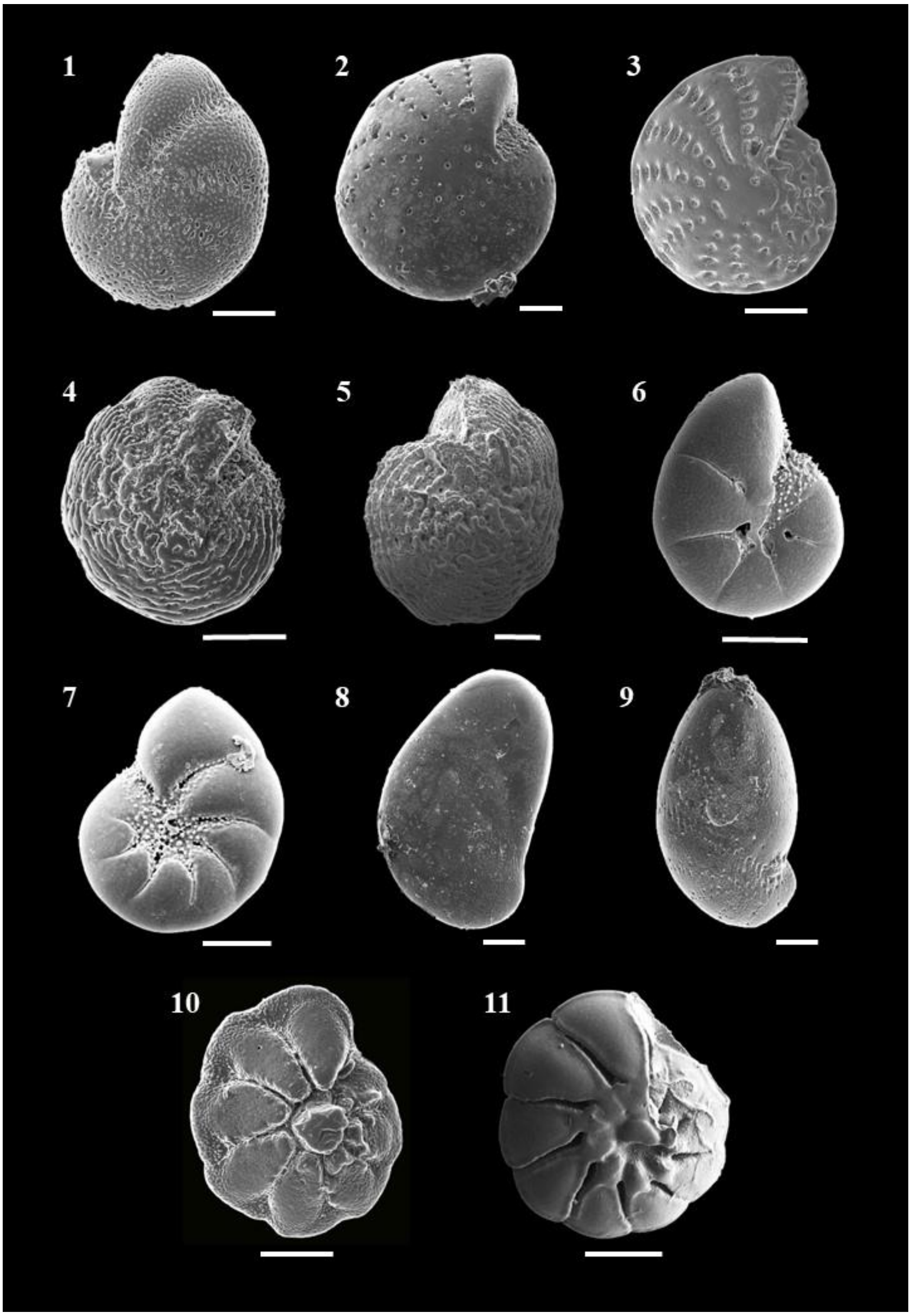


Plate 3.3: 1 – *Cribroelphidium decipiens* (U); 2 – *Cribroelphidium poeynum* (U); 3 – *Elphidium advenum* (U); 4 – *Elphidium crispum* (U); 5 – *Elphidium excavatum* (U); 6 – *Haynesina depressula* (U); 7 – *Haynesina germanica* (U); 8 – *Nonion commune* (U); 9 – *Nonionella turgida* (U); 10 – *Rotalidium annectens* (U); 11 – *Pararotalia nipponica* *(U)*.

Legends: U – Umbilical view. All scale bars represent 100 µm.

4.1 INTRODUCTION

Bakkhali is located on the eastern side of Hooghly River along the coastal tract of West Bengal. This region represents a wide range of diversity in terms of coastal processes, geomorphology and environment. This area is characterized by the presence of the largest tide-dominated Hooghly estuary with numerous channels and creeks along with extensive marshlands. The shoreline of Bakkhali is lined by coastal dunes. Coastal processes are very dynamic which are influenced by the tropical cyclones in this area. There are certain mangrove patches along the coastline. Two such sites are present in the western and eastern margins of the island. The western part of Bakkhali is comprised of the Patibhunia marshes, which are separated from the main island by a narrow creek. In the eastern extremity lie the Henry's island marshes which are again separated by the mainland by a narrow creek. These two marshlands are the main areas of interest in comparison with the northern Sunderban marshes and the Chandipur marshes (southern side).

4.2 FORAMINIFERAL ASSEMBLAGES

A total of sixteen species of foraminifera have been identified, including calcareous and agglutinated forms. Dominant calcareous hyaline forms are *Ammonia tepida*, *Ammonia beccarii*, *Haynesina germanica*, *Haynesina depressula*, *Cribroelphidium poeynum*, *Cribroelphidium hispidulum* and *Asterorotalia trispinosa*. The only calcareous porcelaneous form recorded from the study area is *Quinqueloculina seminulum*. Common agglutinated forms include *Haplophragmoides canariensis*, *Haplophragmoides wilberti*, *Miliammina fusca*, *Miliammina petila* and *Trochammina inflata*.

4.3 SYSTEMATICS

Phylum: Foraminifera d'Orbigny, 1826

Class: Tubothalamea Pawlowski, Holzmann&Tyszka, 2013

Order: Spirillinida Hohenegger & Piller, 1975

Suborder: Ammodiscina Mikhalevich, 1980

Family: Ammodiscidae Reuss, 1862

Genus: *Ammodiscus* Reuss, 1862

Ammodiscus evolutus Zheng, 1988

(Plate 4.1, Figure 1)

Remarks: This form has been recorded from the high marsh areas of Henry's Island.

Order: Miliolida Delage & Hérouard, 1896

Family: Miliamminidae Saidova, 1981

Genus: *Miliammina* Heron-Allen &Earland, 1930

Miliammina fusca Brady, 1870

(Plate 4.1, Figure 2)

Remarks: This form is quite common and is reported from throughout the study area.

Miliammina petila Saunders, 1958

(Plate 4.1, Figure 3)

Remarks: This is also an abundant form and is reported from the marshy regions of Patibhunia and Henry's Island.

Family: Hauerinidae Schwager, 1876

Subfamily: Hauerininae Schwager, 1876

Genus: *Quinqueloculina* d'Orbigny, 1826

Quinqueloculina seminulum Linnaeus, 1758

(Plate 4.1, Figure 8)

Remarks: This form is prevalent all throughout the study area in Patibhunia, Bakkhali intertidal flats and Henry's Island marshes.

Class: Globothalamea Pawlowski, Holzmann&Tyszka, 2013

Subclass: Textulariana Mikhalevich, 1980

Order: Lituolida

Suborder: Lituolina Lankester, 1885

Family: Lituolidae Blainville, 1827

Genus: *Ammotium* Loeblich& Tappan, 1953

Ammotium salsum Cushman &Brönnimann, 1948

(Plate 4.1, Figure 5)

Remarks: This form is reported from the high marsh areas of Henry's Island.

Family: Haplophragmoididae Maync, 1952

Genus: *Haplophragmoides* Cushman, 1910

Haplophragmoides wilberti Andersen, 1953

(Plate 4.1, Figure 4)

Remarks: This form has been observed in the marshy regions of Patibhunia and Henry's Island.

Suborder: Trochamminina Saidova, 1981

Superfamily: Trochamminoidea Schwager, 1877

Family: Trochamminidae Schwager, 1877

Genus: *Trochammina* Parker & Jones, 1859

Trochammina inflata Montagu, 1808

(Plate 4.1, Figures 6 and 7)

Remarks: This is a quite common form found from all over the study area.

Class: Globothalamea Pawlowski, Holzmann & Tyszka, 2013

Subclass: Rotaliana Mikhalevich, 1980

Order: Rotaliida Delage & Hérouard, 1896

Superfamily: Rotalioidea Ehrenberg, 1839

Family: Ammoniidae Saidova, 1981

Subfamily: Ammoniinae Saidova, 1981

Genus: *Ammonia* Brünnich, 1771

Ammonia beccarii Linnaeus, 1758

(Plate 4.2, Figures 1 and 2)

Remarks: This is an abundant species found throughout the study area of Patibhunia, Bakkhali and Henry's Island.

Ammonia tepida Cushman, 1926

(Plate 4.2, Figures 3 and 4)

Remarks: This is a common form prevalent in all the sampling stations of Patibhunia, Bakkhali and Henry's Island.

Genus: *Asterorotalia* Hofker, 1950

Asterorotalia trispinosa Thalmann, 1933

(Plate 4.2, Figures 5 and 6)

Remarks: It is observed from the Bakkhali intertidal flats.

Family: Elphidiidae Galloway, 1933

Subfamily: Elphidiinae Galloway, 1933

Genus: *Cribroelphidium* Cushman and Brönnimann, 1948

Cribroelphidium decipiens Costa, 1856

(Plate 4.2, Figure 7)

Remarks: This is a common marsh foraminifera found from the mangrove regions of Patibhunia and Henry's Island.

Cribroelphidium poeynum

(*Polystomella poeyana* d'Orbigny, 1839)

(Plate 4.2, Figure 8)

Remarks: This form is found frequently from all the sampling stations of Patibhunia, Bakkhali and Henry's Island.

Genus: *Elphidium* Montfort, 1808

Elphidium advenum Cushman, 1922

(Plate 4.2, Figure 9)

Remarks: This form is reported from the marshy areas of Henry's Island.

Family: Haynesinidae Mikhalevich, 2013

Genus: *Haynesina* Banner & Culver, 1978

Haynesina depressula Walker & Jacob, 1798

(Plate 4.2, Figure 10)

Remarks: This form is quite common in the study area and is found from all sampling stations.

Haynesina germanica Ehrenberg, 1840

(Plate 4.2, Figure 11)

Remarks: This form is prevalent in all the sampling stations and is reported from Patibhunia, Bakkhali intertidal flats and Henry's Island.

Superfamily: Nonionoidea Schultze, 1854

Family: Nonionidae Schultze, 1854

Subfamily: Nonioninae Schultze, 1854

Genus: *Nonionella* Cushman, 1926

Nonionella turgida Williamson, 1858

(Plate 4.2, Figure 12)

Remarks: This form is reported from the low marsh areas of Patibhunia and Henry’s Island.

4.4 MODERN SURFICIAL DISTRIBUTION OF FORAMINIFERA

Serial Number	Station code	Name of the location	GPS co-ordinates
1	L1	Fraserganj	N 21° 34’ 48” E 88° 14’ 24”
2	L2	Patibhunia	N 21° 35’ 24” E 88° 15’ 36”
3	L3	Patibhunia	N 21° 35’ 24” E 88° 15’ 00”
4	L4	Patibhunia	N 21° 34’ 48” E 88° 15’ 00”
5	L5	Bakkhali	N 21° 34’ 12” E 88° 17’ 24”
6	L6	Bakkhali	N 21° 34’ 48” E 88° 18’ 36”
7	L7	Henry’s Island	N 21° 34’ 12” E 88° 18’ 00”
8	L8	Henry’s Island	N 21° 34’ 12”E 88° 17’ 24”
9	L9	Henry’s Island	N 21° 34’ 12”E 88° 18’ 36”
10	L10	Henry’s Island	N 21° 34’ 48”E 88° 18’ 00”
11	L11	Henry’s Island	N 21° 34’ 12”E 88° 19’ 12”
12	L12	Henry’s Island	N 21° 34’ 12”E 88° 19’ 48”

Table 4.1: Surface sampling locations from Bakkhali region

The surface sampling results (Figure 4.1) states that the range of the population in the pre-monsoonal (March) month is greater than post-monsoonal (September) abundance in most of the stations. The Total foraminiferal number varies from 20 to 16830 for the pre-monsoonal samples and from 0 to 1280 in the post-monsoonal samples. The western (L2 - L4) and the eastern part (L7 – L12) of the sampling locations have a greater abundance of TFN than the southern part (L5 and L6). This is because the western and eastern fringes of the island are covered with mangrove forests, Patibhunia in the west and Henry’s island in the east. In the southern part of the island lies the Bakkhali beach, which is sandy, devoid of mangrove vegetation and experiences a lot of human interference, thus making it a poor habitat of mangrove foraminifera. Figure 4.2 also shows a similar trend where the abundance of living forms is higher in the pre-monsoonal samples rather than the post-monsoonal samples. These trends can be explained by the fact that during pre-monsoons, there is little influence of fresh water, whereas during post-monsoon times, the rivers drain out the fresh waters into the oceans and the salinity of seawater is reduced. Calcareous foraminifera thrive better in saline waters, so pre-monsoon times are more favourable for them. Another reason is that the reproductive period of foraminifera coincides with the pre-monsoon times. Hence, it is expected that both living foraminiferal populations will be more during this period.

Murray's ternary diagram (Figure 4.3) shows the dominant wall types of the assemblages in the region. Post-monsoon assemblages show slightly more agglutinated population than the pre-monsoon assemblages. This is because post-monsoon samples experience more influence of fresh water than marine water which is not favourable for calcareous forms. Marsh regions on both the eastern and western sides show more agglutinated forms than the other stations.

The Fisher's alpha diversity plot (Figure 4.4) shows the diversity of living foraminifera in the various zones and it is observed that the overall diversity of living foraminifera in the study area is low (< 2), but stations have a good abundance of the forms. Samples from Henry's island have slightly greater diversity (1 – 2) compared to the other locations (<1). This can be explained by the river system surrounding these two areas. The western areas are influenced by river Hooghly which brings in a lot of terrestrial sediments, whereas the eastern part is drained by river Muriganga which has comparatively less terrestrial influence. The overall diversity of this region is low due to more influx of terrestrial sediments in this region.

Figures 4.5 to 4.11 show the variation of the major species, namely; *Ammonia beccarii, Ammonia tepida, Haynesina depressula, Haynesina germainca, Quinqueloculina seminulum, Miliammina fusca* and *Trochammina inflata* in the post-monsoon and the pre-monsoon samplings respectively. *Ammonia beccarii* has good abundance in all stations in the pre-monsoonal samplings, but in the post-monsoonal samplings, it is present only in L2, L3, L4 and L10 (Figure 4.5). *Ammonia tepida* shows a similar trend in having good pre-monsoonal abundance in all the sampling stations but is absent from L1, L5, L7 and L8 in the post-monsoonal sample (Figure 4.6). *Haynesina depressula* and *Haynesina germanica* has good abundance in the pre-monsoonal samples, but H. *depressula* is present only in L6, L10, L11 and L12 in the post-monsoonal samples (Figure 4.7), whereas H. *germanica* is absent from L1, L5, L7, L8 and L9 in the post-monsoonal samples (Figure 4.8). The porcelaneous species *Quinqueloculina seminulum* is completely absent in stations L3, L4 and L5 in both pre- and post-monsoonal samples and present only on L9 and L10 in the post-monsoonal samples (Figure 4.9). Two agglutinated species are prevalent, amongst which, *Miliammina fusca* is present in L4, L8, L9, L10 and L12 in the pre-monsoonal samplings and only in L10 and L12 in the post-monsoonal samplings (Figure 4.10). The other agglutinated species, *Trochammina inflata* is completely absent in the post-monsoonal samples and present only in L2, L3, L4, L10 and L11 in the pre-monsoonal samples (Figure 4.11). The distribution pattern of benthic foraminifera depicts that the marshy regions in the east (Patibhunia marshes) and west (Henry's island marshes) of the study area are comprised mostly of agglutinated forms like *Haplophragmoides canariensis*, *Haplophragmoides wilberti*, *Trochammina inflata* and *Miliammina fusca*. Calcareous forms like *Ammonia tepida*, *Ammonia beccarii*, *Haynesina depressula*, *Haynesina germanica* and *Cribroelphidium poeynum* is mostly observed in the Bakkhlai beach region.

The variations of living foraminifera down the two cores are represented in figure 4.13. Core 1 shows a Type D pattern (Barun K. Sengupta, 2002) where there is a combination of surface (at 1 cm) and one subsurface maximum (9 cm). Core 2 shows a Type C pattern (Barun K. Sengupta, 2002) where there are relatively low values in the first interval(s) and one downcore maxima (at 3 cm). Some of the controlling factors of the vertical distribution patterns are bottom-water oxygenation and food availability. This suggests that the subsurface layers of this region are well oxygenated to sustain live foraminifera. Subsurface sediments are also likely to be nutrient-rich, thus supporting a live population of foraminifera. Figure 4.13 shows the species richness down the two cores. The species richness decreases as we move down the cores. There is one surface and one subsurface maximum (4 cm) for species richness in Core 1 and two subsurface maxima (2 – 4 cm and 8 cm) for species richness in Core 2. Both the cores have good diverse assemblages with a decrease in Core 2 after 10 cm depth of the core. Mostly live specimens of *Ammonia tepida* are found in the downcore maxima.

From Core 1 cluster analysis (Figure 4.15), it is seen that *Haplophragmoides wilberti* and *Ammonia tepida* are found in a clayey substratum, therefore they are clustered as one group (Group A), *Trochammina inflata*, *Haynesina depressula* and *Asterorotalia trispinosa* are found in a silty substratum and are grouped as another group (Group B) and *Ammonia beccarii*, *Haynesina germanica* and *Cribroelpidium hispidulum* are also found in a silty substratum but this group might be having a preference to coarse silt and are clustered as last group (Group C).

From Core 2 cluster analysis (Figure 4.16), it is seen that *Ammonia tepida* and *Haplophragmoides wilberti* are common in clayey substratum and are clustered together as one group (Group A). *Trochammina inflata*, *Cribroelphidium hispidulum*, *Haynesina depressula* and *Haynesina germanica* are common in silty substratum and are grouped as another group (Group B), *Asterorotalia trispinosa* and *Ammonia beccarii* prefers sandy silt and are clustered as last group (Group C).

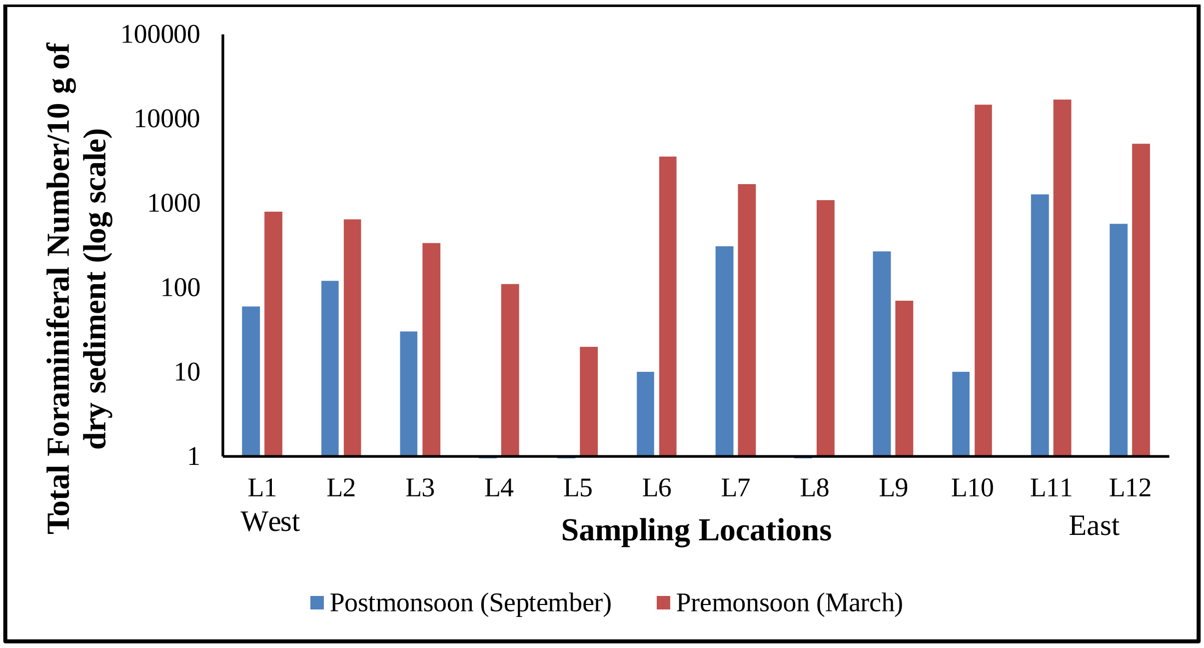


Figure 4.1: Distribution of the Total Foraminiferal Number (live + dead) across the sampling locations

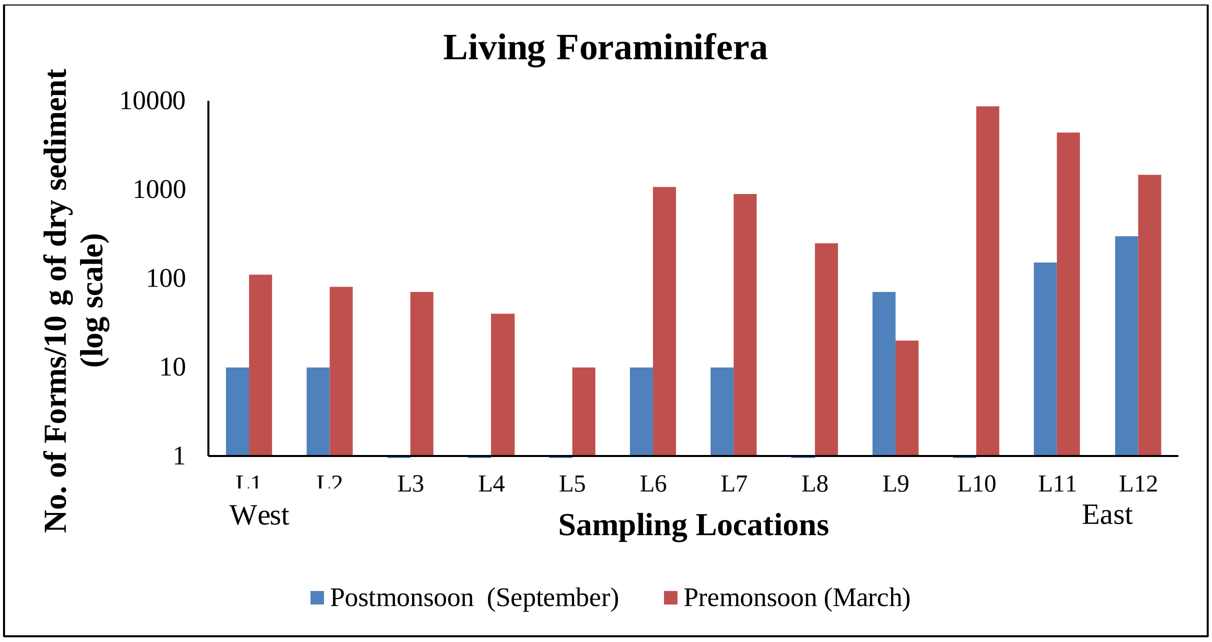


Figure 4.2: Distribution of the living foraminifera across the sampling locations in Bakkhali, West Bengal

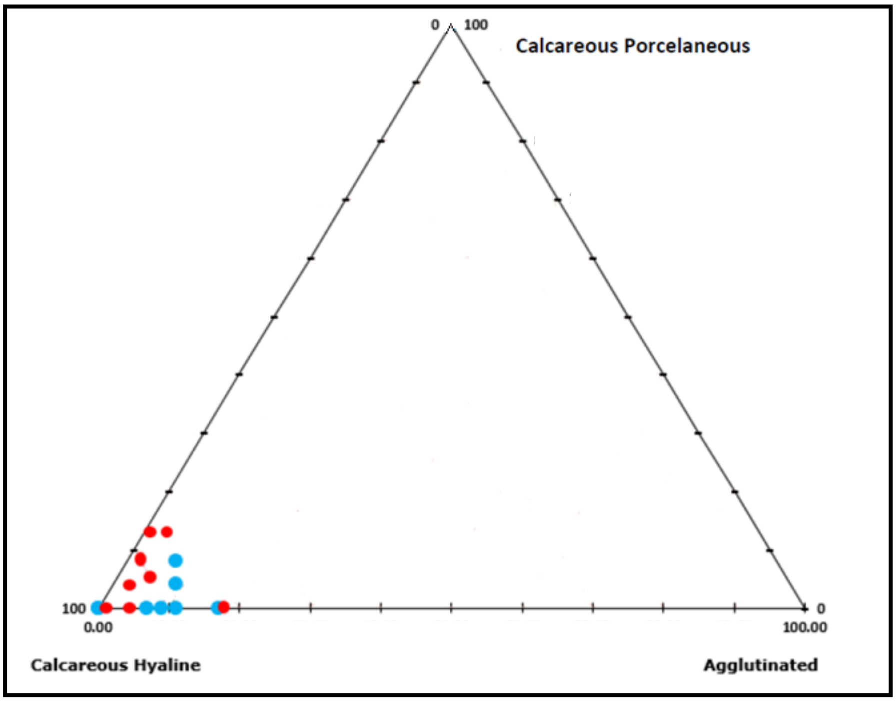


Figure 4.3: Foraminiferal wall structure distribution plot in Bakkhali, West Bengal (red dots – pre-monsoon and blue dots – post-monsoon)

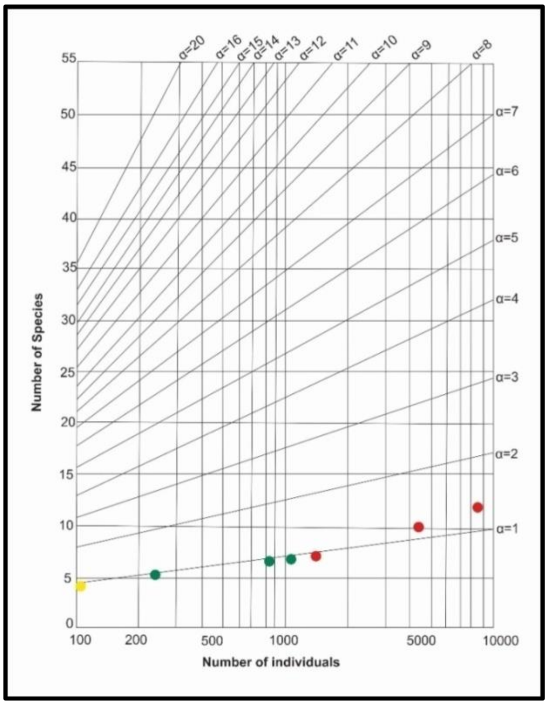


Figure 4.4: Fisher's alpha diversity plot of Bakkhali region during pre-monsoon sampling (yellow dots – Patibhunia, green dots – Bakkhali beach and red dots – Henry's Island)

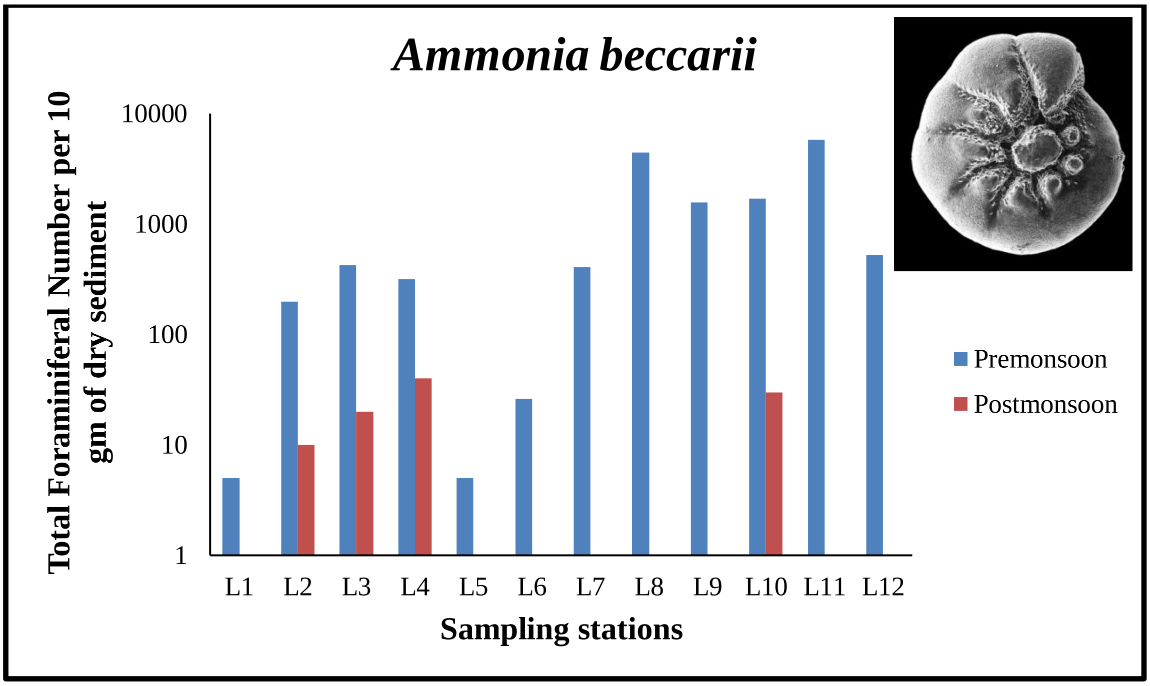


Figure 4.5: Seasonal variation of Ammonia beccarii across the sampling stations

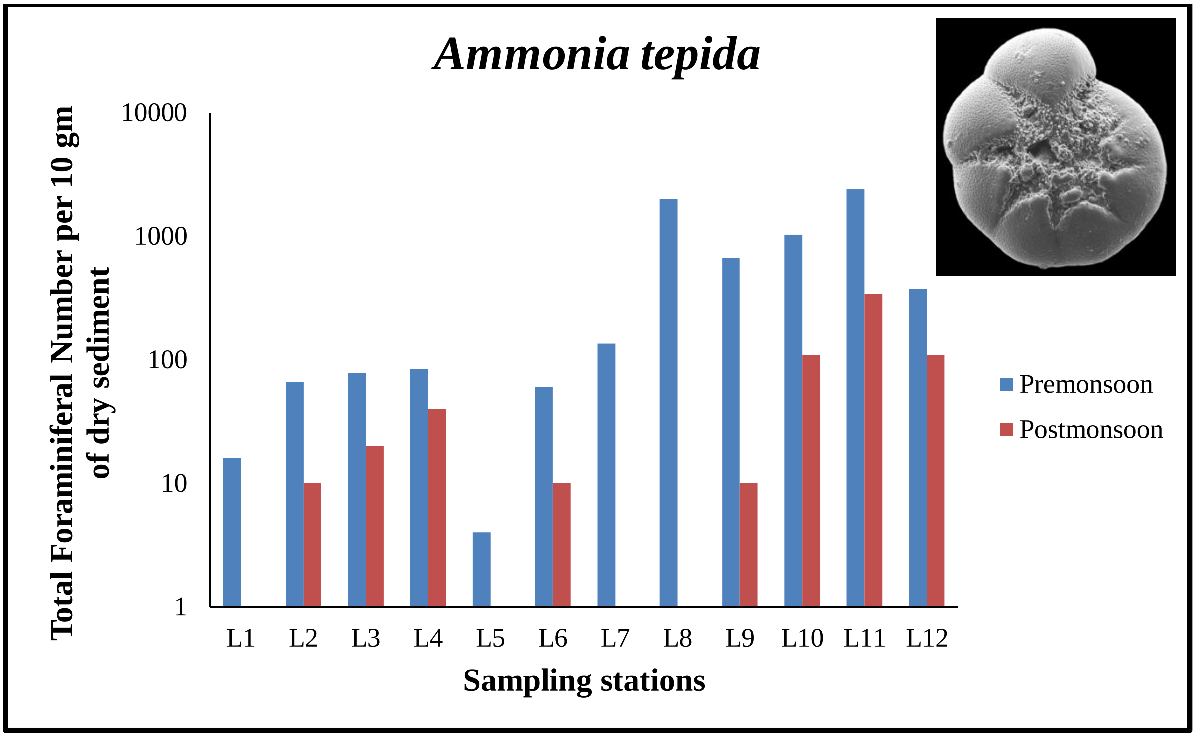


Figure 4.6: Seasonal variation of Ammonia tepida across the sampling stations

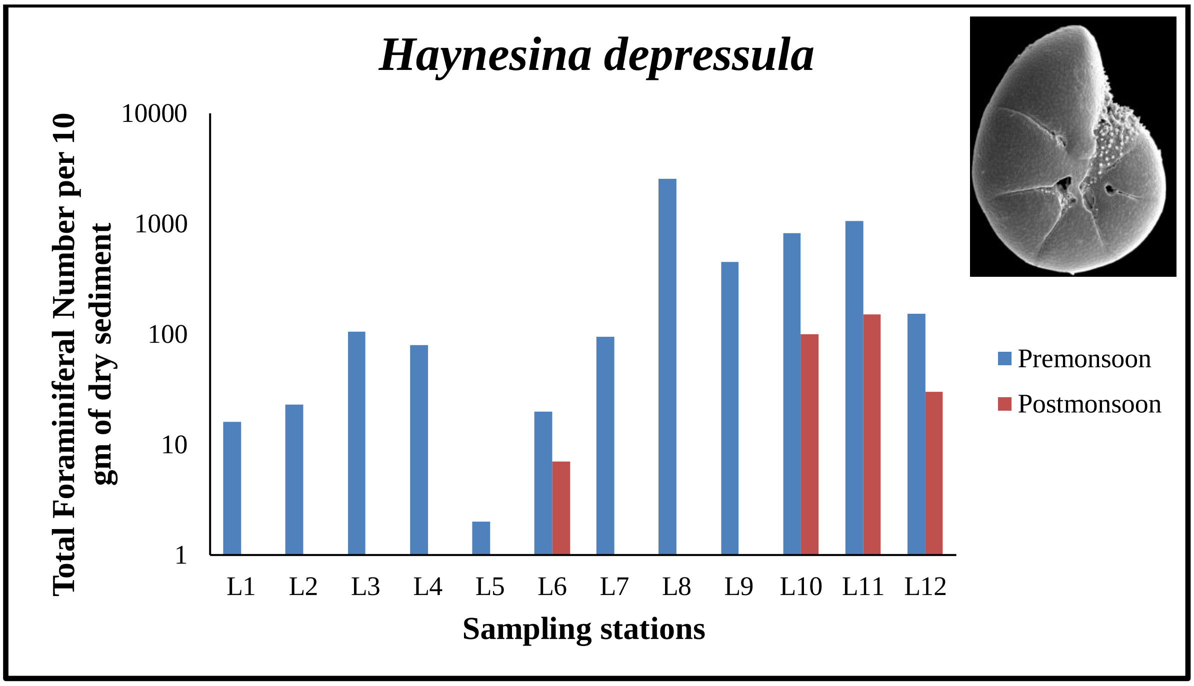


Figure 4.7: Seasonal variation of Haynesina depressula across the sampling stations

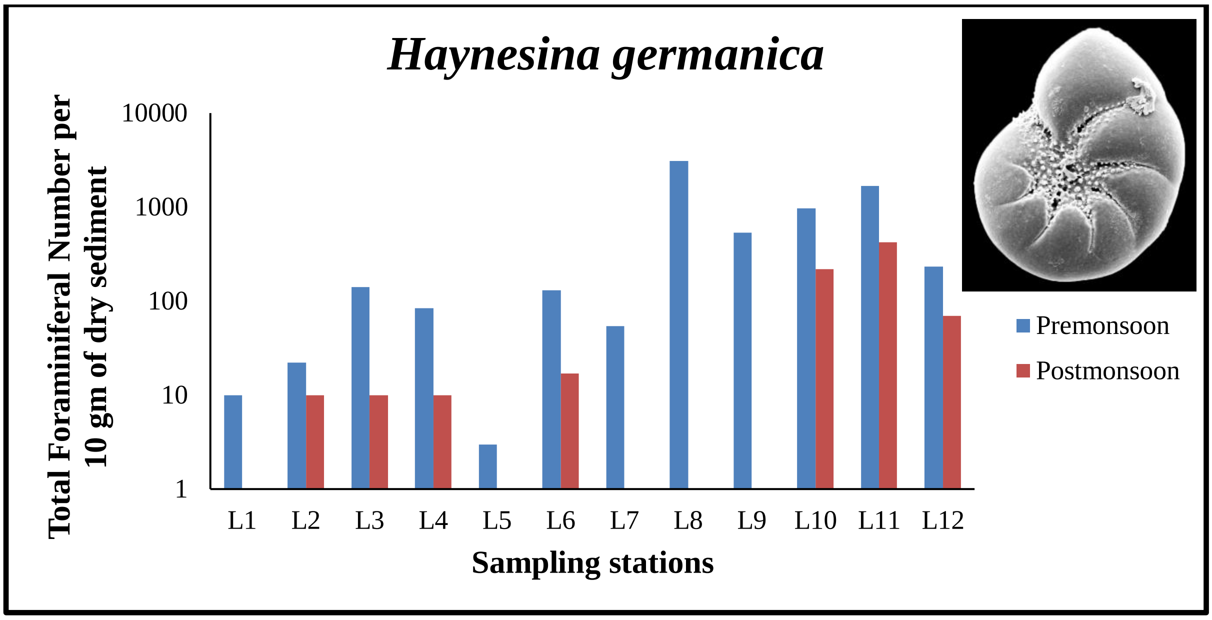


Figure 4.8: Seasonal variation of Haynesina germanica across the sampling stations

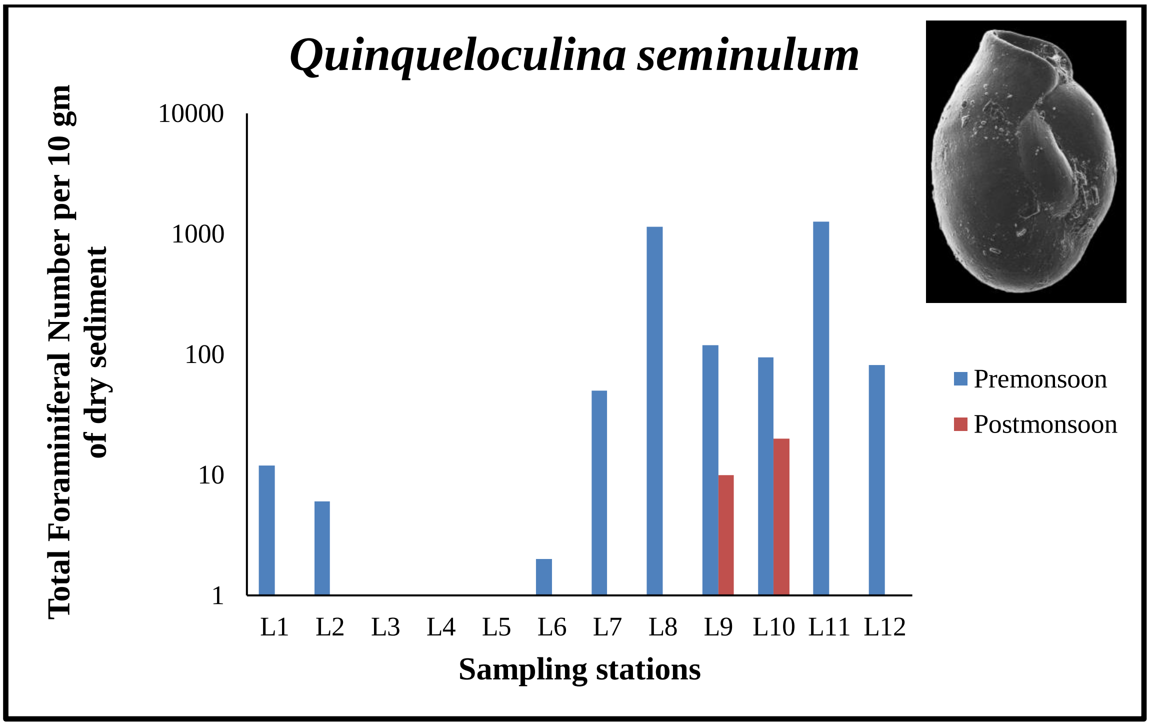


Figure 4.9: Seasonal variation of Quinqueloculina seminulum across the sampling stations

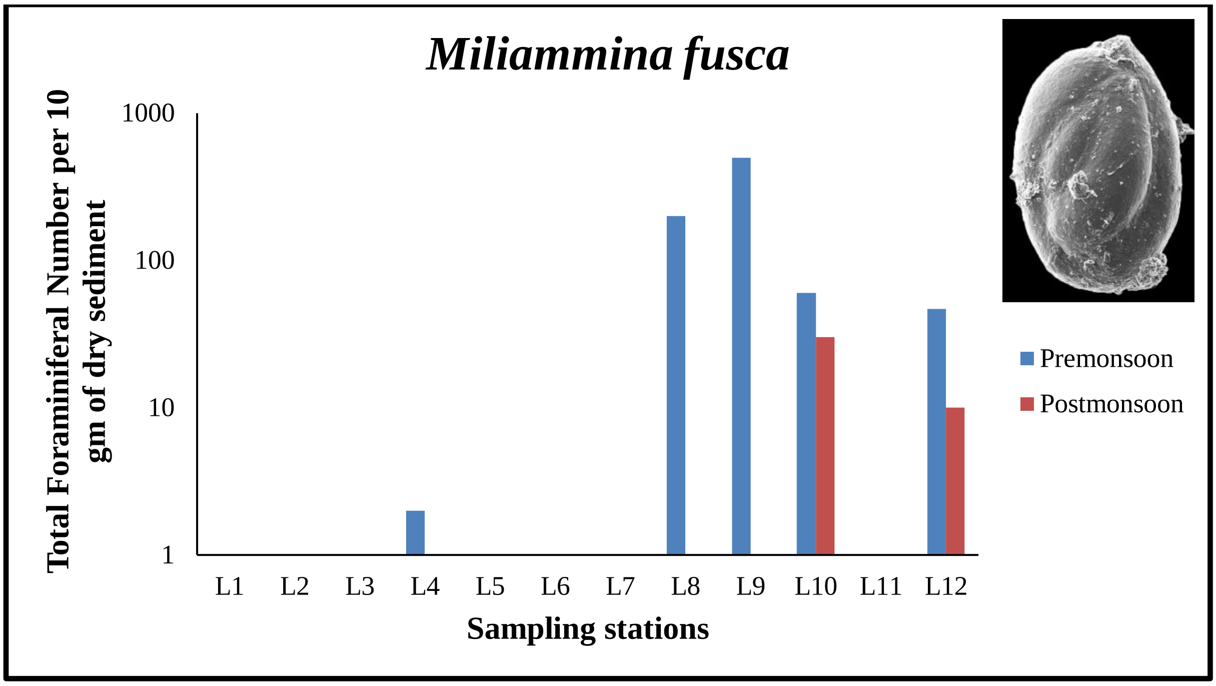


Figure 4.10: Seasonal variation of Miliammina fusca across the sampling stations

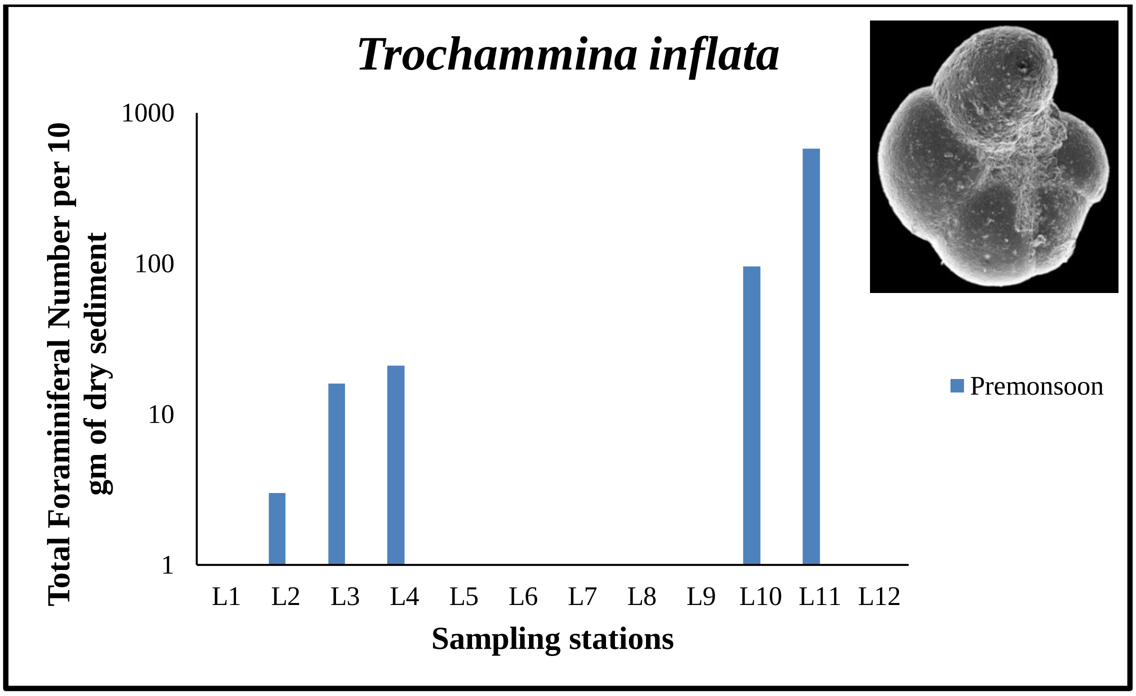


Figure 4.11: Seasonal variation of Trochammina inflata across the sampling stations

4.5 SUBSURFACE DISTRIBUTION OF FORAMINIFERA

Serial Number	Station code	Core Length	Location name	GPS reading
1	C1	16 cm	Patibhunia	N 21° 35’ 24” E 88° 15’ 36”
2	C2	19 cm	Henry’s Island	N 21° 34’ 12” E 88° 18’ 00”

Table 4.2: Core sampling locations from Bakkhali region

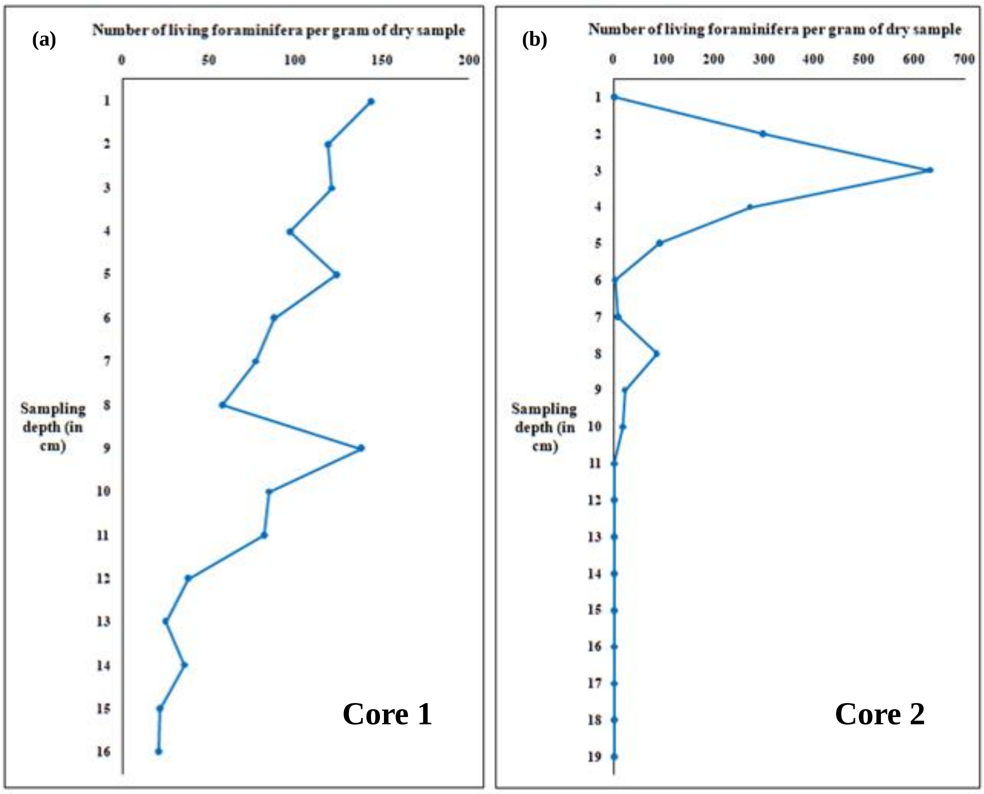


Figure 4.12: Variation in living foraminifera down the cores

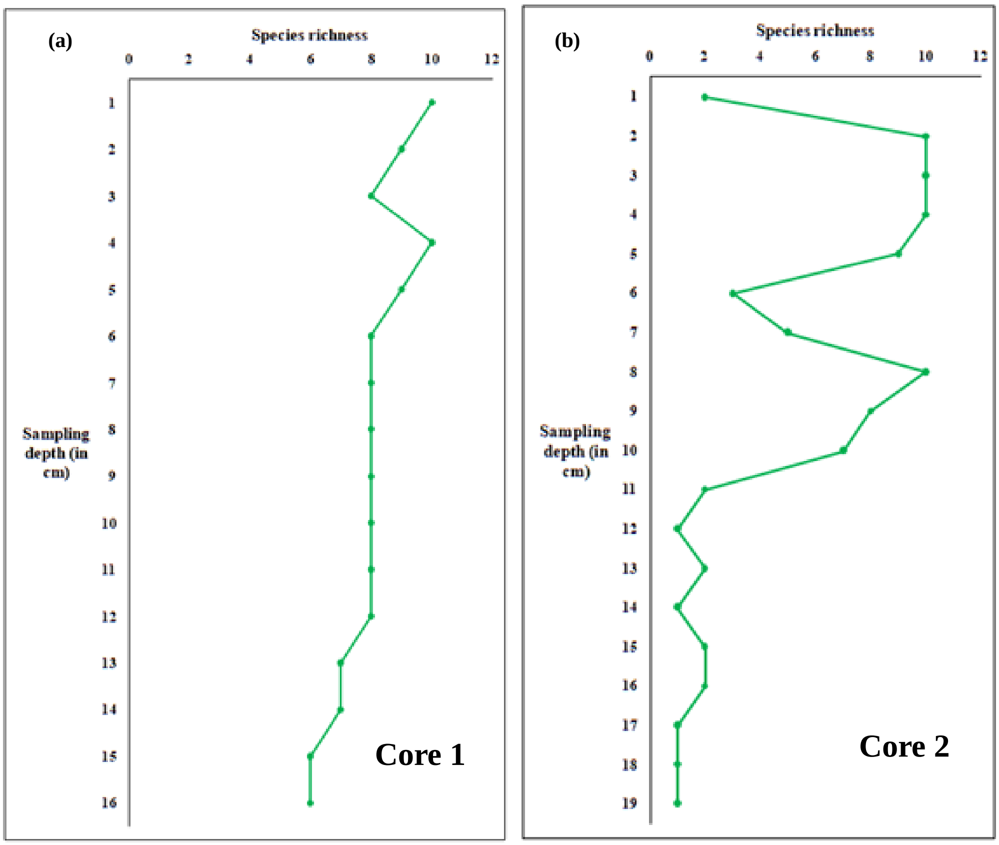


Figure 4.13: Variation in species richness (live + dead) down the cores

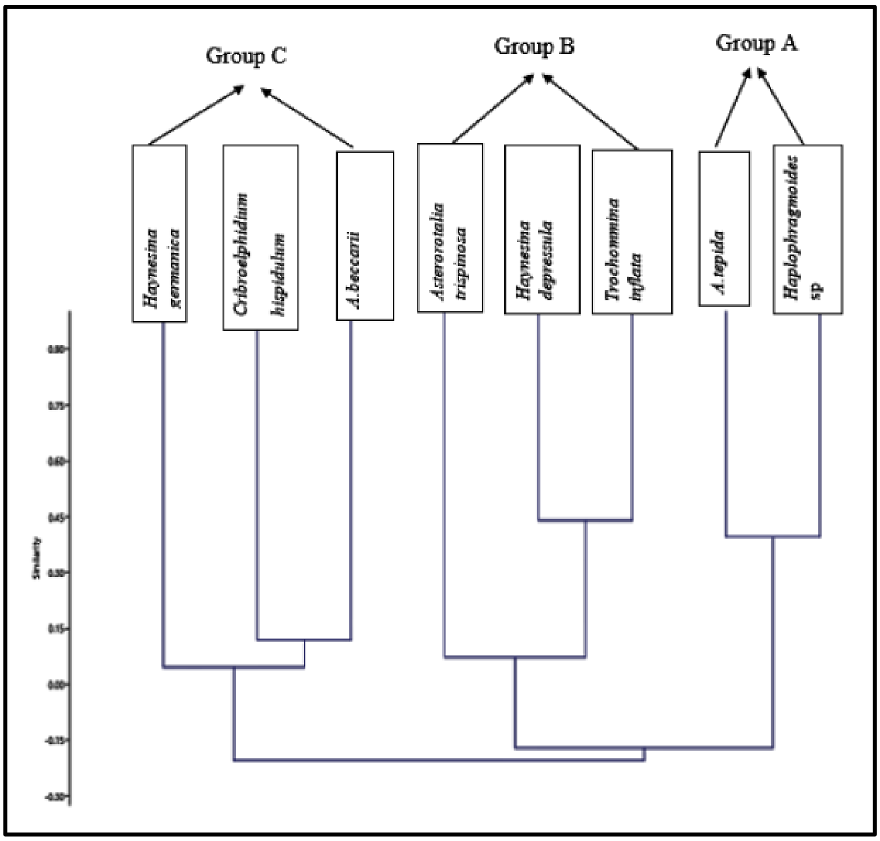


Figure 4.14: Q-mode cluster analysis for Core 1

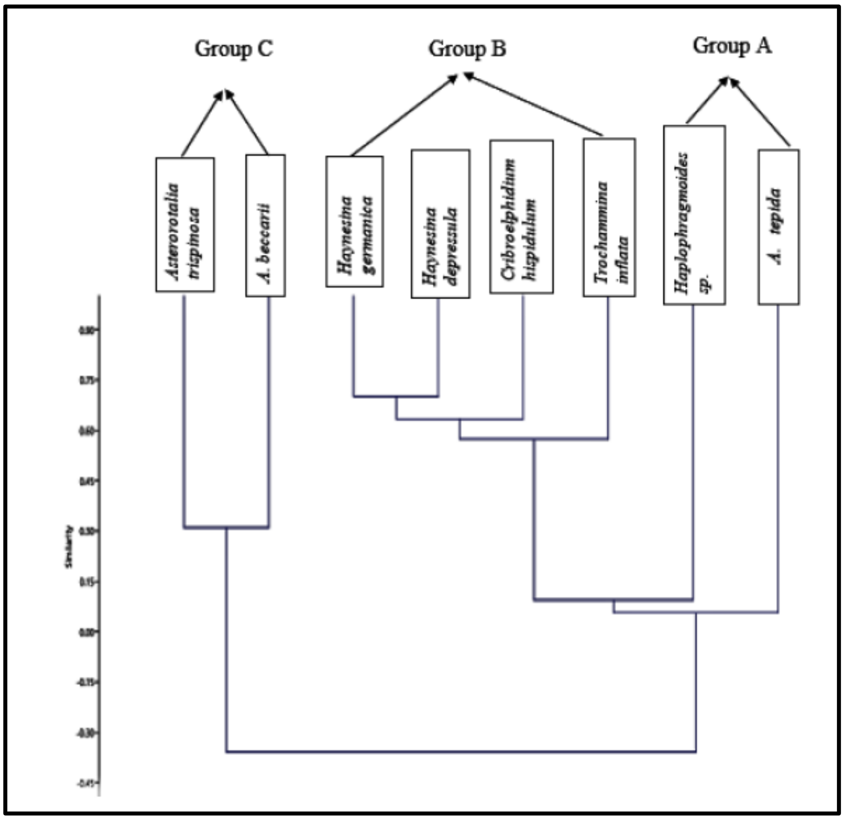


Figure 4.15: Q-mode cluster analysis for Core 2

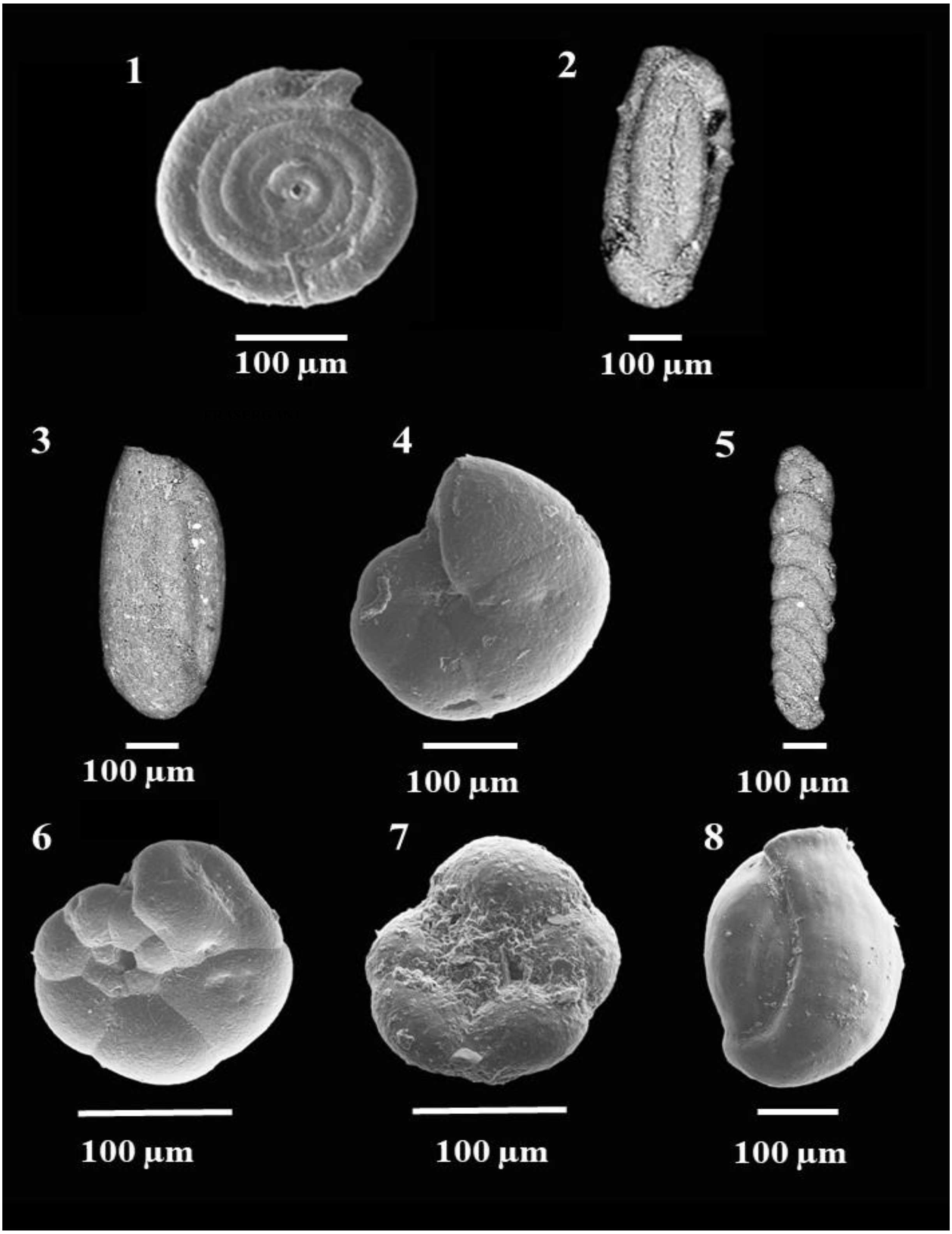


Plate 4.1: 1 – *Ammodiscus evolutus* (U); 2 – *Miliammina fusca* (Si); 3 – *Miliammina petila* (Si); 4 – *Haplophragmoides wilberti*(U); 5 – *Ammotium salsum* (Si); 6 – *Trochammina inflata* (S); 7 – *Trochammina inflata* (U); 8 – *Quinqueloculina seminulum* (Si).

Legends: Si – Side view, U – Umbilical view, S – Spiral view. All scale bars represent 100 µm.

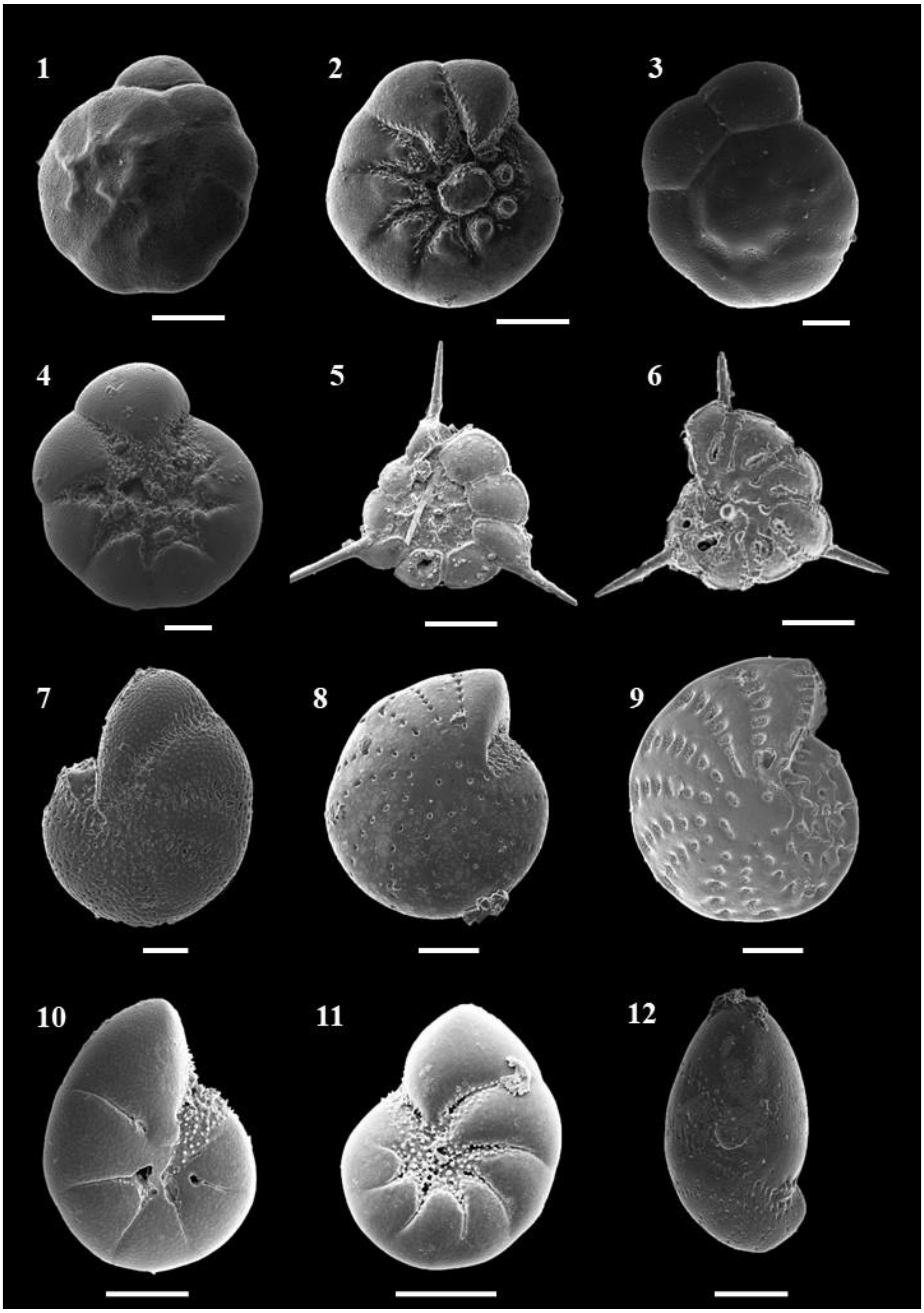


Plate 4.2: 1 – *Ammonia beccarii* (S); 2 – *Ammonia beccarii* (U); 3 – *Ammonia tepida* (S); 4 – *Ammonia tepida (U)*; 5 – *Asterorotalia trispinosa* (S); 6 –*Asterorotalia trispinosa* (U); 7 – *Cribroelphidium decipiens* (U); 8 – *Cribroelphidium poeynum* (U); 9 – *Elphidium advenum* (U); 10 – *Haynesina depressula* (U); 11 – *Haynesina germanica* (U); 12 - *Nonionella turgida* (Si).

Legends: Si – Side view, U – Umbilical view, S – Spiral view. All scale bars represent 100 µm.

5.1 INTRODUCTION

The Chandipur coast constitutes one of the most dynamic parts of India's coastline. It is continuously undergoing both sudden and gradual changes (physical processes), resulting in varied and geomorphic features. Both long term and short-term processes bring about some changes that involve hydrodynamic, geomorphic tectonic and climatic forces operating in the area. There are several environmental types in this short stretch comprising of a beach, tidal flat, swamp, bar and aeolian dunes. The Chandipur marshland is a swampy land adjoining the distal bar. It is a wetland, occurring along shores and dependent upon the natural water level fluctuation. The marshland is present on the landward side of the bar. It hosts a small amount of mangrove vegetation and characteristic marsh foraminiferal assemblages.

5.2 FORAMINIFERAL ASSEMBLAGES

A total of fourteen foraminiferal species have been recorded, the lowest amongst the entire study area. Calcareous hyaline forms include *Ammonia beccarii*, *Ammonia tepida*, Asterorotalia *trispinosa*, *Elphidium advenum*, *Elphidium excavatum*, *Cribroelphidium poeynum*, *Haynesina depressula*, *Haynesina germanica* and *Nonionella turgida*. The only porcelaneous form present is *Quinqueloculina seminulum* and two agglutinated forms are present, namely; *Trochammina inflata* and *Haplophragmoides canariensis.*

5.3 SYSTEMATICS

Phylum: Foraminifera d'Orbigny, 1826

Class: Globothalamea Pawlowski, Holzmann & Tyszka, 2013

Subclass: Textulariana Mikhalevich, 1980

Order: Lituolida Blainville, 1827

Suborder: Trochamminina Saidova, 1981

Superfamily: Trochamminoidea Schwager, 1877

Family: Trochamminidae Schwager, 1877

Genus: *Trochammina* Parker & Jones, 1859

Trochammina inflata Montagu, 1808

(Plate 5, Figures 14 and 15)

Remarks: This species is found mostly near the swampy regions and is entirely absent in the tidal flat region.

Suborder: Lituolina Lankester, 1885

Family: Haplophragmoididae Maync, 1952

Genus: *Haplophragmoides* Cushman, 1910

Haplophragmoides canariensis d'Orbigny, 1839

(Plate 5, Figure 16)

Remarks: This is another agglutinated species which is observed only in the swamp.

Class: Tubothalamea Pawlowski, Holzmann & Tyszka, 2013

Order: Miliolida Delage & Hérouard, 1896

Family: Hauerinidae Schwager, 1876

Subfamily: Haueininae Schwager, 1876

Genus: *Quinqueloculina* d'Orbigny, 1826

Quinqueloculina seminulum Linnaeus, 1758

(Plate 5, Figure 13)

Remarks: This species is found in all three sub environments of Chandipur, i.e., tidal flat, estuary mouth and swamps.

Class: Globothalamea Pawlowski, Holzmann & Tyszka, 2013

Subclass: Rotaliana Mikhalevich, 1980

Order: Rotaliida Delage & Hérouard, 1896

Superfamily: Rotalioidea Ehrenberg, 1839

Family: Ammoniidae Saidova, 1981

Subfamily: Ammoniinae Saidova, 1981

Genus: *Ammonia* Brünnich, 1771

Ammonia beccarii Linnaeus, 1758

(Plate 5, Figures 1 and 2)

Remarks: This species is dominant in the tidal flat area and have minor occurrences in the estuarine mouth area and the swampy regions.

Ammonia tepida Cushman, 1926

(Plate 5, Figures 3 and 4)

Remarks: This species is abundant in all the sub environments, the swamps, tidal flat and the estuarine mouth.

Genus: *Asterorotalia* Hofker, 1950

Asterorotalia trispinosa Thalmann, 1933

(Plate 5, Figures 5 and 6)

Remarks: This is a unique species reported only from the east coast of India. It is reported from the tidal flat region mainly and has minor occurrences in the swamps and estuarine mouth region.

Family: Elphidiidae Galloway, 1933

Subfamily: Elphidiinae Galloway, 1933

Genus: *Cribroelphidium* Cushman and Brönnimann, 1948

Cribroelphidium poeynum

(*Polystomella poeyana* d'Orbigny, 1839)

(Plate 5, Figure 7)

Remarks: This is also an abundant species, found from all the three sub environments; the tidal flat, the estuarine mouth and the swamps.

Genus: *Elphidium* Montfort, 1808

Elphidium advenum Cushman, 1922

(Plate 5, Figure 8)

Remarks: This species is reported mainly from the estuary mouth region.

Elphidium excavatum Terquem, 1875

(Plate 5, Figure 9)

Remarks: This species is observed in the estuary mouth region and the tidal flat region.

Family: Haynesinidae Mikhalevich, 2013

Genus: *Haynesina* Banner & Culver, 1978

Haynesina depressula Walker & Jacob, 1798

(Plate 5, Figure 10)

Remarks: This is found abundantly in all the sub environments, i.e., swamp, estuarine mouth and the tidal flat region.

Haynesina germanica Ehrenberg, 1840

(Plate 5, Figure 11)

Remarks: This species is also prevalent in all the sub environments; tidal flat, swamp and the estuarine mouth region.

Superfamily: Nonionoidea Schultze, 1854

Family: Nonionidae Schultze, 1854

Subfamily: Nonioninae Schultze, 1854

Genus: *Nonionella* Cushman, 1926

Nonionella turgida Williamson, 1858

(Plate 5, Figure 12)

Remarks: This species is found mostly in the tidal flat region.

5.4 MODERN SURFICIAL DISTRIBUTION OF FORAMINIFERA

Serial Number	Station code	Environment	GPS co-ordinates
1	S1	Mudflat	N 21° 27’ 36” E 87° 03’ 36”
2	S2	Mudflat	N 21° 27’ 36” E 87° 04’ 12”
3	S3	Estuary mouth – Southern side	N 21° 28’ 12” E 87° 03’ 36”
4	S4	Estuary mouth	N 21° 28’ 12” E 87° 04’ 12”

5	S5	Tidal creek (Marshy region)	N 21° 28’ 12” E 87° 03’ 00”
6	S6	Inner channel	N 21° 27’ 36” E 87° 03’ 00”
7	S7	Tidal flat	N 21° 27’ 00” E 87° 03’ 00”
8	S8	Back Swamp (Marshy region)	N 21° 27’ 36” E 87° 00’ 36”

Table 5.1: Surface sampling locations from Chandipur region

Total Foraminiferal Number (Figure 5.1) shows high abundance in all environments during the pre-monsoonal sampling (March) season, whereas low abundance is found in some of the sampling stations, namely; S1, S2, S7 and S8 in the post-monsoonal sampling season (September). A similar trend is also observed in the living foraminifera graph (Figure 5.2), where the number of living foraminifera is much more in the pre-monsoonal sampling season (March) than in the post-monsoonal season (September). There is a good abundance of living populations in all stations of the pre-monsoonal samples, but S2, S6, S7 and S8 shows a low abundance of foraminifera in the post-monsoonal samples. Murray’s ternary plot (Figure 5.3) shows that the assemblage is mostly hyaline (almost 95%) with very few agglutinated and porcelaneous members. Location S5 has a higher amount of agglutinated foraminifera than the rest of the stations. Fisher’s alpha plot (Figure 5.4) shows a low diversity where the diversity value ranges in between 1 to 3 for both pre- and post-monsoon samplings. Figure 5.5 to 5.11 shows the species variations in the post-monsoon and the pre-monsoon sampling seasons, respectively. Calcareous species are mostly present in the tidal flat region and the marshy regions contain mostly the agglutinated forms.

Figures 5.5 to 5.12 show the seasonal variation of the dominant forms in the study area. *Ammonia beccarii* (Figure 5.5) and *Ammonia tepida* (Figure 5.6) has a good abundance in almost all stations during the pre-monsoonal and post-monsoonal samples, except station S6, which shows an absence of these two species in the post-monsoonal samples. *Asterorotalia trispinosa* is present in almost all stations except S2 in the pre-monsoonal samples and S6 in the post-monsoonal samples (Figure 5.7). *Elphidium advenum* is absent from S8 in the pre-monsoon sample and from S2, S6 and S7 from the post-monsoonal sample (Figure 5.8). *Haynesina depressula* (Figure 5.9) and *Haynesina germanica* (Figure 5.10) is present in all locations in the pre-monsoonal samples, but H. *depressula* is absent in S3, S4 and S6 in the post-monsoon samples, whereas H. *germanica* is absent in S6 in the post-monsoonal samples.

The agglutinated form *Trochammina inflata* is completely absent in S3 and present only in S5 in the post-monsoonal samples (Figure 5.11). The porcelaneous *Quinqueloculina seminulum* is completely absent from S3 and S4. It is present in S2, S5, S6, S7 and S8 in the pre-monsoonal samples and in S1, S2, S5 and S8 in the post-monsoonal samples (Figure 5.12).

Figure 5.13 shows the downcore variation of different foraminiferal orders, namely; rotalids, miliolids and textularids. Miliolids and textularids are quite less in number. Rotalids decrease in abundance down the first core but increases in abundance in the remaining cores. Figure 5.14 shows the subsurface distribution of living foraminifera. All the cores show subsurface maxima. Core 1 shows a Type D pattern (Sengupta, 2002) where there is a combination of surface and subsurface maxima. Core 2 and 3 shows a Type C pattern (Barun K. Sengupta, 2002) where there are relatively low values in the first interval(s) and one or more downcore maxima. The living forms found at the deeper levels are of *Ammonia tepida*. Figure 5.15 shows the species richness down the three cores. Core 1 has one surface and one subsurface maximum (at 8 cm), Core 2 has one subsurface maximum (at 3 cm) and Core 3 has two subsurface maxima (at 4 cm and 7 cm). The cross plot of Shannon-Weiner index and Fisher's alpha index (Figure 5.16) shows two distinct clusters, the upper cluster is represented by the upper part of the core (from 1 to 10 cm) and the lower part of the core (11 to 20 cm) is a clear indication of a change in environment from brackish marginal marine to normal marine conditions (Murray, 2006).

Figure 5.17 shows the R-mode cluster analysis for the three different cores. The cluster analysis for Core 1 shows two distinct clusters and three single stocks. The cluster containing *Ammonia beccarii* and *Asterorotalia trispinosa* corresponds to the coarser sediments, whereas the cluster containing *Ammonia tepida*, *Haynesina depressula* and *Haynesina germanica* corresponds to the finer fraction of the sediments. For the Core 2, three different clusters have been observed; one cluster containing of *Ammonia tepida* and *Ammonia beccarii*, representing the silty fraction of the sediment; the second cluster contains *Asterorotalia trispinosa* and *Ammonia beccarii* representing the coarser fraction of the sediment and the third cluster consists of the forms *Quinqueloculina seminulum* and *Trochammina inflata* which represents the silty fraction of the sediment. For Core 3, again, two distinct clusters are observable, out of which the cluster containing *Ammonia tepida* and *Haynesina germanica* can be the representative of a finer substrate and the other cluster consisting of *Ammonia dentata*, *Asterorotalia trispinosa* and *Ammonia beccarii* represents the coarser fraction of the sediments.

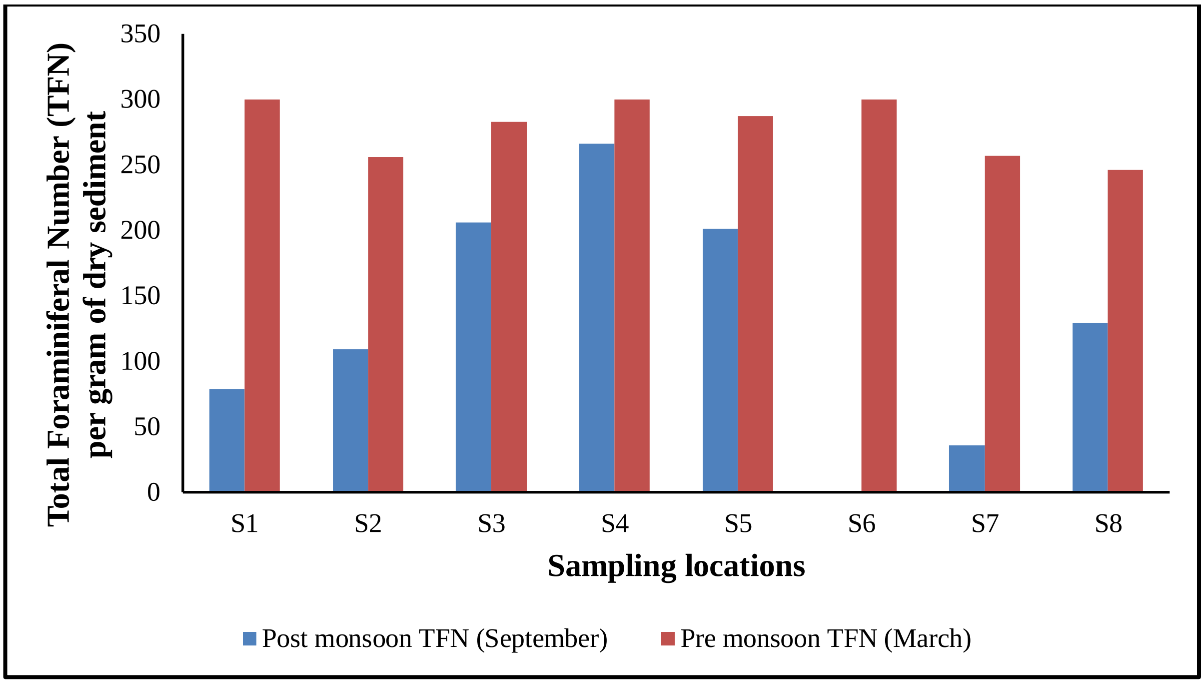


Figure 5.1: Distribution of the Total Foraminiferal Number (live + dead) across the sampling locations in Chandipur, Odisha

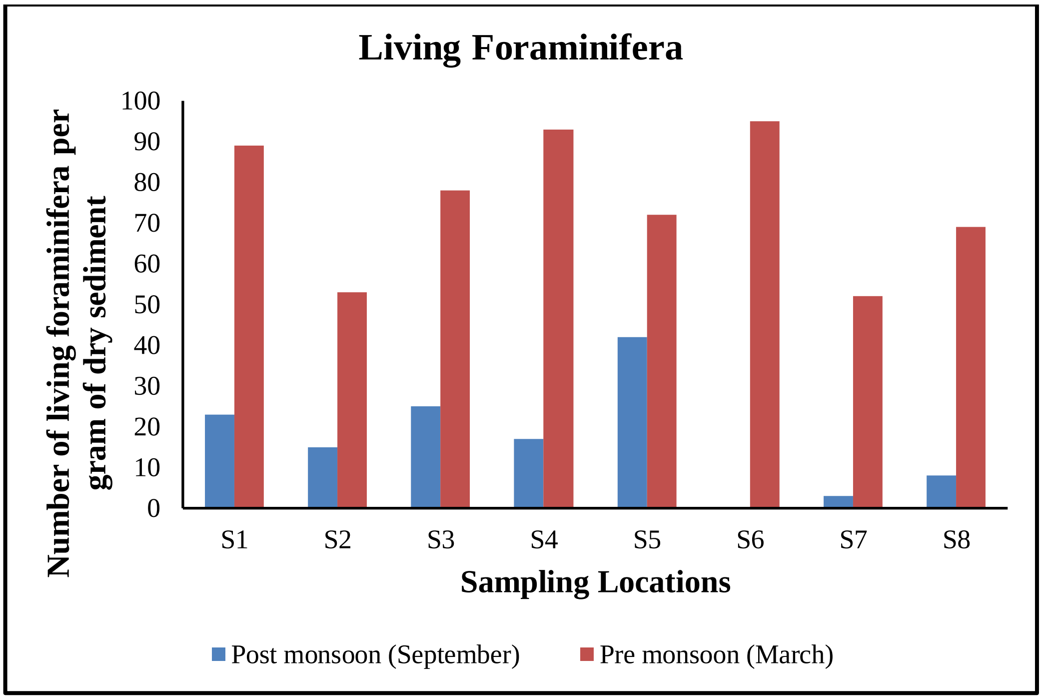


Figure 5.2: Distribution of living foraminifera across the sampling locations in Chandipur, Odisha

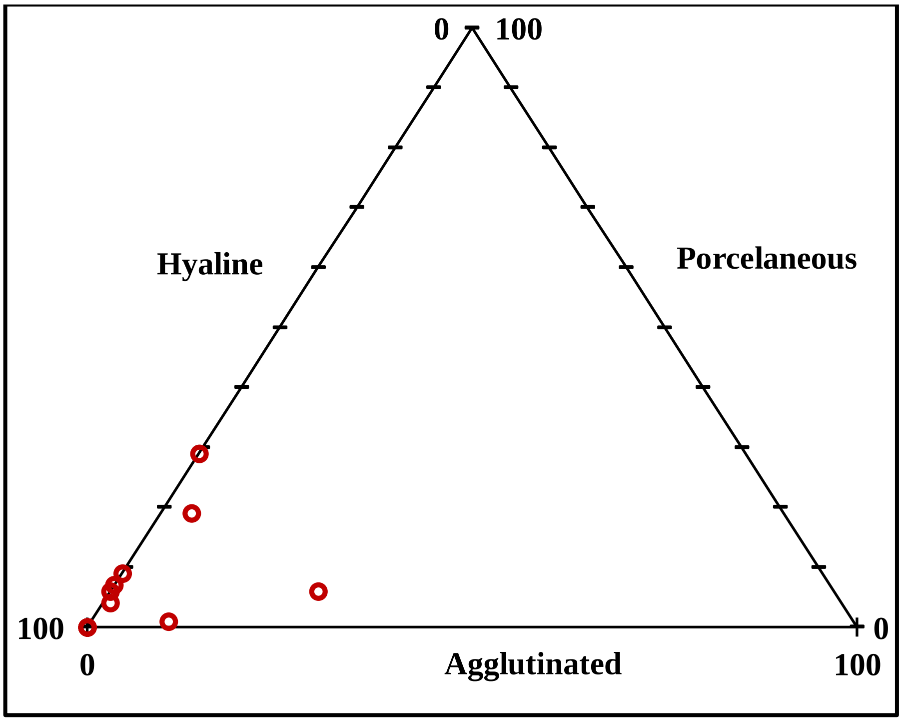


Figure 5.3: Foraminiferal wall structure distribution plot in Chandipur, Odisha

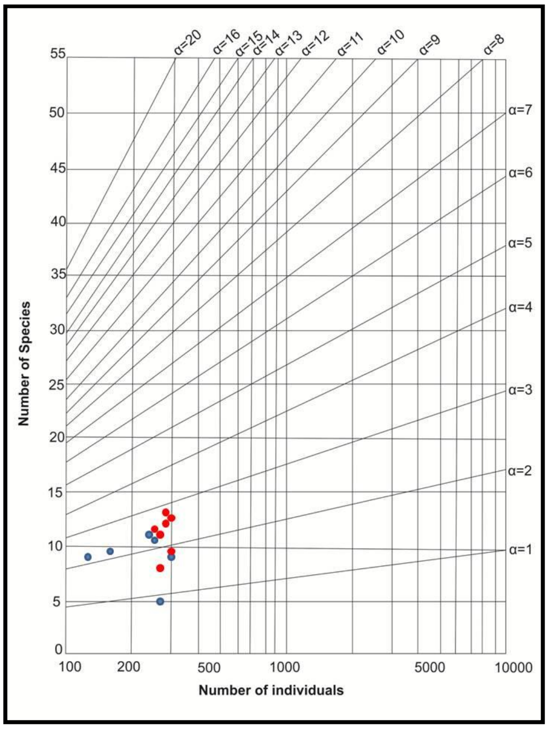


Figure 5.4: Fisher's alpha diversity plot of pre-monsoon (marked in red) and post-monsoon (marked in blue) samplings

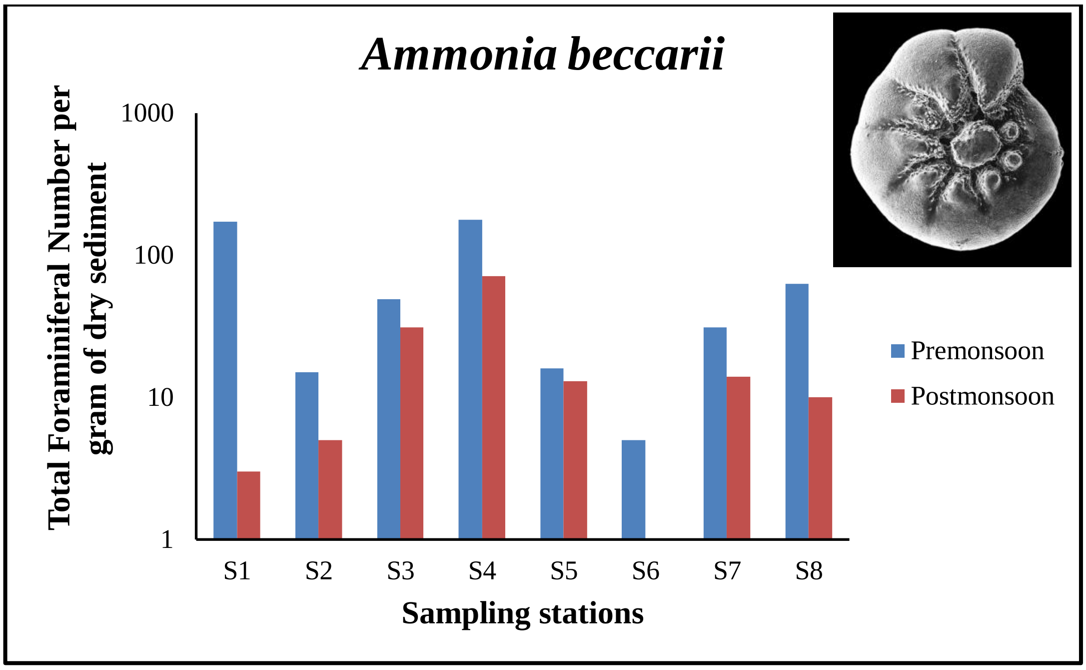


Figure 5.5: Seasonal variation of Ammonia beccarii across the sampling stations

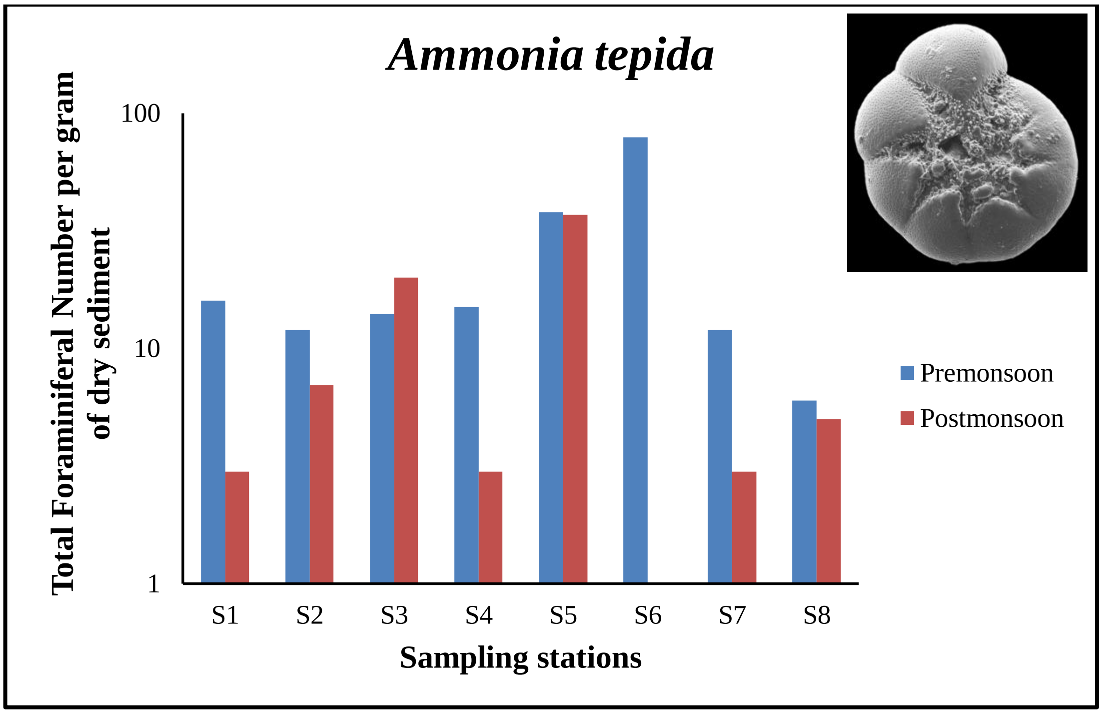


Figure 5.6: Seasonal variation of Ammonia tepida across the sampling stations

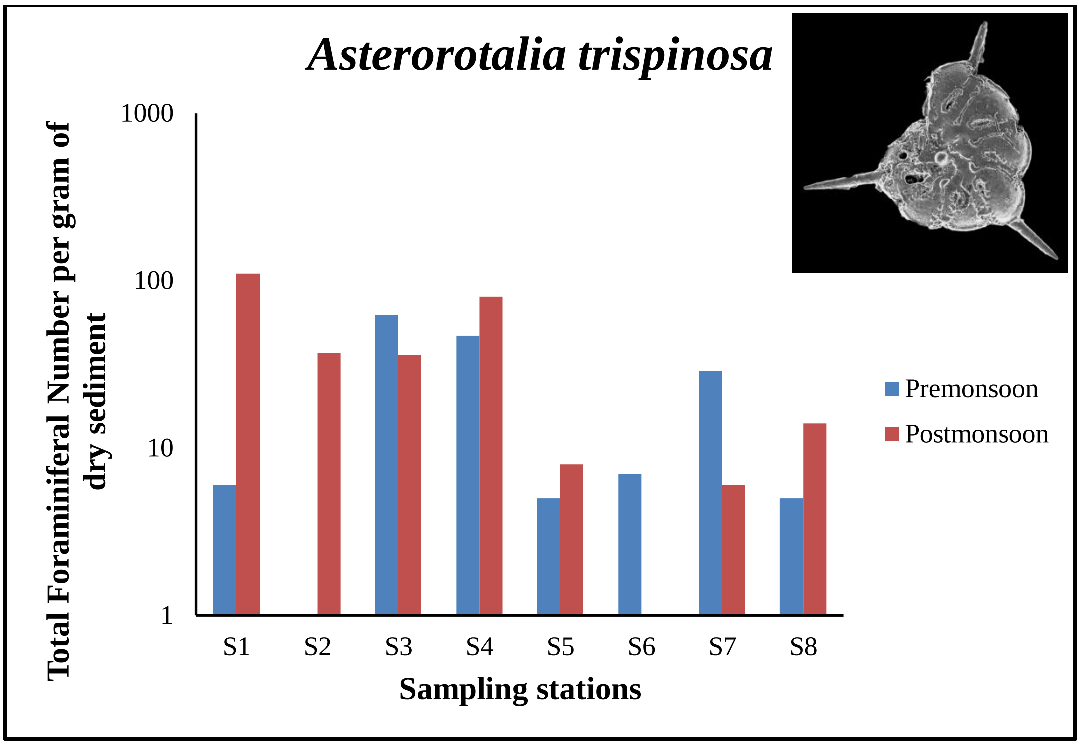


Figure 5.7: Seasonal variation of Asterorotalia trispinosa across the sampling stations

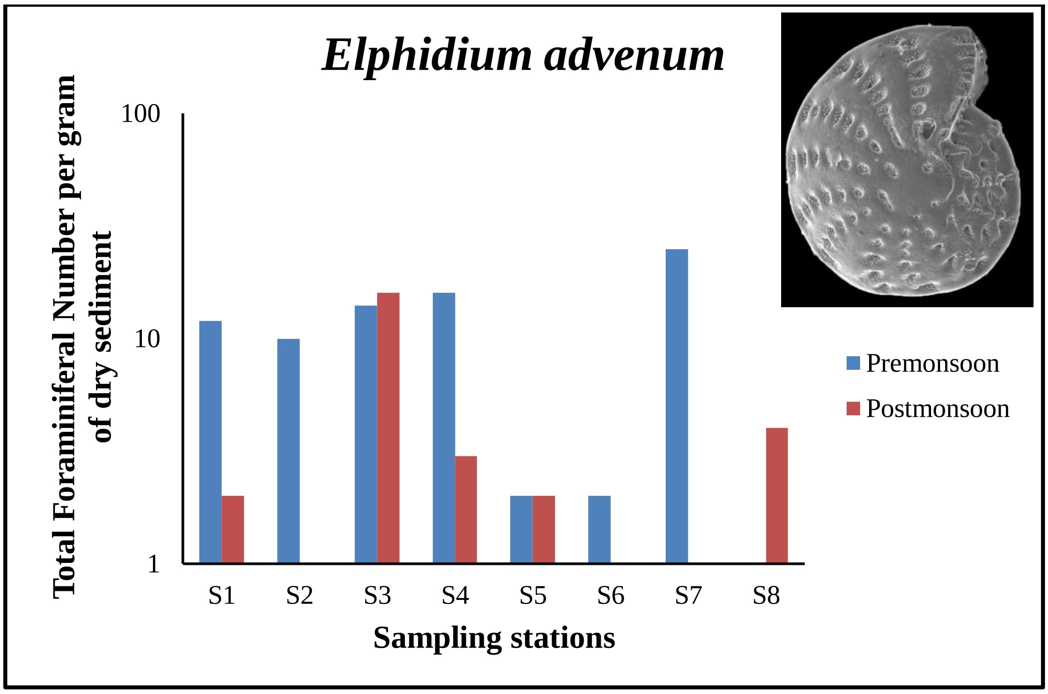


Figure 5.8: Seasonal variation of Elphidium advenum across the sampling stations

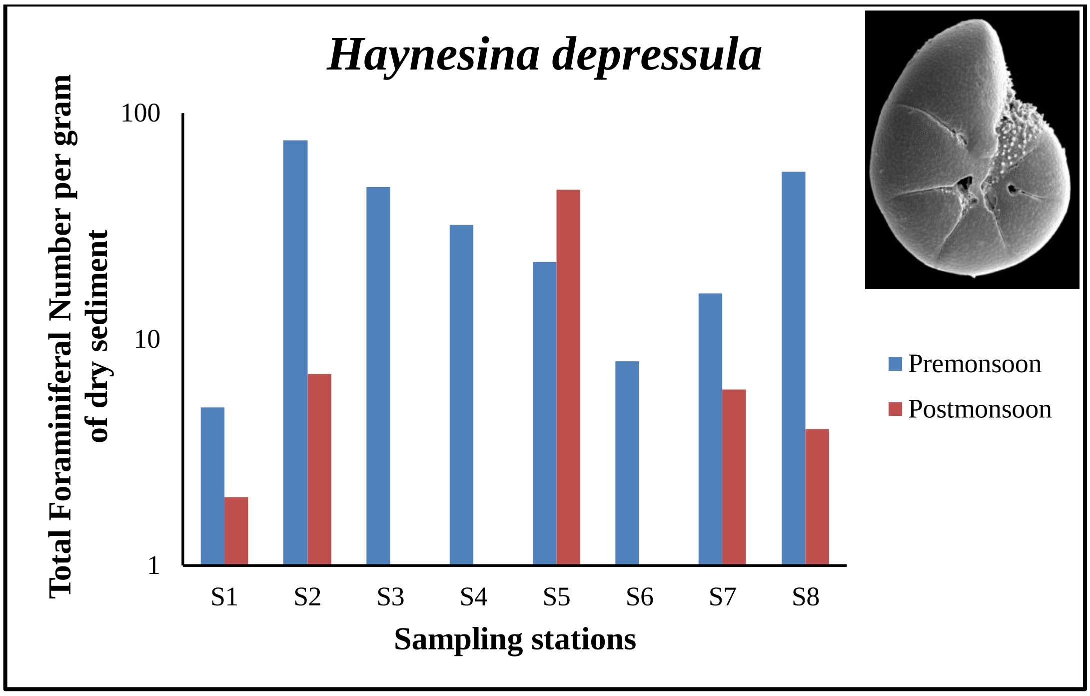


Figure 5.9: Seasonal variation of Haynesina depressula across the sampling stations

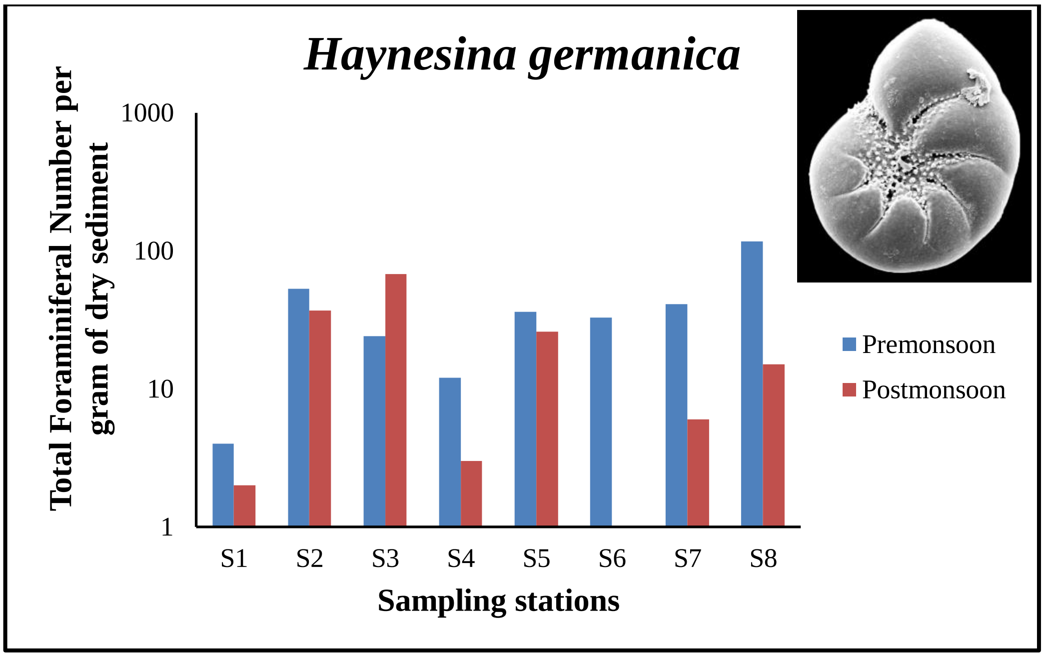


Figure 5.10: Seasonal variation of Haynesina germanica across the sampling stations

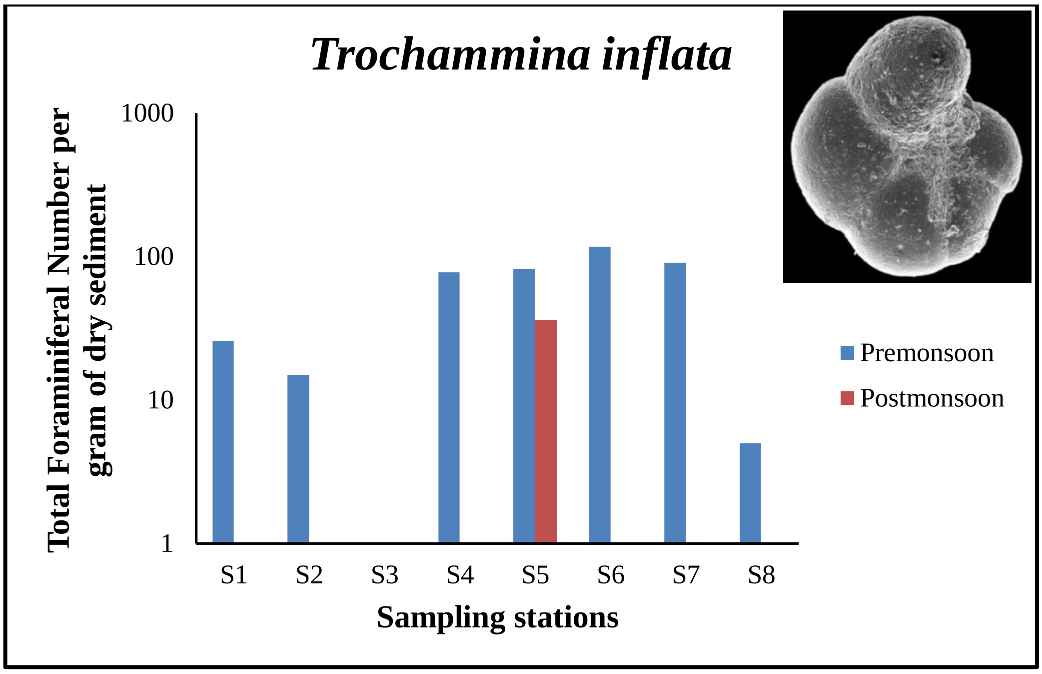


Figure 5.11: Seasonal variation of Trochammina inflata across the sampling stations

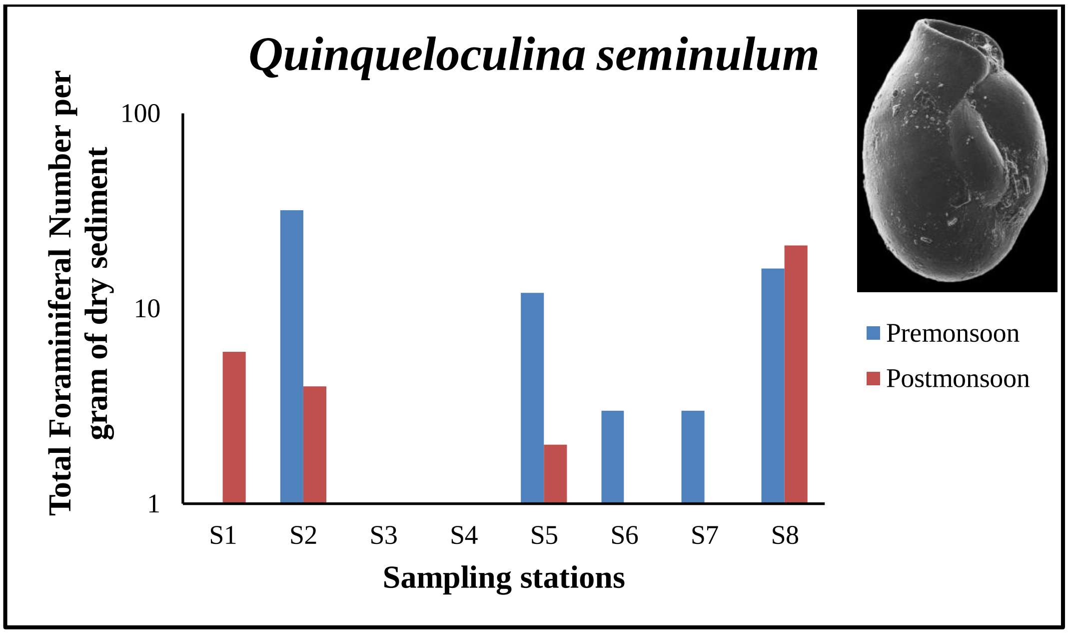


Figure 5.12: Seasonal variation of Quinqueloculina seminulum across the sampling stations

5.5 SUBSURFACE DISTRIBUTION OF FORAMINIFERA

Serial Number	Station code	Location name	GPS reading
1	C1	Chandipur Mudflat	N 21° 27' 36" E 87° 03' 36"
2	C2	Chandipur Swamp	N 21° 28' 12" E 87° 03' 36"
3	C3	Chandipur Tidal Flat	N 21° 27' 00" E 87° 03' 00"

Table 5.2: Core sampling locations from Chandipur region

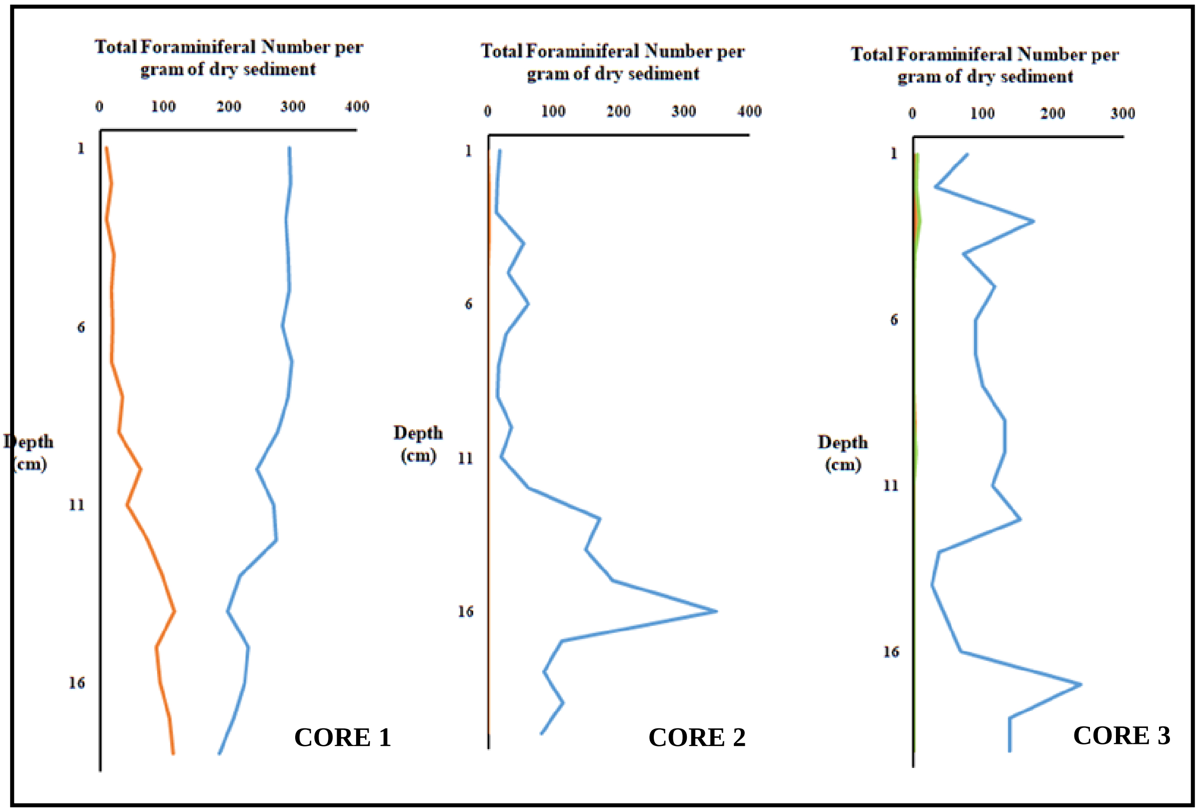


Figure 5.13: Down-core variation of the different orders of foraminifera (orange line indicates miliolids, blue line rotalids and green line textularids)

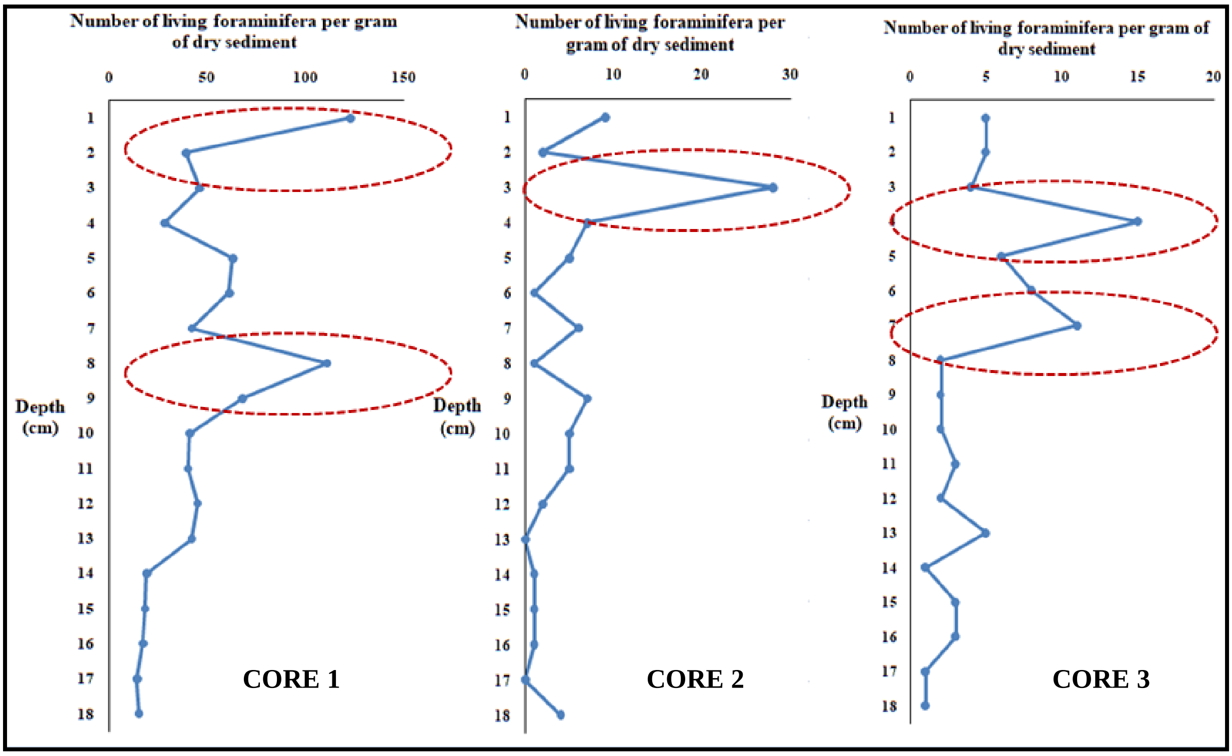


Figure 5.14: Variation in living foraminifera down the cores

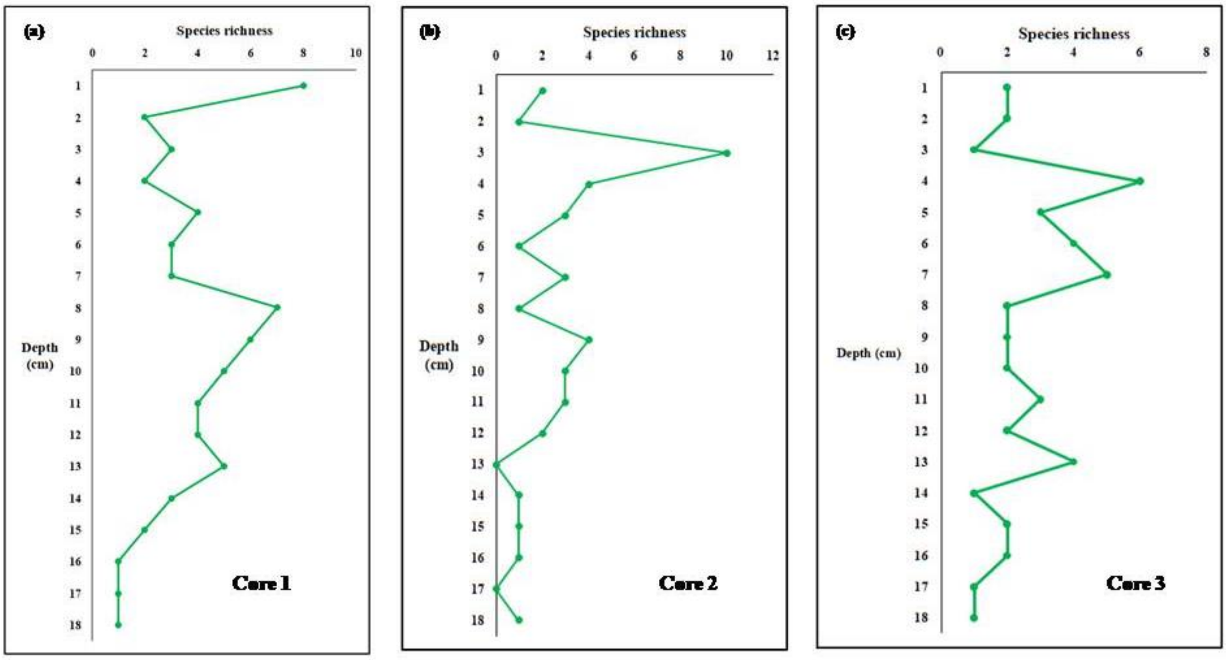


Figure 5.15: Variation in species richness (live + dead) down the cores

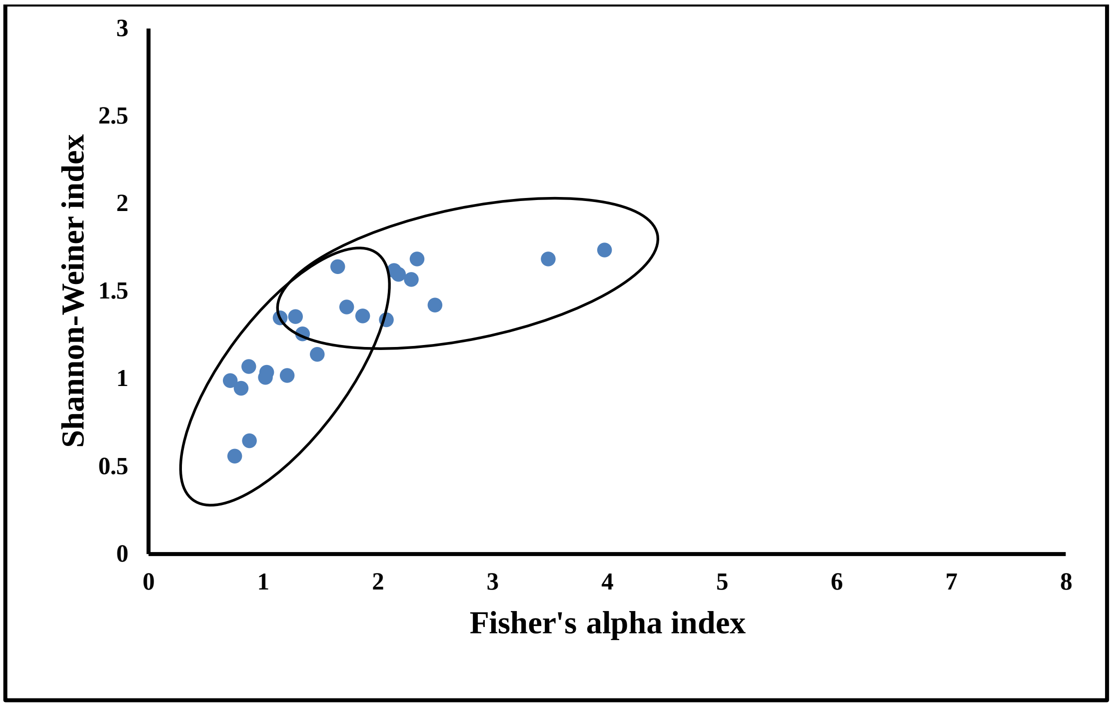


Figure 5.16: Cross-plot of Core 3 showing two distinct assemblages

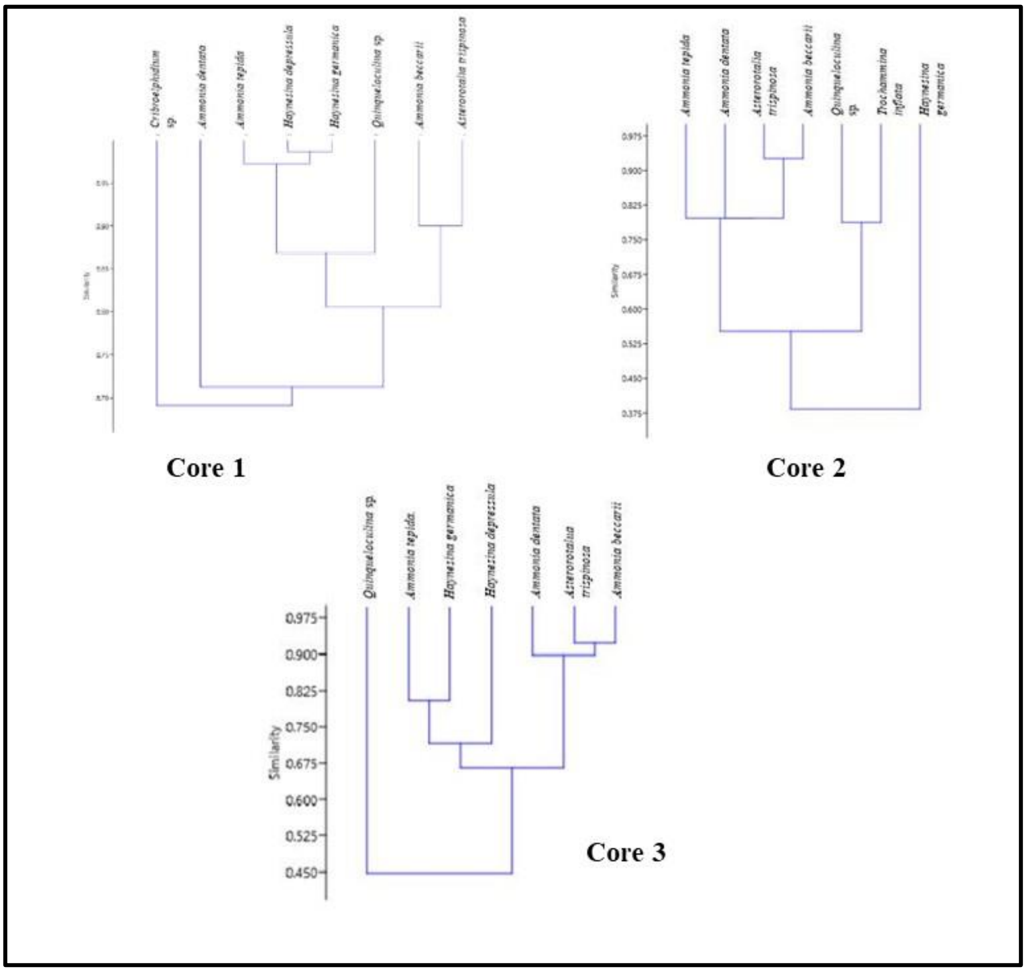


Figure 5.17: Cluster analysis of the different cores

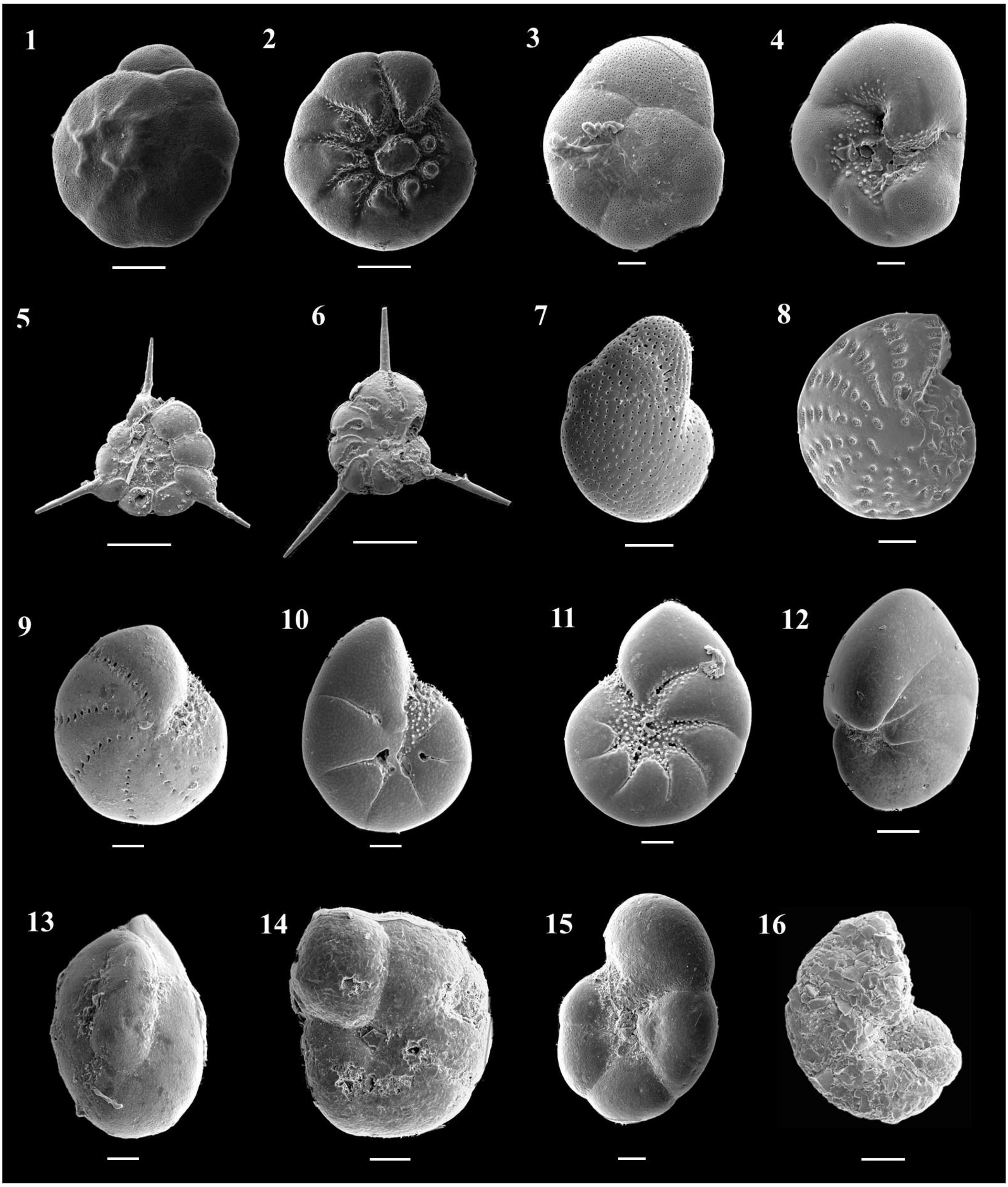


Plate 5: 1 – *Ammonia beccarii* (S); 2 – *Ammonia beccarii* (U); 3 – *Ammonia tepida* (S); 4 – *Ammonia tepida* (U); 5 – *Asterorotalia trispinosa* (S); 6 – *Asterorotalia trispinosa* (U); 7 – *Cribroelphidium poeynum* (U); 8 – *Elphidium advenum* (U); 9 – *Elphidium excavatum* (U); 10 – *Haynesina depressula* (U); 11 – *Haynesina germanica* (U); 12 – *Nonionella turgida* (Si); 13 – *Quinqueloculina seminulum* (Si); 14 – *Trochammina inflata* (S); 15 – *Trochammina inflata* (U); 16 – *Haplophragmoides canariensis* (U).

Legends: S – Spiral view, U –Umbilical view; Si – Side view. All scale bars represent 100 µm.

Marsh foraminiferal assemblages have been studied along the east coast of India. The study area starts from the Sunderban marshes in the north, Bakkhali towards the south of it and Chandipur lying at the southernmost part. The Sunderban area has distinct high marsh and low marsh zones because of its pristine conditions and middle marsh areas are also present at a few locations. This enables detailed foraminifera study from all the marsh zones. Bakkhali region has some marsh conditions in the western and eastern part of the study area, namely Patibhunia in the west and Henry's island in the east. However, marsh regions here are not differentiated into high marsh and low marsh. Only low marsh assemblages could be studied from the marsh areas of the Bakkhali region. Marsh region in the Chandipur region is relatively scanty. Only one low marsh area is represented near the estuary mouth of the Buribalam River, thus allowing the study of only one low marsh assemblages from this region.

6.1 THE SUNDERBAN MARSHES

Thirty-one species of foraminifera have been identified from the study area comprising of both calcareous and agglutinated forms. The most common agglutinated forms include *Haplophragmoides* spp., *Trochammina inflata* and *Miliammina* spp. High abundances of calcareous hyaline forms like *Ammonia* spp., *Cribroelphidium* spp., *Haynesina* spp., *Elphidium* sp., *Nonion commune*, *Nonionella turgida* and *Cocoarota madrasensis* have been observed. The most prevalent porcelaneous form is *Quinqueloculina seminulum*. The highest foraminiferal occurrences are found from the January sampling. The maximum TFN reaches 5656 in 1 gram of dry sediment. Highest measure of living foraminifera is 970 in 1 gram of dry sediment. The lowest foraminiferal occurrences are observed in the April samples. Here, the maximum TFN is 291 and the maximum living foraminifera is 26. From Murray's ternary plot, it is evident that the population mostly comprises of calcareous hyaline foraminifera, however; some pre-monsoonal and monsoonal samples show significant amounts of agglutinated population. Fisher's alpha plot indicates that the pre-monsoonal samples show slightly greater diversity than the monsoonal or the post-monsoonal samples.

A biofacies map has been constructed for the Sunderban marshes (Figure 6.2). Five biofacies have been identified; three comprising of the high marsh fauna and two of the low marsh fauna. The westernmost high marsh biofacies is the *Trochammina inflata – Haplophragmoides wilberti* biofacies, followed by the *Haplophragmoides wilberti – Haplophragmoides canariensis* biofacies in the middle and the *Haplophragmoides canariensis – Srinivasania sundarbanensis* biofacies in the easternmost part of the study area. For the low marsh area, the western part consists of the *Ammonia tepida – Ammonia parkinsoniana – Cocoarota madrasensis – Haynesina depressula – Haynesina germanica* biofacies and the eastern part comprises of *Haynesina germanica – Haynesina depressula – Cribroelphidium poeynum – Ammonia tepida – Nonionella turgida* biofacies zone.

6.2 THE BAKKHALI MARSHES

Sixteen species of foraminifera have been identified, including both calcareous and agglutinated forms. Most common agglutinated forms are *Haplophragmoides* spp., *Miliammina* spp., and *Trochammina inflata*. Dominant calcareous hyaline forms are *Ammonia* spp., *Haynesina* spp. and *Cribroelphidium* spp. The only calcareous porcelaneous form recorded is *Quinqueloculina seminulum*. The highest foraminiferal number recorded in March (pre-monsoon) is 16830, whereas the highest TFN for September (post-monsoon) is 1280. The western and eastern part of the study area shows more TFN than the southern part. Murray's ternary diagram shows more agglutinated populations in the post-monsoonal assemblages than the pre-monsoonal ones. Fisher's alpha diversity plot suggests a low diversity of living foraminifera in the study area. Samples from the eastern side of the study area show a slightly higher diversity than the other areas.

A biofacies map has been constructed for the Bakkhali study area (Figure 6.2). Three biofacies zones have been identified. In the western part lies the *Ammonia tepida – Ammonia beccarii* biofacies, followed by the *Haynesina germanica – Ammonia tepida* biofacies in the middle and the *Ammonia tepida – Haynesina germanica* biofacies at the easternmost part of the study area.

6.3 THE CHANDIPUR MARSHES

Fourteen species of benthic foraminifera have been recorded from the study area, including both calcareous and agglutinated forms. Calcareous hyaline forms include *Ammonia* spp., *Asterorotalia trispinosa*, *Elphidium* spp., *Cribroelphidium poeynum*, *Haynesina* spp. and *Nonionella turgida*. The only calcareous porcelaneous form present is *Quinqueloculina seminulum* and only two agglutinated forms; *Trochammina inflata* and *Haplophragmoides canariensis* have been observed. The highest TFN observed during March is 300, whereas highest TFN during September is 266. Murray's ternary plot shows that the assemblage is mostly hyaline with very few agglutinated and porcelaneous members. Fisher's alpha plot shows a low diversity in both seasons. Calcareous species are mostly found in the tidal flat region and the marshy regions contain mostly the agglutinated forms.

A biofacies map has been constructed for the Chandipur region (Figure 6.3). This area comprises of three biofacies zones. Towards the estuarine mouth region lays the *Ammonia tepida – Ammonia beccarii* biofacies; the proximal area to the beach consists of *Ammonia tepida – Asterorotalia trispinosa* biofacies and the portion close to the distal bar (the swampy region) is composed of *Ammonia tepida – Cribroelphidium poeynum* biofacies.

6.4 COMPARISON BETWEEN THE THREE MARSHES

The abundance of both total foraminiferal number (living + dead) and total foraminiferal number (living) is maximum in the Sunderban regions (Chapter 6.1). The low marsh regions of the Sunderbans show the maximum abundance of foraminifera amongst the study locations. Towards the southern part of the study region, there is a decrease in the abundance of both total foraminiferal number (living + dead) and total foraminifera number (living). Chandipur shows the least values of abundance of foraminifera. A similar trend is also observed in the diversity and species richness of foraminifera. Sunderban shows the highest diversity as well as species richness followed by Bakkhali and Chandipur regions. A steep decrease in the number of agglutinated taxa is also noticed as we move from the northern Sunderbans to Bakkhali and then Chandipur. The dominant taxa in the Sunderban high marshes are *Trochammina inflata*, *Haplophragmoides wilberti* and *Haplophragmoides canariensis*. The dominant taxa reported from the low marshes of Sunderbans are *Ammonia tepida*, *Haynesina germanica* and *Cribroelphidium poeynum*. *Haynesina germanica*, *Ammonia tepida* and *Haynesina depressula* are the dominant taxa in the Bakkhali region. The dominant taxa in Chandipur are *Asterorotalia trispinosa*, *Ammonia tepida* and *Quinqueloculina seminulum*. *Ammonia tepida* is undoubtedly the most abundant form found in the study area and is found ubiquitously in almost all the locations throughout the study area.

Comparative parameters	Sunderban high marshes	Sunderban low marshes	Bakkhali marshes	Chandipur marshes
Range of total Foraminiferal Number (living + dead) (per gram of dry sediment)	88 to 1525	36 to 5656	8 to 894	3 to 296
Diversity (α)	2 – 3	1 – 2	1 – 2	1 – 2
Species richness	24	19	13	11
Agglutinated taxa	10	7	6	3
Dominant taxa	*Trochammina inflata*, *Haplophragmoides canariensis*, *Haplophragmoides wilberti*	*Ammonia tepida*, *Haynesina germanica*, *Cribroelphidium poeynum*	*Haynesina germanica*, *Ammonia tepida*, *Haynesina depressula*	*Asterorotalia trispinosa*, *Ammonia tepida*, *Quinqueloculina seminulum*
Average salinity (in psu)	22	26	27	29
Average pH	7.8	7.9	8.1	8.4
Average temperature (in °C)	25.6	25.7	27.8	28.4

Table 6.1: Comparison chart between the different study areas

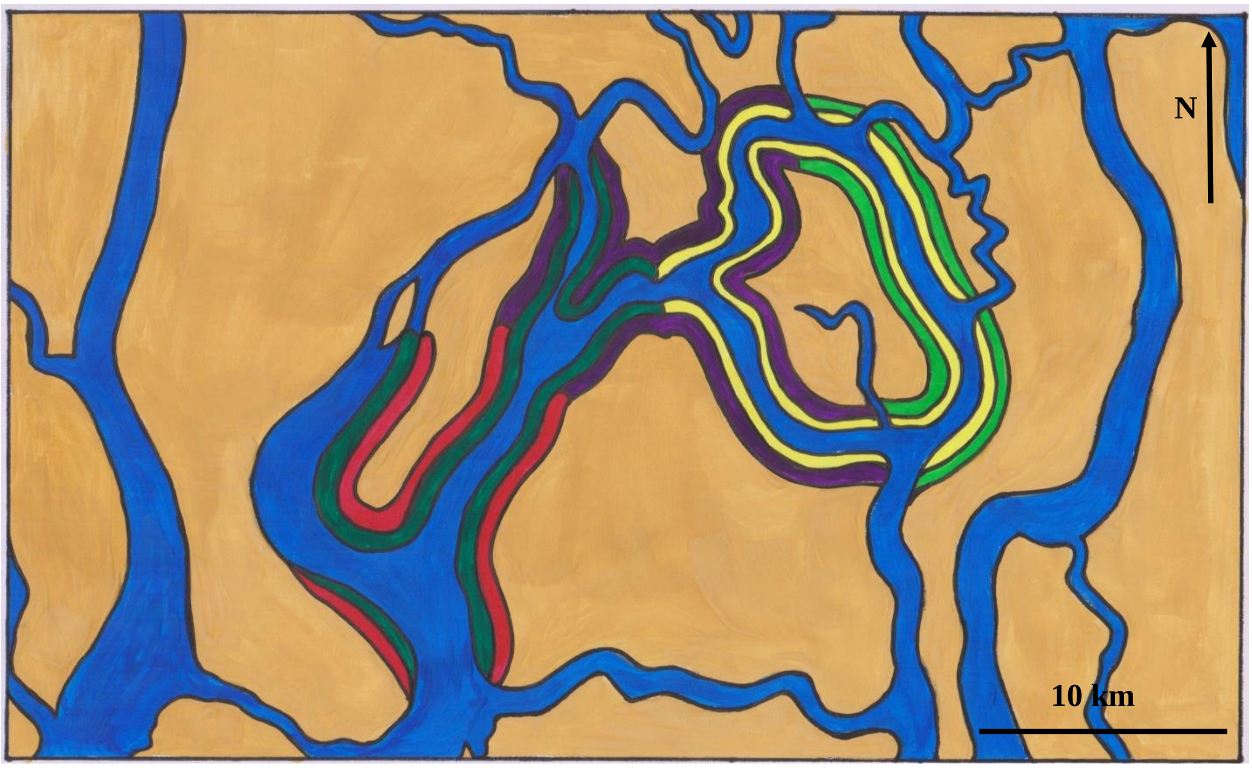
6.5 CONCLUSION

- Marshlands host small sized organisms with more significant abundances and lower diversities: unstable environmental conditions indicate an r-selective population pattern.

- Marsh foraminifera show a higher Total Foraminiferal Number (TFN) during the pre-monsoonal samplings, as compared to the post-monsoonal samplings.
- High marsh foraminifera are characteristically agglutinated whereas low marsh foraminifera are typically calcareous hyaline in nature. A mixture of both agglutinated and calcareous taxa is observed in the middle marsh stations.
- Characteristic high marsh assemblage of the east coast of India comprises of *Trochammina inflata*, *Haplophragmoides wilberti*, *Haplophragmoides canariensis* and *Miliammina fusca*.
- Typical low marsh assemblage from the east coast of India consists of *Ammonia tepida*, *Ammonia beccarii*, *Haynesina germanica*, *Haynesina depressula* and *Quinqueloculina seminulum*.
- Total foraminiferal number, total living foraminifera, diversity and species richness all decrease as we move from the northern part (Sunderbans) of the study area to the southern part (Chandipur).
- The abundance of agglutinated foraminifera decreases as one moves from the Sunderban marshes toward the Chandipur region.
- In places where marshes and beach area/tidal flat are both present in close vicinity, the species richness of foraminifera decreases towards the beach/tidal flat region.
- Marsh foraminifera are directly proportional on the moisture content and inversely proportional to the sand content of the sediment.
- Marsh foraminifera prefers an alkaline medium in its growing stage with optimum temperatures around 25 to 26 degrees Celsius and optimum salinity around 30 to 32 PSU.
- Biofacies maps have been proposed using the live foraminiferal content of the study regions. Sunderban marshes show three high marsh biofacies zones and two low marsh biofacies zones. Bakkhali and Chandipur both show the presence of three biofacies zones each; throughout the study area.

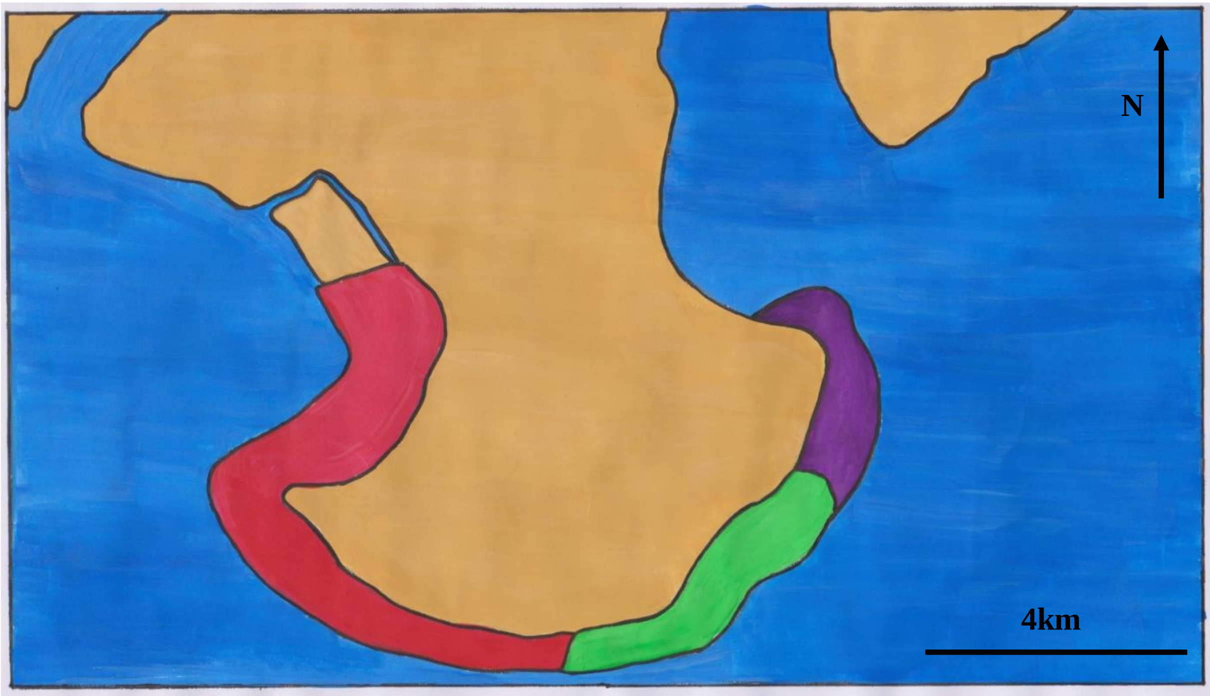
6.6 IMPLICATION OF THE STUDY

The study of distinctive marsh assemblages would contribute in determining palaeo-tide levels. High marsh assemblages denote the high tide line. Marsh foraminifera are also excellent indicators of palaoenvironment, owing to their sensitive nature. Establishing proper taxonomy would be helpful in future studies on palaeonenvironment using marsh foraminifera.



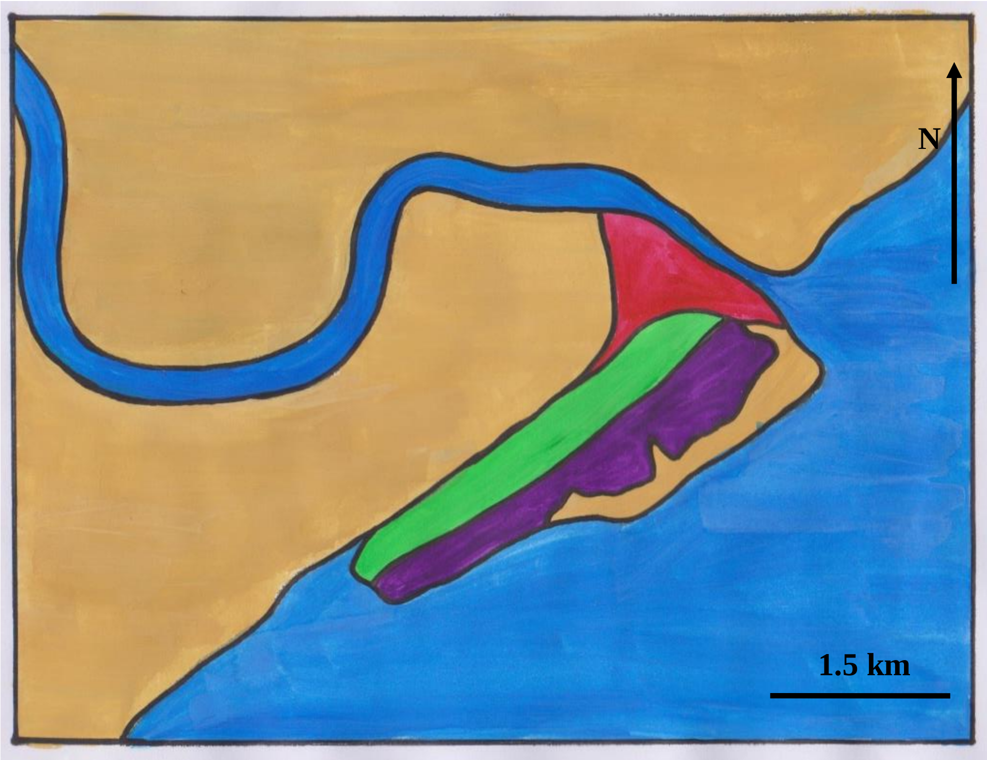
Index: Land area   Water bodies   *Trochammina inflata – Haplophragmoides wilberti* biofacies   *Haplophragmoides wilberti – Haplophragmoides canariensis* biofacies   *Haplophragmoides canariensis – Srinivasania sundarbanensis* biofacies   *Ammonia tepida – Ammonia parkinsoniana – Cocoarota madrasensis – Haynesina depressula – Haynesina germanica* biofacies   *Haynesina germanica – Haynesina depressula – Cribroelphidium poeynum - Ammonia tepida – Nonionella turgida* biofacies

Figure 6.1: Biofacies map for the Sunderban marshy region



Index: Land area Water bodies Ammonia tepida – Ammonia beccarii biofacies *Haynesina germanica – Ammonia tepida* biofacies *Ammonia tepida – Haynesina germanica* biofacies

Figure 6.2: Biofacies map for the Bakkhali region



Index: Land area Water bodies *Ammonia tepida – Ammonia beccarii* biofacies *Ammonia tepida – Asterorotalia trispinosa* biofacies *Ammonia tepida – Cribroelphidium poeynum* biofacies

Figure 6.3: Biofacies map for the Chandipur region

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