

Benthic foraminiferal response to changes in mining pattern: A case study from the Zuari estuary, Goa, India

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Abstract

Being sensitive to environmental changes, foraminifera have been extensively used to monitor pollution level in the marine environment, including the effect of mining in coastal areas. In the Goa state of India, the rejects from open-cast mining on land, largely find their way to the estuaries, as washout during monsoon. Additionally, the Mormugao Port at the mouth of the Zuari estuary is the hub of activities due to the transport of ore from hinterland areas by barges and its subsequent loading for export. On the directive of the Supreme Court of India, all the mining-related activities abruptly stopped throughout India, including that in Goa in 2012, and got reinstated in 2015. Therefore, it provided a fit case to test the effectiveness of benthic foraminifera as an indicator of environmental impact due to mining activities. A total of 10 surface sediment samples from 5 locations in Zuari estuary were collected from a depth range of 4.5 m to 8.5 m in the years of 2013 and 2016 and were analyzed for both the living (stained) and dead benthic foraminifera. The year 2013 represents a time interval immediately after the closure of extensive mining activity, and the sampling during 2016 represents minimal mining. The living benthic foraminiferal abundance was higher (19 to 54/g sediment) during 2013 and decreased substantially during 2016 (3 to 22/g sediment), suggesting an adverse effect of activities associated with mine closure on benthic foraminifera. Additionally, the relative abundance of *Ammonia* was also significantly low during the year 2016. The temporal variation in dead foraminifera was, however, different than that of the living foraminifera. The differential response was attributed to the terrigenous dilution as a result of change in sedimentation rate. Therefore, we conclude that living foraminifera correctly incorporate the changes in mining pattern and may be used as an effective tool to monitor the impact of mining. We further suggest that the potential counter-effect of terrigenous dilution on total and living benthic foraminiferal population should be considered while interpreting, temporal variations in foraminiferal abundance in marginal marine settings.

Keywords: Zuari estuary, Benthic foraminifera, *Ammonia*, mining, pollution

Introduction

Goa is among the major iron ore producers in India, and nearly half of the iron ore export of India comes from this state (Gadgil and Dongre 2013). About 5% of Goa's Gross Domestic Product (GDP) accounts for mining-related activities, the second most important activity after tourism industry (Xavier et al. 2013). The biggest concern in the mining industry, are the rejects, which often find its way into the water bodies. The open cast iron ore mining in Goa creates a huge amount of dumps and rejects. The majority of these dumps and rejects are washed away into the estuaries during the monsoon season. This mining rejects in water bodies may or may not affect the biota. Therefore, it is necessary to understand the effect of mining activities on the microorganisms, as it may, in turn, affect the whole food chain. There are two major estuaries in the state of Goa, namely Mandovi and Zuari. Both the estuaries are interconnected by Cumbharjua canal. The ore from hinterland areas is transported by barges through the estuaries to the Mormugao port, for export. Out of the two major estuaries in Goa, the Zuari is more affected as during monsoon season, ore transport through Mandovi is difficult due to the sand bar formation near its mouth. Therefore, the iron ore is transported through Cumbharjua canal to the Mormugao harbor. The transport and handling processes enhance pollution and thus affect the health and ecology of the Zuari. In the year 2012, on the directive of the Supreme Court of India, all the mining-related activities abruptly stopped throughout India, including that in Goa. The orders for reinstatement of mining activities were issued in the year 2015, but it took some time for the actual mining to begin. Also, a cap of only 20 million metric ton each year was also imposed. The cap and a much-reduced demand for iron ore in the international market further delayed full-fledged mining operations. Therefore, it provided a fit case to further test the effect of mining activities on pollution in estuaries.

The adverse effect of mining, if assessed through the organisms at the lower end of the food chain can help in the timely prevention or remedial measures before it percolates further and affects human beings. The good preservation potential of such lower food chain members can further help in assessing changes in the level of pollution, even in the absence of any baseline data. Foraminifera, single-celled micro-organisms, abundant in the oceans are one of the efficient microorganisms to assess the state of pollution. Their small size, widespread distribution, high biodiversity, sensitivity to small changes in the surrounding environment and incorporation of signatures of these changes in the test and high preservation potential makes them very useful in all pollution studies (Saraswat and Nigam 2013). Foraminifera being a good pollution indicator (Resig 1960; Setty and Nigam 1984; Alve 1995; Saraswat et al. 2004; Nigam et al. 2005, 2009; Linshy et al. 2013), can be used to assess

and monitor the health and ecology of the coastal waters and estuaries (Nigam et al. 2006; Jayaraju et al. 2011; Jeshma et al. 2016; Reddy et al. 2016).

Some early workers documented foraminiferal distribution in estuaries of Goa (Tab. 1). A considerable increase in total foraminiferal number as well as species diversity in the Zuari estuary over the last three decades, as compared to the reports by Rao (1974), was reported by Panchang et al. (2005). It was further reported that the total suspended matter (TSM), an indicator of the volume of mining rejects and is linked to the extent of mining activity has also reduced over the same period. The positive change in foraminiferal abundance and diversity was attributed to the shift of mining from south Goa to the north Goa in the recent decades. The shift was a result of the change in demand from manganese (in south Goa) to iron (north Goa) (Panchang et al. 2005). However, most of such studies were based on the total (dead) fauna in sediments. The total fauna might have, however, accumulated over time and may not correctly reflect the environment at the time of collection of samples. Based on above information, we decided to assess the effect of the change in mining on the health of the estuaries by collecting the samples close to the locations sampled by Panchang et al. (2005). Additionally, we decided to work on living (stained) benthic foraminifera. The main aim of this work is to assess the response of the foraminiferal population to the blanket closure of all mining-related activities in 2012 and its subsequent reinstatement in 2015.

Study area

Out of the seven major rivers in the state of Goa, Mandovi and Zuari are of great importance. The Mandovi and Zuari estuaries are known to be monsoonal estuaries, and together their basin covers about 69% of the total geographical area of Goa. The Mandovi and Zuari together with interconnecting Cumbharjua canal form an economically important estuarine complex on the west coast of India. The Zuari, a part of the Mandovi-Zuari estuarine complex is an important geographic feature in the southern Goa. The extent of Zuari lies between the 14°54'-15°30'N latitude and 73°44'-74°20'E longitude, and its catchment area is nearly 1152 km² (Shetye et al. 2007) (Fig. 1).

The temperature of Zuari water increases from January to May during pre-monsoon season, and decreases during the monsoon and again increases during post-monsoon season. The temperature of Zuari water varies between 24.80°C and 31.02°C, the annual variation being ~5-7°C (Qasim and Sengupta 1981). The salinity of the Zuari water is higher as compared to that of the Mandovi. The estuary is well mixed vertically during the dry pre- and post-monsoon season and the salinity increases throughout its course. The runoff induced advection of salt out of the estuary and the tidally induced diffusion into the estuary controls the salinity of the Zuari during pre- and post-

monsoon season (Shetye and Murty 1987). The area receives maximum rainfall during southwest monsoon at a seasonal average of 3000 mm/yr (Anand et al. 2014). However, this region experiences active (period of intense rains) and breaks (break in rainfall for a considerable number of days) monsoon phases. About 80% of the annual rainfall occurs during the active phase. The average annual runoff measured over the period 1981–1998 (before the Selaulim Dam was built), at the confluence of the Cumbharjua Canal, where it opens into the Mormugao Bay (at 10 km upstream from the Zuari mouth), is estimated to be about $2190 \times 10^6 \text{ m}^3$. At present, the runoff [$491 \times 10^6 \text{ m}^3$, as reported in Shetye et al. (2007) based on Water Resources Department, Government of Goa] at the head of the estuary is partially controlled by the Selaulim Dam on the Guloli river.

South Goa holds the highest grade of manganese and ferromanganese deposits. Mining started in 1950 in the southern districts (through which the Zuari river flows) to meet the increase in industrial demand. In early days, mining production was manual, and the demand was for manganese and ferromanganese. Later on, iron ore mining began, and demand level lead to mechanized operation. Until 1980, 129 industries and ten mines in the Zuari basin generated 1000 to 4000 tons of reject per day per mine (Qasim and Sengupta 1981). In recent years, high-grade iron ore mined from Karnataka is brought to Goa for blending with low-grade ore, and then transported by barges to ocean-going vessels to their export destinations (Rangaraj and Raghuram 2005). At its peak, 54 million metric tons of ore was mined, and about 30 million tons of rejects generated. A colossal figure of 76899187 tons of mine waste was attributed to the mining in the year 2006-2007 (Basu 2012). The mining waste is stacked in large dumps. The heavy rain and the wind during monsoon season transports these dumps into the water bodies and increases the total suspended material in the estuary. Mining in the catchment area, ore transport, handling of ore and harbor operations affect the ecology of the estuary.

The Mormugao Port is one of the major ports for maritime trade in India, being the largest iron ore exporter with an annual turnout of around 27.33 million tons of iron ore (mptgoa.com). The Mormugao Port had been designed to deal with iron ore for export through barge shipments in different ways; by stacking on the ground and loading onto ships through conveyors. Transferring of ore from barges to ships is done through anchored points called mooring dolphins at the port and by transhippers or own equipment of ships docked at anchorage in deep water locations at Panaji Port or Mormugao Port (Rangaraj and Raghuram 2005). The monsoonal estuary Zuari, serves as good mode of transport for the mined ore in the monsoons.

Material and Methodology

A total of 10 surface sediment samples were collected from the mouth of the Zuari estuary, in two field surveys onboard fishing trawler, by using a Van-veen grab. A total of 5 stations were sampled in both 2013 (immediately after mining ban) as well as 2016 (immediately after restoration of mining) (Fig. 1). The sampling stations fall in the maximum activity zone and also matched with the previously studied stations (Panchang et al. 2005). A part of the top 2 cm of the sediment sample was scrapped carefully and immediately stained with a buffered Rose-Bengal ethanol solution, to identify and preserve living benthic foraminifera (Walton 1952). The remaining sediment from the top 2 cm section was stored in zip-lock plastic bags for picking dead benthic foraminifera. The samples were stored at 5°C to avoid drying and thus digenetic alteration. The ambient physico-chemical parameters (salinity, pH) were measured onboard, with a portable multi-parameter meter. Additionally, water samples were collected by using a Niskin sampler, to measure total suspended matter (TSM and dissolved oxygen (DO)).

The standard procedure was followed for processing the sediment samples for foraminiferal studies. The appropriate amount of sediment sample (10-20 g) was transferred to clean pre-weighed petri-dishes and covered with plastic cling film. The cling film was perforated with a fine needle for the water to escape during freeze drying. The samples were frozen at -30°C. The frozen sediment samples were transferred to lyophilizer for freeze drying. After freeze drying, the samples were weighed to obtain dry sediment weight. The dried and weighed sediment samples were transferred to 1000 ml glass beakers and soaked overnight. The overlying water was decanted after 24 hr to remove suspended colloidal material. The soaking and decanting was repeated till the overlying water was clear. Finally, the sediments were gently washed by using a 63 µm sieve, to avoid foraminiferal test breakage. After washing, the coarse fraction retained on the sieve was transferred to a glass beaker and dried overnight. The dried coarse fraction was weighed and transferred to properly labeled vials. The effort was made to pick a minimum of 300 benthic specimens from each sample. In a few samples, however, the foraminiferal population was too low to pick 300 living specimens. The stained foraminifera were counted separately. Living (stained) and dead benthic foraminiferal abundance in per gram dry sediment was estimated. Additionally, the relative abundance of dominant benthic foraminiferal genera was also counted.

Results

Physico-chemical Parameters

Both the surface seawater salinity and pH at all the stations during two sampling years are comparable (Fig. 2). The salinity decreases from station S0 to S4 (Fig. 2A). The highest salinity (34.24 psu and 34.27 psu for the years 2013 and 2016, respectively) is at station S0 as it is close to the sea (lower estuary). The lowest salinity (32.01 psu and 31.94 psu for the years 2013 and 2016, respectively) is at station S4 as it is relatively away from the sea (upper estuary). Likewise, pH also follows a similar trend decreasing from lower estuary to upper estuary (Fig. 2B). The highest pH (7.99 and 8.00 for the respective years of 2013 and 2016) is at station S0 and the lowest (7.83 and 7.74 for the respective years of 2013 and 2016) is at station S4. The dissolved oxygen was low during the year 2016 (Fig. 2C). Contrary to salinity and pH, a large temporal difference in total suspended matter (TSM) is observed during the year 2013 and 2016 (Fig. 2D). As expected, TSM is comparatively higher during the year 2013. Additionally, TSM decreases towards the lower estuary. Interestingly, no clear trend in TSM is observed during the year 2016. The minimum TSM in the year 2013 (10.7 mg/l) and 2016 (11.6 mg/l) is at station S0 and station S4, while it peaks (98.2 mg/l and 26.8 mg/l) at station S3 and station S0, respectively, for the years 2013 and 2016. The coarse fraction (CF%) varies from 9.0% to 68.1% during 2013 and from 29.0% to 92.9% during 2016 (Figure 3). The CF% is comparatively much higher during 2016.

Living and total benthic foraminifera

In the year 2013, the maximum living benthic foraminiferal abundance (54/g sediment) was at station S0 and the minimum (19/g sediment) at S2. As compared to this, in the year 2016, the maximum abundance (22/g sediment) was at S3 and the minimum (3/g sediment) at station S1. The difference in living benthic foraminiferal abundance between the two years is significantly high, as the highest living abundance in the year 2016 is comparable to the minimum abundance of the year 2013. The living benthic foraminiferal abundance in the year 2013 is higher as compared to the year 2016, at all the stations (Fig. 4).

The highest total foraminiferal number (1354/g sediment in 2013 and 1693/g sediment in 2016) was at S0, and the lowest (110/g sediment in 2013 and 316/g sediment in 2016) was at station S3 and S4 respectively (Fig. 5). The total foraminiferal number, in general, is lower during the year 2013 as compared to that in 2016 except at station S1 and S4. The relative abundance of living benthic foraminifera is significantly lower during the year 2016 (Fig. 6). The living benthic foraminiferal population is dominated by four genera namely, *Ammonia*, *Nonion*, *Quinqueloculina*

and *Bolivina* (Fig. 7). *Ammonia* constitutes more than half of the living benthic foraminifera during the year 2013, being as high as 86% at station S3 (Fig. 8). The decrease in living benthic foraminiferal abundance during the year 2016 is also observed in a decrease in the relative abundance of *Ammonia* (Fig. 8).

Discussion

Physico-chemical parameters

A linear relationship between seawater salinity and pH suggests that the pH in the estuarine region is closely linked with the salinity or the fresh water runoff. Previously, the decrease in salinity as a result of monsoon induced fresh water runoff has been suggested as the prime factor responsible for low pH in the shallow water coastal regions (Kurtarkar et al. 2011). A similar relationship has also been reported from the Mandovi-Cumbharjua-Zuari estuarine complex (Saraswat et al. 2015). The change in pH as a result of a change in salinity has implications for the foraminifera as the calcareous foraminifera are sensitive to ambient pH (Saraswat et al. 2007; Saraswat 2010; Saraswat et al. 2015). The living benthic foraminiferal abundance is positively correlated with pH and salinity during both the years. Foraminiferal response in marginal marine environments, specifically the estuaries with frequent pollutant contamination (Olausson and Cato 1980), also depends on the type of effluents discharged into the estuary (Alve 1995; Debenay 2001). Therefore, in estuaries, the total suspended matter plays an important role in limiting the abundance of living benthic foraminifera (Nigam 1984). The increase in turbidity hampers the food availability and the growth of foraminifera (Nigam et al. 2002). Previous studies suggest that the major part of the total suspended matter in the Zuari estuary is attributed to the mining rejects and associated ship building industry (Shynu et al. 2013). The different behavior in the lower estuary (station S1) in both years is due to the tremendous harbor activities in the Mormugao Port and its surrounding bay. The spillover during loading and unloading of ore at port and washing of mining rejects into river/estuaries during monsoon affects the suspended load into the Zuari estuary and thus the living foraminiferal population.

Living benthic foraminifera

The higher living benthic foraminiferal abundance at all the stations in the year 2013, representing a period just after the mining ban, as compared to that in the year 2016, the interval after prolonged mining closure in Goa, suggests an adverse effect of mining closure on benthic foraminifera. The increase in mining reject increases the turbidity. Therefore, intense mining activity results in increased turbidity as evident in the higher TSM during the year 2013. The difference in TSM during the two sampling years, however, is not uniform. The response of living benthic foraminifera in the

Zuari estuary is in contrast with the widely held view that turbidity adversely affects foraminifera (Ortiz et al. 2011). The minimal effect can be attributed to the perennial prevalence of threshold turbidity in the sampling area, as a result of complex interaction of tidal action, rainfall, winds, and currents during different seasons (Rao et al. 2011). We suggest that the intense mining activity does not increase the turbidity in the Zuari Bay region, large enough to affect the living benthic foraminiferal population. The findings imply that in specialized settings, turbidity may not always be crucial in controlling benthic foraminifera. Instead, we attribute the decline in living benthic foraminiferal abundance to the decrease in the supply of nutrients, especially iron brought by the mining reject (Kessarkar et al. 2015). The reduced nutrient supply might have affected the phytoplankton population and a resultant decrease in organic matter availability in the sediments. *Ammonia*, which is extensively used as pollution bio-indicator (Setty and Nigam 1984, Yanko et al. 1998; Debenay et al. 2001; Du Chatelet 2004), was the only genera present at all the stations in both the years of sampling (2013 and 2016). The significantly high abundance of *Ammonia* was only restricted to the year 2013 as compared to 2016. The high relative abundance of *Ammonia* during the year 2013 is attributed to its greater stress tolerance. The lull in mining activities reduced TSM, and thus other less tolerant species proliferated. *Ammonia* along with other species have often been used for pollution monitoring in marginal marine regions (Setty 1984; Sharifi et al. 1991; Youssef 2017). Our study confirms the unique characteristics of *Ammonia* to monitor pollution in the regional setting of the Zuari estuary and reaffirms its prevalence over other taxa.

The change in elemental concentration, as a result of the mining activities, can also affect foraminiferal population (Saraswat et al. 2004; Nigam et al. 2006; Madkour and Youssef 2009). The high concentration of iron and manganese in the Zuari estuary is ascribed to mining (Kessarkar et al. 2013). The shipping activity increases the concentration of a few metals in and near the harbor (George 1993). The mining ban decreased iron concentration in the estuarine sediments (Kessarkar et al. 2015). Considering these factors, the living benthic foraminiferal population should have positively responded to the ban on mining and other associated activities. The opposite response of living benthic foraminifera is therefore, intriguing. The lack of mining activities, however, also results in reduced influx of finer sediments. The percentage of finer particles further decreases due to more effective flushing of remaining finer particles during every monsoon season (Kessarkar et al. 2015). The relatively higher CF% at almost all the station, post mining ban, clearly indicates reduced influx and/or enhanced flushing of finer particles (Fig. 3). The finer sediments are not only likely to support high benthic foraminiferal population but also are comparatively more suitable for organic matter preservation (Keil 2011), that acts as food for foraminifera. Thus, the decrease in fine grained

sediments and associated organic carbon, post mining ban, appears to be more critical for benthic foraminifera than the positive effect of reduced metal concentration in the Zuari estuary.

Total foraminiferal number (TFN)

The results were compared with the data of Panchang et al. (2005) to understand the developments during the last decade. Total foraminiferal number (TFN) was the lowest in the year 2005, followed by that in 2013, both representing an interval of extensive mining. The total foraminiferal number at stations S1, S2 and S3 increased during the year 2016 as compared to that in both 2005 and 2013. The reason for the anomalous behavior of total foraminiferal number in the year 2016 is ascribed to low sedimentation rate in the area. The mining closure led to the reduced total suspended matter and thus slow sediment accumulation. The reduced sedimentation over the years resulted in increased accumulation of benthic foraminiferal test in the sediments. The abundance of living and dead or total foraminiferal number need not coincide with one another, and the ratio of the two provides the relative rate of sedimentation (Walton 1955). If the living to dead ratio is low, then the rate of sedimentation is quite slow in any given area (Phleger 1951, 1955; Walton 1955; Buzas 1965; Schafer 1968). The most dominating species of TFN were *Ammonia*, *Nonion*, *Quinqueloculina*, and *Bolivina*, with an exceptionally high abundance of *Ammonia* as compared to others, in the year 2013. Setty (1984; 1982) and Youssef (2015) reported *Ammonia*, *Elphidium* and *Nonion* to be most stress tolerant taxa. Therefore, we suggest, that in specialized settings like the present study area, the living benthic foraminiferal population and specifically the relative abundance of *Ammonia* is a better indicator of environmental changes as compared to the total foraminiferal population.

The effect of dilution by terrigenous input on dead foraminiferal abundance was very evident in the temporal variation in the Zuari estuary. The restricted influx of mining rejects caused reduced dilution and thus increased the abundance of foraminiferal tests in the unit sediments, in spite of a decline in living benthic foraminiferal population. The finding has important implication in interpreting fossil data, in specialized settings where large variations are expected in terrigenous influx under contrasting climatic conditions. We suggest that in marginal marine regions, terrigenous dilution may cause a large change in foraminiferal abundance and thus the calcium carbonate percentage of the sediments. Similar changes have been reported from shelf regions during glacial-interglacial intervals (Hoogakker et al. 2004). Thus, the potential counter-effect of terrigenous dilution and living benthic foraminiferal population should be considered while interpreting, temporal variations in foraminiferal abundance in marginal marine settings.

Conclusion

A comparison of foraminiferal distribution in the surface sediments of the Zuari estuary during the period of extensive mining and post mining closure indicates that living benthic foraminiferal population reduced after the prolonged ban on mining. The decrease in living benthic foraminiferal population is attributed to a lack of fine grained sediments as a result of reduced mining related activities and associated organic matter. The trend in living benthic foraminiferal abundance does not always coincide with the total foraminiferal number. The difference is attributed to a slower rate of sedimentation post mining closure (the year 2016) as compared to that during the year 2013. Given it, we suggest that in specialized settings, the living benthic foraminiferal population is a better indicator of changes in ambient condition and further that the relative abundance of *Ammonia* is a good indicator of the environmental impact of mining activities.

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Legend to Figures and Tables

Figure 1: The sampling location in the Zuari estuary. The inset shows the location of the study area in the Indian subcontinent. The symbols are marked for different years of sampling. The major rivers are also marked.

Figure 2: The salinity (A), pH (B), dissolved oxygen (C) and total suspended matter (D), for the years 2013 and 2016, at all the stations. Note that the salinity and pH at all the stations is comparable during both the collection years.

Figure 3: The coarse fraction percentage (CF%) at all stations during the years 2013 and 2016.

Figure 4: A comparison of living (stained) benthic foraminiferal abundance at different stations during the years 2013 and 2016.

Figure 5: A comparison of total benthic foraminiferal number at different stations in the Zuari estuary, during the years 2013 and 2016.

Figure 6: A comparison of living benthic foraminiferal percentage at different stations in the Zuari estuary, during the years 2013 and 2016.

Figure 7: The most abundant benthic foraminiferal genera in the study area, namely *Ammonia* (a-b), *Nonion* (c-d), *Quinqueloculina* (e-f), *Bolivina* (g-h). Scale bar is 50 μm .

Figure 8: A comparison of the relative abundance of *Ammonia* at different stations in the Zuari estuary during the year 2013 and 2016.

Table 1: Previous studies on foraminiferal distribution in the estuaries of Goa, India.

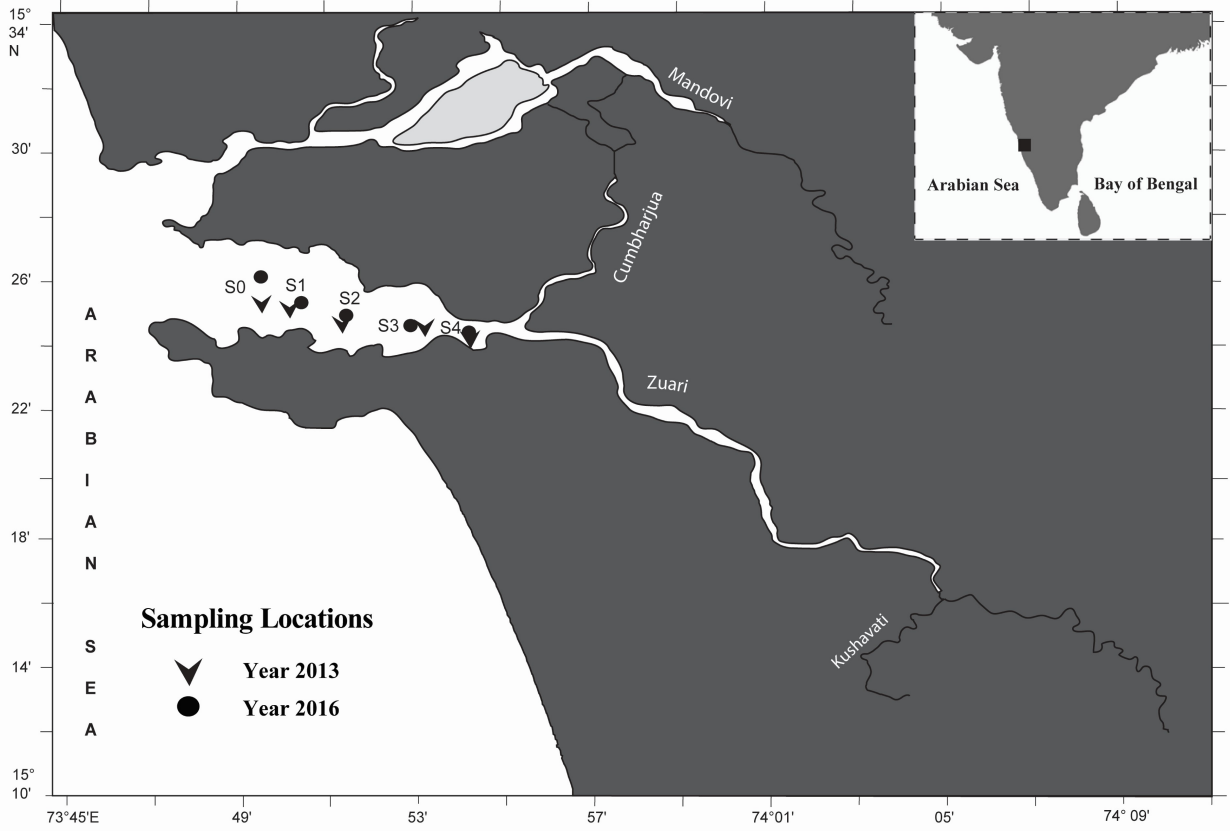


Figure 1

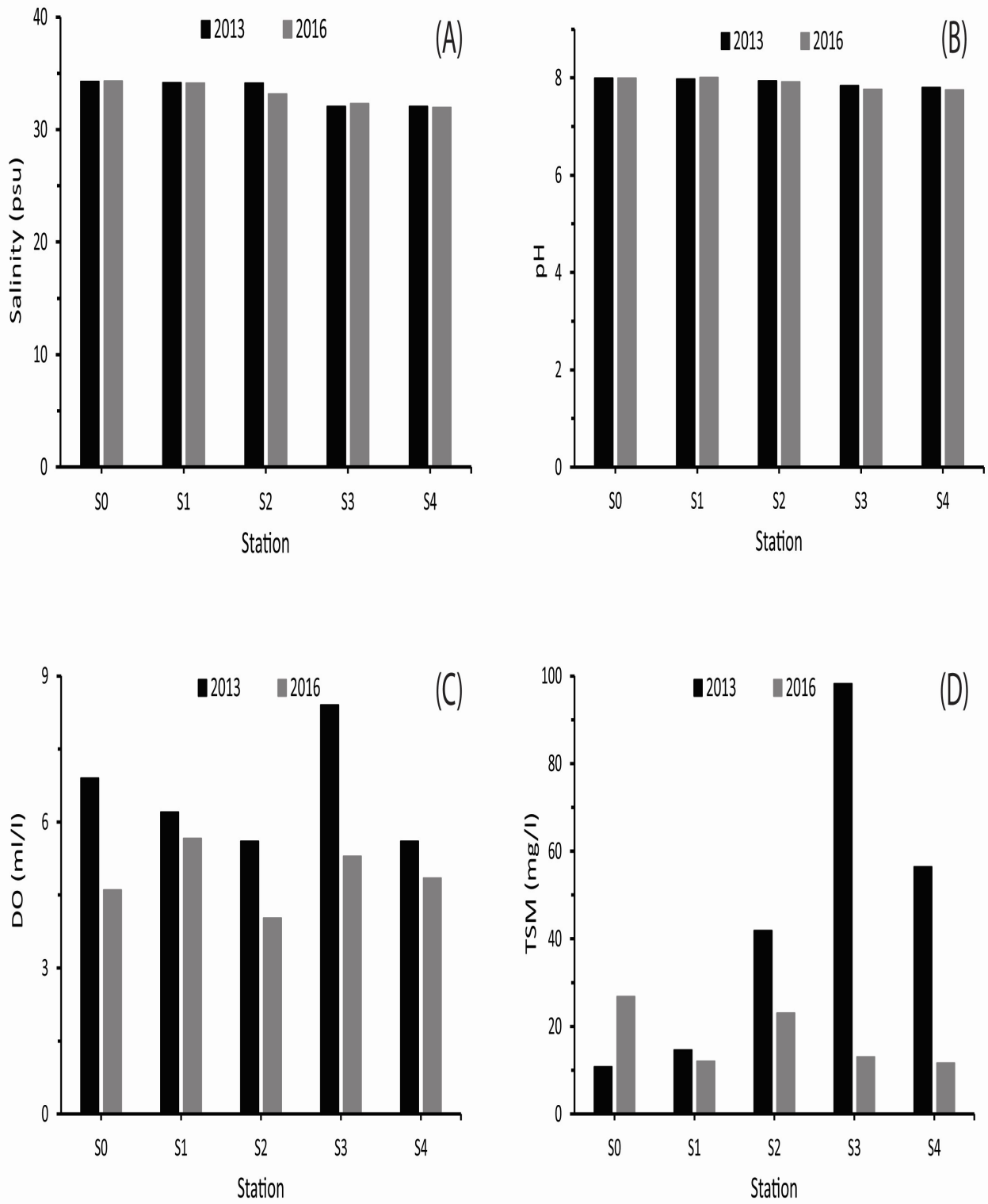


Figure 2

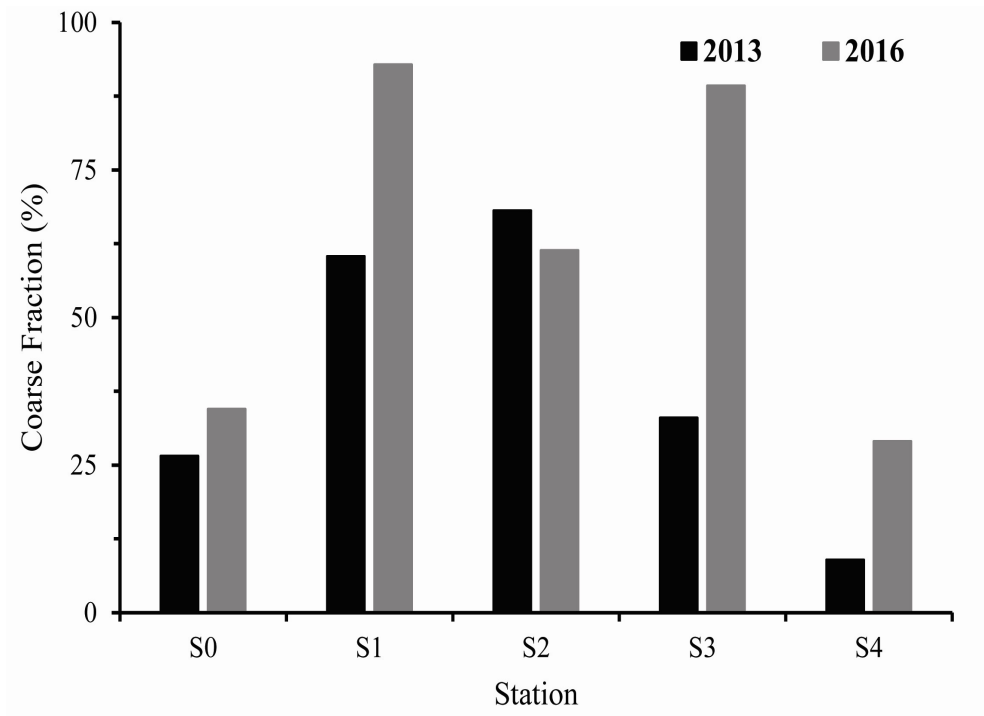


Figure 3

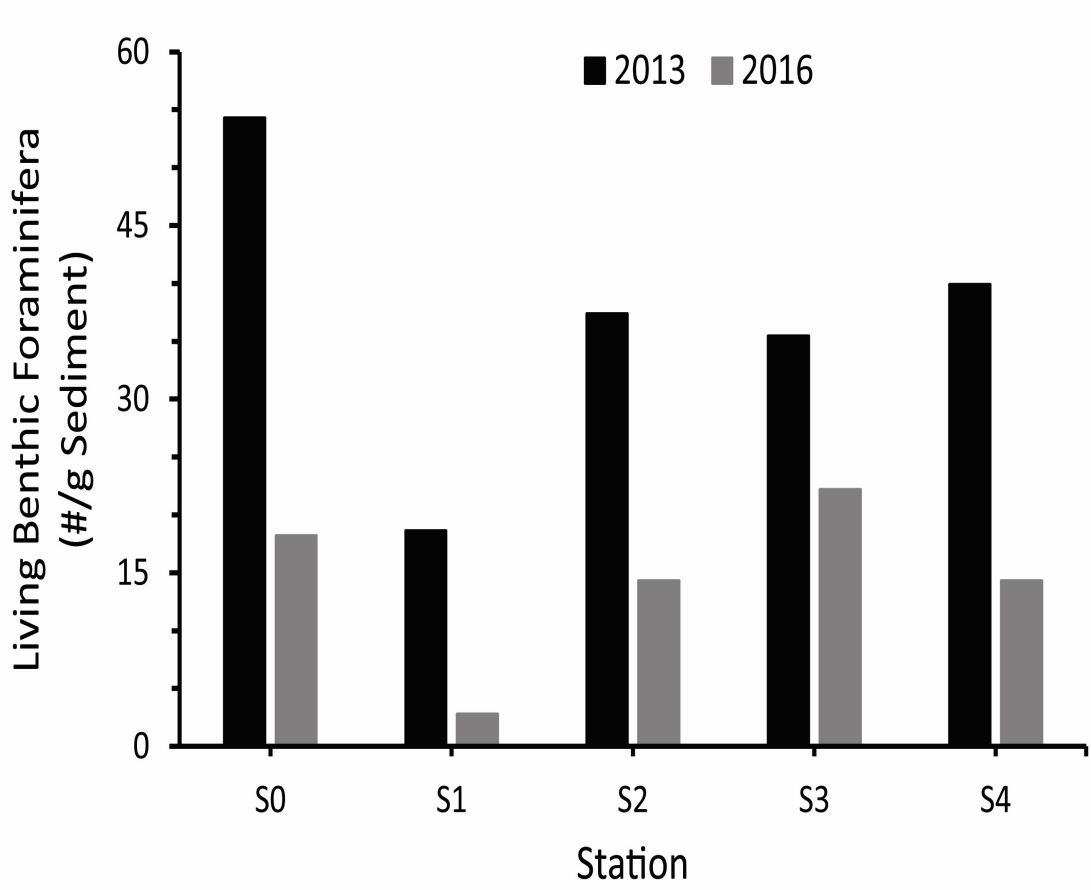


Figure 4

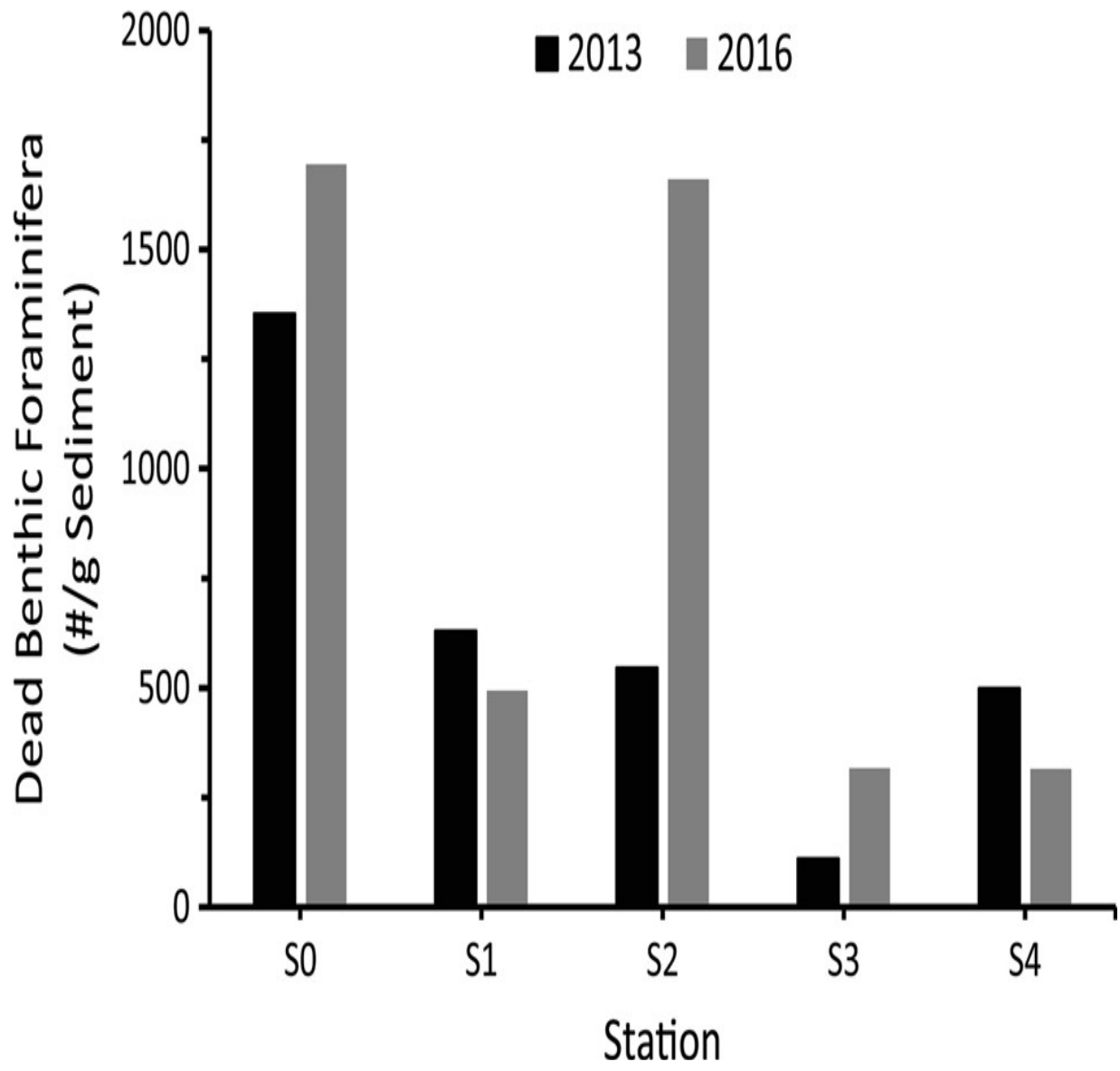


Fig. 5

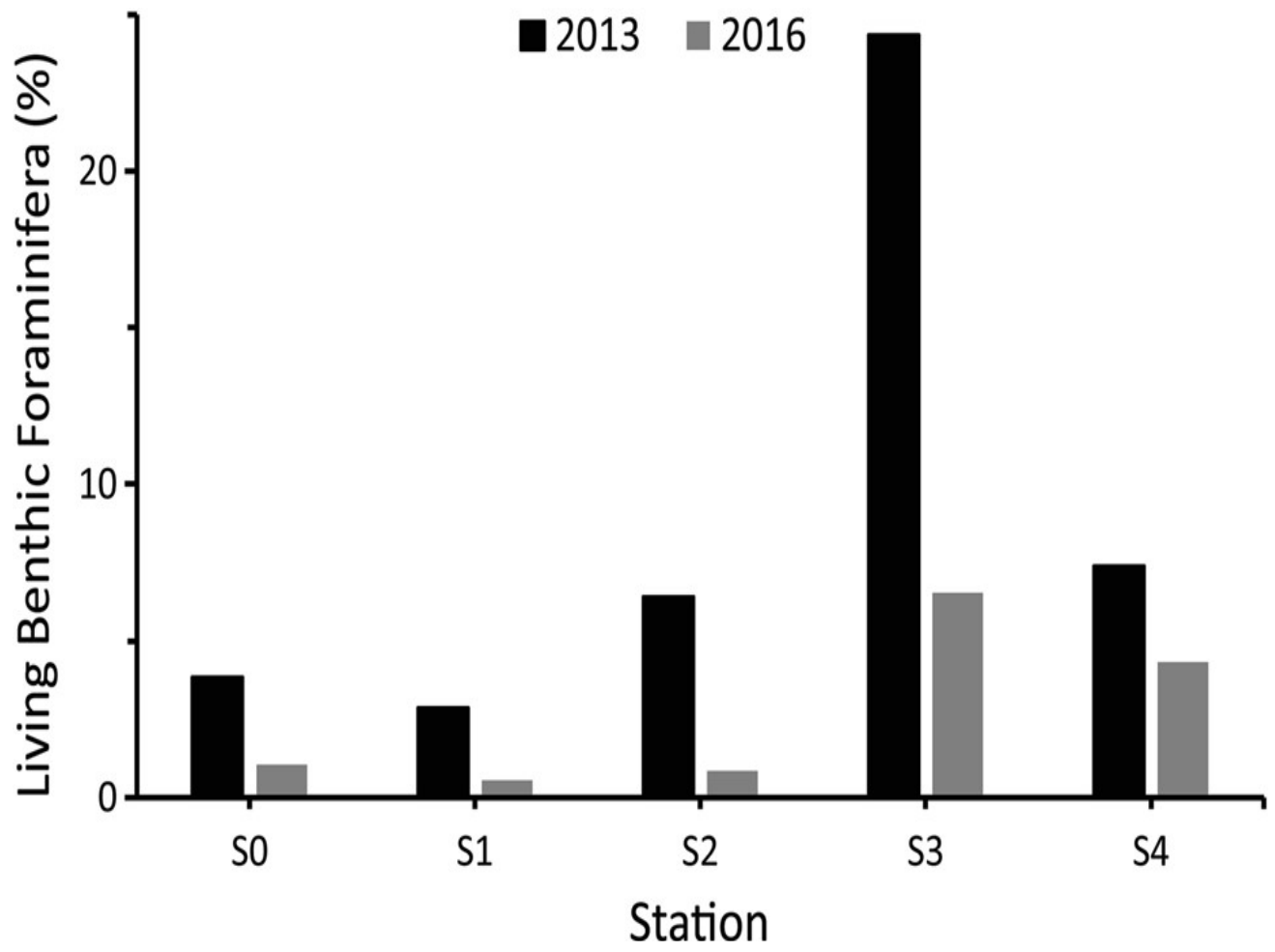


Figure 6



Figure 7

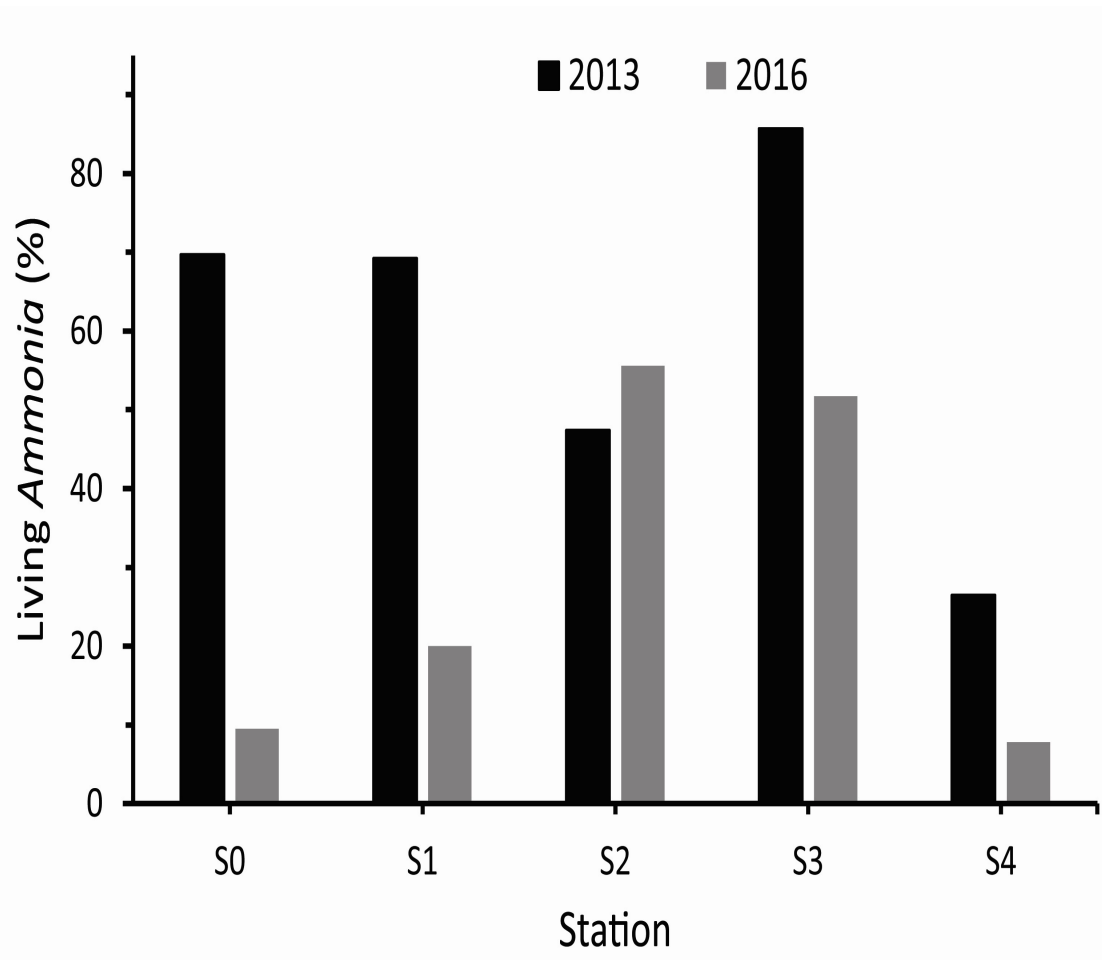


Figure 8

Table 1

Author	Title	Major Findings
Rao 1974	Ecology of Mandovi and Zuari estuaries, Goa: Distribution of foraminiferal assemblages	Poor living population in the lower reaches of both the estuaries. High total foraminiferal number (TFN) (live+dead) and high species diversity in the Zuari estuary.
Dalal 1976	Relationship between environmental parameters and foraminiferal species in Mandovi and Zuari estuaries	A reanalysis of Rao (1974) foraminiferal data.
Setty 1984	Benthic foraminifera biocoenoses in the estuarine regions of Goa.	Foraminifera are abundant in upper estuary zone. Canal zone is enriched by agglutinated species.
Nigam et al. 2002	Does mining pollution affect foraminiferal distribution in Mandovi Estuary, Goa, India	Decrease in total foraminiferal number and total suspended matter (TSM) when compared to those reported by Rao (1974). Decline in fauna attributed to continuous increase in suspended load.
Nigam et al. 2005	Foraminifera in surface sediments of Mandovi River Estuary: indicators for mining pollution and high sea stand in Goa, India	Decrease in TFN at the lower reaches of the estuary due to the increase in TSM and increase in mining activities.
Panchang et al. 2005	A foraminiferal testimony for the reduced adverse effects of mining in Zuari Estuary, Goa.	Increase in TFN as well as in TSN, which indicates clearly that health of the Zuari has improved as a result of control on mining activities.
Thejashree 2013	Study of foraminifera in cores (sub surface sediments) from Zuari Estuary, Goa and shelf	A complete absence of foraminifera due to decrease in salinity as a result of fresh water influx and high

	area of northern Bay of Bengal	mobility of the estuary.
Kannaik 2013	Assessment of the historical environments of the Mandovi-Cumbharjua- Zuari estuarine complex by using foraminifera.	Increase in TFN at the confluence of the Zuari and Cumbharjua due to reduction in mining activities.
Amol 2015	Foraminiferal response to mining activity in Goa over the last few decades: A case study from Zuari estuary	Increase in TLN and TFN due to reduction in mining which suggests improved health conditions for the Zuari estuary.