

## **Abundance and Ecology of Endemic *Asterorotalia trispinosa* from the western Bay of Bengal: Implications for its Application as Paleomonsoon Proxy**

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### **Abstract**

A total of 97 surface sediment samples were collected from the continental shelf and slope of the western Bay of Bengal to assess the potential application of *Asterorotalia trispinosa* as a paleomonsoon proxy. The relative abundance of living as well as total (living and dead) *A. trispinosa* ranges from being absent to a maximum of ~31%. The highest abundance of *A. trispinosa* is close to the outfall region of Ganga-Brahmaputra Rivers and decreases away from the river mouths. Contrary to that, *A. trispinosa* is rare in front of both the Cauvery and Pennar river outfall regions, in the central part of the western Bay of Bengal. The living *A. trispinosa* abundance is the lowest in between two major river systems, viz. Ganga-Brahmaputra-Mahanadi and Krishna-Godavari. The relative abundance of both the total and living *A. trispinosa* is strongly positively correlated with ambient seawater temperature, and negatively correlated with %C<sub>org</sub> and salinity. Based on the spatial distribution, we conclude that *A. trispinosa* is stenohaline in nature, rather than euryhaline and further that the increased relative abundance of *A. trispinosa* indicates warmer and only marginally hyposaline environment. Even though the ecological preference of *A. trispinosa* suggests it as a potential paleomonsoon proxy, the restricted distribution implies limited application.

Key words: *Asterorotalia trispinosa*, ecology, Bay of Bengal, paleomonsoon, riverine influx

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## Introduction

Reconstructing high resolution sub-centennial paleomonsoon records helps in understanding short-term monsoon dynamics. Riverine influx dominated marginal marine regions, like the northern Bay of Bengal, with very high sedimentation rate, are suitable to reconstruct high resolution multi-decadal paleomonsoon intensity. Benthic foraminifera are abundant in the marginal marine regions. Therefore, continuous efforts are made to develop benthic foraminiferal proxies to reconstruct high-resolution paleomonsoon intensity changes from marginal marine regions with high sedimentation rate. *Asterorotalia trispinosa*, a typical warm-water epifaunal benthic foraminifera, is reported by various workers from a range of shallow water environments, including estuaries, lagoons and inner shelves (Thalman, 1933; Ganapati and Satyavati 1958; Bhatia and Bhalla, 1959; Ghose, 1966; Bhalla, 1968; Rasheed and Ragothaman, 1978; Subbarao *et al.*, 1979; Min, 1989; Murray, 1991; Rao, 1998; Lambert, 2003; Gandhi and Rajamanickam 2004; Mellis and Violanti, 2006; Rana, 2009; Jayaraju *et al.*, 2011; Panchang and Nigam, 2012; Kumar *et al.*, 2012; Rao *et al.*, 2013; Anil Kumar *et al.*, 2013) (Table 1). In the northern Indian Ocean, *Asterorotalia trispinosa* is reportedly endemic to the riverine influx dominated northern Bay of Bengal and is completely absent from the comparatively hypersaline Arabian Sea (Rao *et al.*, 2013, Devi and Patil, 2009). Gandhi and Rajamanickam (2004) reported *Asterorotalia* from silty, low saline, shallow environment with a depth range of 5-7 m, in the Palk Strait along with a few other abundant genera like *Ammonia*, *Elphidium*, *Nonionoides* and *Bolivina*. In the eastern Bay of Bengal and the Andaman Sea also, *Asterorotalia trispinosa* is abundant in a shallow marine environment with a special preference for low salinity (Panchang and Nigam, 2012). The shallow water, low salinity preference of *A. trispinosa* prompted several workers to use its relative abundance as a paleomonsoon proxy (Panchang and Nigam, 2012). However, recently, Rao *et al.* (2013) studied the ecology of *A. trispinosa* from Muthupet Lagoon in the east coast of India and reported that this species is euryhaline rather than a typically marine fauna, but with an ability to tolerate salinity only as low as 29 psu. Additionally, the substrate preference of *A. trispinosa* is also debated with several workers reporting it being dominant in fine-grained silty to muddy substrate (Rao *et al.*, 2013) and others reporting its abundant presence in the medium grained (silty-sand) substrate (Jayaraju *et al.*, 2011). The majority of previous studies on the ecology of *A. trispinosa* from the eastern continental margin of India, a fresh water influx dominated region of the bay, are based on samples collected from very shallow water beach, estuarine, lagoon and inner shelf environments. From these restricted samples,

it is difficult to understand the complete range of ecological conditions preferred by *A. trispinosa*. Additionally, the ecology and distribution of *A. trispinosa* have not been studied in detail from the freshwater influx dominated western Bay of Bengal, which is influenced by major river systems, viz. Ganga-Brahmaputra-Mahanadi, Krishna-Godavari-Pennar, and Cauveri. Therefore, it is important to understand the complete ecological preferences of *A. trispinosa* by studying its distribution from the fresh water flux dominated continental shelf and slope of the western Bay of Bengal, to assess its applicability as a paleomonsoon proxy.

## 2. Environmental Settings

The Bay of Bengal is one of the largest fresh water and sediment input sites of the Indian Ocean (Emmel and Curray, 1984). The annual fresh water discharge into the Bay exceeds  $1.6 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$  (UNESCO, 1979) with heavy precipitation ( $\sim 2 \text{ m yr}^{-1}$ ) (Prasad, 1997). The main fresh water contribution into the bay is by Ganga, Brahmaputra and Ayeyarwaddy rivers. The peninsular Indian rivers, Mahanadi, Krishna-Godavari and Cauvery also contribute a large volume of water to the western Bay of Bengal. Presently, these rivers together also supply about 1350 million tons of sediments per year to the Bay of Bengal, which accounts for  $\sim 8\%$  of the total riverine supply to the oceans (Milliman and Syvitski, 1992; Milliman, 2001). The fluvial input is the major source of nutrients to the bay. The annual supply of nutrients by the Ganga and Brahmaputra Rivers to the Bay of Bengal is  $133 \times 10^9 \text{ mol yr}^{-1}$  and is  $\sim 2\%$  of the riverine input to the world ocean (Sarin *et al.*, 1989). The fresh water influx considerably lowers the salinity of marginally marine regions of the western Bay of Bengal (Sengupta *et al.*, 2006; Durand *et al.*, 2011). The Bay is forced by the seasonally reversing monsoon winds that drive the East India coastal current (Shankar *et al.*, 1996; Durand *et al.*, 2009). It flows northward from February to September and southward from October to January. The East India coastal current is responsible for the southward propagation of relatively hyposaline water, in a narrow ( $\sim 100 \text{ km}$  wide) strip along the eastern coast of India, during the post southwest monsoon season (Chaitanya *et al.*, 2014). The Bay of Bengal is traditionally considered to be a region of low biological productivity. The low productivity is attributed to strong stratification driven by freshwater runoff that limits nutrient recycling by wind-driven mixing, as well as cloud cover and suspended particulates that disrupt light availability for phytoplankton (Gomes *et al.*, 2000; Madhupratap *et al.*, 2003; Prassana Kumar *et al.*, 2010). An oxygen minimum zone within a depth range of  $\sim 100 \text{ m}$  to  $800 \text{ m}$ , with strong latitudinal and seasonal variations, is also reported from the western Bay of Bengal (Wyrтки, 1971; Naqvi *et al.*, 1979; Rao *et al.*, 1994).

### 3. Materials and Methodology

The top 0-1 cm section of 64 multi-cores (MC 02 to MC 71) and 33 box cores (SC 01 to SC 46), collected from the western Bay of Bengal, from a depth range of 27 m to 2540 m, during the 308<sup>th</sup> expedition of *ORV Sagar Kanya* (SK 308) and 35<sup>th</sup> cruise of *RV Sindhu Sankalp* (SSK 35) were used for this study (Figure 1, Table 2). The half of the top section was stained with Rose-Bengal, immediately after collection, to distinguish the abundance of living benthic foraminifera. The Rose-Bengal technique is considered to be an inexpensive and easy method to recognize foraminifera that were alive (or recently alive) at the time of sample collection (Walton, 1952; Murray and Bowser, 2000). The stained samples were stored in ethanol until further processing. The standard procedure was followed for the processing of sediment samples for foraminiferal studies. An appropriate amount (15-20 g) of sediment was collected in pre-weighed and properly labeled petri dish. The petri-dish was covered by cling film and deep frozen for 24 hours at -30 °C. The frozen sediment samples were then freeze-dried. Freeze-drying helped in avoiding the hard lumps that usually form if the clay and organic matter rich sediments are oven dried. The dried sediment samples were weighed and transferred to 1000 ml beakers. The samples were soaked in distilled water. The overlying water was decanted from the beakers after 24 hr, and again filled with distilled water, to remove suspended colloidal matter. The procedure of decanting and re-filling of the overlying water was repeated until the overlying water was clear. The water from the beakers was finally decanted. The wet sediment samples were sieved by using a 63 µm mesh with very low water pressure to prevent foraminiferal test breakage. The >63 µm fraction (coarse fraction, CF) was transferred to a glass beaker and dried overnight. The dried coarse fraction was weighed and stored in plastic vials. Foraminifera were picked from a representative fraction taken out of the total coarse fraction by coning and quartering, by using Olympus SZX 12 stereozoom microscope. A minimum of 300 living benthic foraminifera (Rose-Bengal stained) and total benthic foraminifera (both living and dead assemblage) were picked from each sample. In the case of lack of living specimens, a specific coarse fraction weight (0.5 g) was used to pick all the available benthic foraminifera, which at times yielded less than 300 specimens. A strict staining criterion was applied to reduce the overestimation of the living benthic foraminiferal number. The number of *A. trispinosa* specimens was then counted to calculate its relative abundance.

The bottom water salinity and pH at all the 64 multi-core locations were measured onboard. The advantage of multi-core is the sampling of the completely intact sediment-water interface. The

salinity and pH of the seawater overlying the sediments was measured immediately after the samples were brought onboard, by using a hand-held multimeter (model number: S47-K/SevenMulti'). The salinity, temperature and dissolved oxygen (DO) at the 33 box core stations, as well as the temperature and DO at the multi-core stations, were downloaded from the World Ocean Atlas 2009 (Locarnini *et al.*, 2010; Antonov *et al.*, 2010; Garcia *et al.*, 2010), by using Ocean Data View website (Schlitzer, 2015) (Table 3). The total inorganic carbon (TIC) was measured by using UIC CM 5014 coulometer after acidification of the sample with 1N HCl and measuring the CO<sub>2</sub>. The analytical accuracy is  $\pm 0.43\%$ , and precision of total inorganic carbon analysis is  $\pm 0.95\%$ . The total carbon (TC) and nitrogen (TN) was measured with a CE NCS 2500 elemental analyzer. The total organic carbon (%C<sub>org</sub>) was calculated by subtracting total inorganic carbon from total carbon. Both the principal component analysis (PCA) and Pearson's correlation analysis performed by using STATISTICA 6.0, were used to evaluate how well the environmental variables explained the distribution of *Asterorotalia trispinosa* in the western Bay of Bengal.

## 4. Results

### 4.1. Environmental Parameters

A large variation was found in the environmental parameters within the sampling locations. The bottom water salinity varies from a minimum of 32.28 psu (at 29 m water depth) to the maximum of 35.50 psu (at 259 m water depth). The bottom water temperature varies from  $\sim 2.0$  °C (at 979 m water depth) to  $\sim 27.5$  °C (at 28 m water depth). The bottom water dissolved oxygen varied from 0.43 ml/l (at 120 m water depth) to 4.78 ml/l (at 73 m water depth). The pH of the bottom water varied from a minimum of 7.53 (at 2482 m water depth) to 8.15 (at shallower water depths,  $\sim 30$  to 70 m). The coarse fraction was very low at the majority of the stations with its abundance varying from  $\sim 0.09\%$  (at 69 m water depth) to  $\sim 98\%$  (at 36 m water depth) (Table 2) (Figure 2). The sediments are comparatively coarser in the shelf between the Ganga-Brahmaputra and Mahanadi outfall regions. The coarse fraction abundance decreases from the shelf to slope region. Another patch of higher coarse fraction lies in the southern part of the study area. The maximum %C<sub>org</sub> is in the slope region of the central western Bay of Bengal (Figure 3). The spatial variation in %C<sub>org</sub> is opposite to that of coarse fraction. The continental shelf region has comparatively less %C<sub>org</sub>, and the highest %C<sub>org</sub> is in front of the Godavari River outfall region (Figure 3). The C<sub>org</sub>:TN ratio (which describes the origin of organic carbon) varies from as low as  $\sim 6$  to as high as  $\sim 35$ . The C<sub>org</sub>:TN ratio is the highest in the shelf region in front of the major river systems (Figure 4). The highest TIC is observed in the

northern and southern part of the study area with the lowest values in the lower slope and abyssal regions of the central western Bay of Bengal (Figure 5). The zones of high TIC are away from the major river systems' outfall regions.

#### 4.2. Distribution of *Asterorotalia trispinosa*

*Asterorotalia trispinosa* (living and dead) was found in only 33 samples out of the total 97 samples. The relative abundance of total *A. trispinosa* varies from being absent at more than half of the stations to a maximum of 23% at 28 m water depth in front of Ganga-Brahmaputra river outfall region (SC 16). The highest *A. trispinosa* (living and total) abundance is in the inner continental shelf region, very close to the river mouths. The abundance decreases away from the river mouths, and it is rarely present in the continental slope and abyssal regions (Figure 6A and 6B). *A. trispinosa* is absent at stations deeper than ~100 m and its relative abundance is <1% below ~50 m, with only a few exceptions. The abundance in front of the river outfall regions is proportional to their fresh water influx. The highest relative abundance is in front of Ganga-Brahmaputra, followed by that in front of the Mahanadi and Krishna-Godavari and rare in front of Pennar and Cauvery river outfall region. The living *A. trispinosa* are present in 25 samples out of the total 97 samples. The relative abundance of living *A. trispinosa* varies from being zero to a maximum of 31.5% at SC 01 (at 31 m water depth) (Table 3). The living *A. trispinosa* is absent in between two major river systems, viz. Ganga-Brahmaputra-Mahanadi and Krishna-Godavari's outfall region. The relative abundance of total *A. trispinosa* is also very low (<2%) in between these river systems. The range of relative abundance of both the total and living *A. trispinosa* (0-23.0% and 0-31.5%, respectively) is comparable, except in the southern part of the study area. A difference in the relative abundance of living and total *A. trispinosa* is observed only in the southern part of the study area, in front of Pennar and Cauvery rivers. From the figures 6A and 6B also, it is clear that the relative abundances of total and living *A. trispinosa* are comparable, except in the southern part of the study area, suggesting limited transport and reworking of the sediments.

Principal Component Analysis (PCA) was carried out to understand the relationship between the relative abundance of *A. trispinosa* and environmental variables (CF, TIC, %C<sub>org</sub>, C<sub>org</sub>/TN, Salinity, Temperature, DO). The relative abundance of both the total and living *A. trispinosa* have a similar trend with the environmental variables (Figure 7). Out of all the environmental variables, *A. trispinosa* relative abundance is strongly positively correlated with seawater temperature. On the other hand, %C<sub>org</sub> and salinity are negatively correlated with both the total and living *A. trispinosa*

relative abundance. The TIC, CF, DO and  $C_{org}/TN$  do not exert a dominant control on the relative abundance of *A. trispinosa*. The findings were further confirmed by simple correlation analysis (Table 4). The marked correlations are significant at  $p < 0.05$ .

## 5. Discussion

The relative abundance of *A. trispinosa* in the continental shelf region of the western Bay of Bengal is lower than that reported from estuaries and lagoons of the east coast of India. In the Muthupet Lagoon, both the living and total benthic foraminiferal population almost entirely (>90%) comprise of *A. trispinosa* (Rao *et al.*, 2013). *A. trispinosa* is comparatively more abundant (with relative abundance ~42%) in the eastern Bay of Bengal (Panchang and Nigam, 2012) than in the western Bay of Bengal. The reported presence of *A. trispinosa* only in the inner shelf sediments has often been used to infer tsunamigenic sediments from the terrestrial regions (Nagendra *et al.*, 2005; Sugawara *et al.*, 2009; Yawsangratt *et al.*, 2012; Brill *et al.*, 2014), as well as to reconstruct paleo-sea level (Biswas, 1973). But, here we report that the relative abundance of *A. trispinosa* is not uniformly high throughout the shallow water regions including lagoons and estuaries, off the eastern continental margin of India. Therefore, even though, *A. trispinosa* are abundant in the continental shelf region, its distribution in the western Bay of Bengal is controlled by several parameters other than water depth.

### 5.1. Relationship with Substrate

We do not find any significant relation between sediment grain-size and the relative abundance of both the living (correlation = -0.0409) and total (correlation = 0.0077) *A. trispinosa* in the western Bay of Bengal (Figure 7). Most of the previous reports suggested that the substrate is one of the major parameters that control *A. trispinosa* distribution. *A. trispinosa* is abundant in silty sand and muddy substrate (Inoue, 1989; Rao *et al.*, 1990; Orpin *et al.*, 1999; Gallagher *et al.*, 2009; Gandhi and Solai, 2010; Panchang and Nigam 2012; Natsir *et al.*, 2012; Rao *et al.*, 2013). Ghose (1966) discussed the significance of spines in *A. trispinosa* and inferred that the long slender spines helped the species to increase its buoyancy to remain suspended just above the substrate. *A. trispinosa* was also present in the Visakhapatnam Beach sands (Bhalla, 1968). Contrary to that, at a few other places, *A. trispinosa* was reported from comparatively fine-grained silty and clayey substrate (Gandhi *et al.*, 2014; Yahya *et al.*, 2014). In the middle of the Uppateru River Estuary, on the east coast of India, *A. trispinosa* were abundant in medium grained sediments, and their population

decreased towards both the seaward and upstream of the river, suggesting a close relationship between sediment grain size and its abundance (Jayaraju *et al.*, 2011). In the Malacca Strait off Malaysia, *Asterorotalia* is abundant in clayey and silty sediments (Yahya *et al.*, 2014). Based on this work, however, we suggest that *A. trispinosa* does not prefer any particular substrate and further that the previously reported abundant presence of several *Asterorotalia* species in the comparatively coarse grained substrate is because a majority of the studies were based on samples collected from shallow water regions dominated by coarse-grained substrates.

## 5.2. Relationship with seawater temperature-salinity

The highest relative abundance of *A. trispinosa* in the vicinity of two major river systems (Ganga-Brahmaputra-Mahanadi and Krishna-Godavari) clearly confirms its preference for hyposaline waters. The preference of *A. trispinosa* for low salinity is further confirmed by the significant correlation between the relative abundance of both the living (correlation = -0.3372) and total (correlation = -0.4080) *A. trispinosa* and ambient seawater salinity (Table 4). The living and dead *A. trispinosa* were present at stations with ambient seawater salinity varying from 32.28 psu to 35.35 psu (Table 2). The enormous amount of fresh water influx from these rivers considerably decreases the seawater salinity. Several previous workers have mentioned that salinity is an important factor that influences *A. trispinosa* distribution (Rao, 1998; Rana, 2009; Panchang and Nigam, 2012; Rao *et al.*, 2013). The reported high relative abundance of *A. trispinosa* only in the outer channel of Chilka Lagoon (Jayalakshmy and Rao, 2001), however, suggests that it does not tolerate very low saline water. Rather, *A. trispinosa* prefers regions with salinity varying within a range, as observed in areas affected by the riverine influx. A similar conclusion was also drawn by Rao *et al.* (2013) based on the ecology of *A. trispinosa* from Muthupet Lagoon in the east coast of India. They reported that *A. trispinosa* is euryhaline rather than a typically marine fauna, with an ability to tolerate salinity only as low as 29 psu. The laboratory culture studies also confirm a wide salinity tolerance range of a few other shallow water epifaunal benthic foraminiferal species of the northern Indian Ocean (Nigam *et al.*, 2006; Linshy *et al.*, 2007; Nigam *et al.*, 2008; Kurtarkar *et al.*, 2011; Saraswat *et al.*, 2015). It should, however, be noted here that *A. trispinosa* is rarely present in front of Cauvery and Pennar river outfall regions in the central-western Bay of Bengal. Similarly, *A. trispinosa* was absent in the region further south, that is the inner shelf of Gulf of Mannar, off Tuticorin (Babu *et al.*, 2014).

Based on PCA analysis, we infer that *A. trispinosa* prefers warm water. The living *A. trispinosa* was present at stations with ambient seawater temperature varying from 23.05 °C to 27.54 °C, and

dead were found at stations with temperature varying from 21.7 °C to 27.54 °C (Table 2). The preference of *A. trispinosa* for warmer water is further confirmed by the strong positive correlation between the relative abundance of both the living (correlation = 0.4705) and total (correlation = 0.3130) *A. trispinosa* and ambient seawater temperature. The earlier higher abundance of *A. trispinosa* was observed in the samples collected during pre-monsoon than in the post monsoon (Gandhi and Solai, 2010; Jayaraju *et al.*, 2011). The relative abundance was higher at stations with more than 36 psu salinity (Jayaraju *et al.*, 2011). The higher abundance during pre-monsoon season at stations having comparatively higher salinity, suggests that *A. trispinosa* prefers relatively warmer water. Panchang and Nigam (2012) also reported that the relative abundance of *A. trispinosa* is positively correlated with temperature of the ambient seawater, in the eastern Bay of Bengal and the Andaman Sea. In the Malacca Strait off Malaysia also, *A. trispinosa* were abundant in relatively hyposaline (29.11 psu) but warmer (29.97±0.05 °C) waters (Yahya *et al.*, 2014). The fresh water discharge causes warm anomalies, as fresher surface waters increase the vertical stability of the water column that inhibits the downward export of heat. The heat entrained in the surface waters, warms the upper layers (Durand *et al.*, 2011). Interestingly, *A. trispinosa* was not present at all stations with warm ambient seawater (Table 2). Therefore, we conclude that *A. trispinosa* is significantly abundant only in the inner shelf adjacent to the outfall regions of large river systems. It implies that even though *A. trispinosa* prefers euryhaline warmer waters found in front of the outfall regions of large rivers, the application of temporal variations in its relative abundance to reconstruct paleomonsoon intensity will be limited to very restricted regions.

### **5.3. Relationship with organic matter**

The relative abundance of *A. trispinosa* is inversely related to %C<sub>org</sub>. In the Palk Strait region of the western Bay of Bengal, rare dead *A. trispinosa* were, also reported from regions having low %C<sub>org</sub> (0.64 %) (Gandhi and Rajamanickam, 2004). Contrary to this, no apparent relationship was observed between *A. trispinosa* relative abundance and %C<sub>org</sub> in the Muthupet Lagoon, where %C<sub>org</sub> varies from 0.69 to 1.48 % (Rao *et al.*, 2013). It was however, noted that *A. trispinosa* inhabit regions with sufficient amount of %C<sub>org</sub> (Rao *et al.*, 2013). But in the present study, based on the statistical analyses, we infer that %C<sub>org</sub> negatively affects the abundance of *A. trispinosa* in the western Bay of Bengal. The high relative abundance at stations having low %C<sub>org</sub> also indicates its preference for the regions close to river mouths, as the productivity is usually low, very close to the river mouths, due

to high turbidity that limits light penetration and thus hampers phytoplankton growth (Prasanna Kumar *et al.*, 2010).

#### **5.4. Other Factors (Dissolved Oxygen, pH)**

We do not find any relation between the relative abundance of *A. trispinosa* and dissolved oxygen concentration in the western Bay of Bengal. The findings based on samples collected from the wider shelf and slope of the western Bay of Bengal are in contrast with that based on samples collected from the shelf and upper slope of the northwestern Bay of Bengal, wherein high abundance of *A. trispinosa* is observed in well-oxygenated waters (Manasa *et al.*, 2016). It should, however, be noted here that the samples in the northwestern Bay of Bengal covered a limited range of physico-chemical parameters as compared to the samples used in this study (Manasa *et al.*, 2016). The response of *A. trispinosa* to dissolved oxygen is, however, mixed as Frerichs (1970) found *A. trispinosa* in less oxygenated waters of the inner shelf regions of the Andaman Sea. Similarly, just the sufficient availability of dissolved oxygen was reported as the prerequisite for abundant presence of *A. trispinosa* (Rao *et al.*, 2013). The higher abundance of *A. trispinosa* in front of the outfall region of Ganga-Brahmaputra rivers than that of the Mahanadi, Krishna and Godavari River could be related to the pH of the river water. The more alkaline pH correlates well with, the higher relative abundance of *A. trispinosa*. The pH of the Ganga-Brahmaputra rivers (8.13) is higher than Mahanadi (7.020), Krishna (7.219) and Godavari River (7.470) (Sarma *et al.*, 2012). Rao *et al.* (2013) also observed a positive relation between *A. trispinosa* relative abundance and pH. Since pH values are missing for a few of the sampling locations, we could not include pH in the statistical analyses.

#### **6. Conclusions**

Based on the distribution in the surface samples collected from the shelf and slope of the western Bay of Bengal, we report that living and total *Asterorotalia trispinosa* is abundant in the inner shelf adjacent to the outfall regions of large Ganga-Brahmaputra-Mahanadi River system. The species is rarely present in front of Krishna-Godavari-Pennar River system. We further report that *A. trispinosa* is more abundant in the western Bay of Bengal than in the eastern Bay of Bengal. The abundant presence of *A. trispinosa* positively correlates with temperature and is negatively related to salinity and %C<sub>org</sub>. We conclude that the spatial variation of *A. trispinosa* abundance in the study area is controlled by the terrigenous and freshwater influx and resultant changes in physico-chemical conditions. It implies that even though *A. trispinosa* prefers stenohaline warmer waters found in front

of the outfall regions of large rivers, the application of temporal variations in its relative abundance to reconstruct paleomonsoon intensity will be limited to very restricted regions.

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**Fig. 1.** The study area map showing sampling locations and bathymetry. The inset map shows the study area in the northern Indian Ocean. The major rivers draining in to the western Bay of Bengal, are shown in black line. The sample locations are marked by filled inverted triangles. The bathymetry is marked by black contours.

**Fig. 2.** The distribution of coarse fraction percentage (CF%) in the western Bay of Bengal. The scale is on the right side. The major rivers draining in to the western Bay of Bengal, are shown in black line. The sample locations are marked by filled inverted triangles. The bathymetry is marked by black contours.

**Fig. 3.** The distribution of organic carbon (%C<sub>org</sub>) in the western Bay of Bengal. The scale is on the right side. The major rivers draining in to the western Bay of Bengal, are shown in black line. The sample locations are marked by filled inverted triangles. The bathymetry is marked by black contours.

**Fig. 4.** The distribution of C<sub>org</sub>/TN in the western Bay of Bengal. The scale is on the right side. The major rivers draining in to the western Bay of Bengal, are shown in black line. The sample locations are marked by filled inverted triangles. The bathymetry is marked by black contours.

**Fig. 5.** The distribution of total inorganic carbon (TIC%), in the western Bay of Bengal. The scale is on the right side. The major rivers draining in to the western Bay of Bengal, are shown in black line. The sample locations are marked by filled inverted triangles. The bathymetry is marked by black contours.

**Fig. 6.** The distribution of relative abundance of living (A), and total *Asterorotalia trispinosa* (B) in the western Bay of Bengal. The major rivers draining in to the western Bay of Bengal, are shown in black line. The sample locations are marked by filled inverted triangles. The bathymetry is marked by black contours.

**Fig. 7.** PCA diagram showing biota and environmental variables. Living aster = Living *Asterorotalia trispinosa*, Dead Aster = Total *Asterorotalia trispinosa*, %C<sub>org</sub> = Organic carbon, Sal = Salinity, TIC% = Total inorganic carbon, CF% = Coarse fraction percentage, DO = Dissolved oxygen, T = Temperature.

**Table 1** Previous reports of *Asterorotalia trispinosa* from different regions of the world.

**Table 2** Details of the sample locations and environmental parameters in the study area.

**Table 3** Details of living and total *Asterorotalia trispinosa* and sampling locations.

**Table 4** Correlation between different environmental variables and *Asterorotalia trispinosa*. \* indicate the significance. Marked correlations are significant at  $p < 0.05$ .

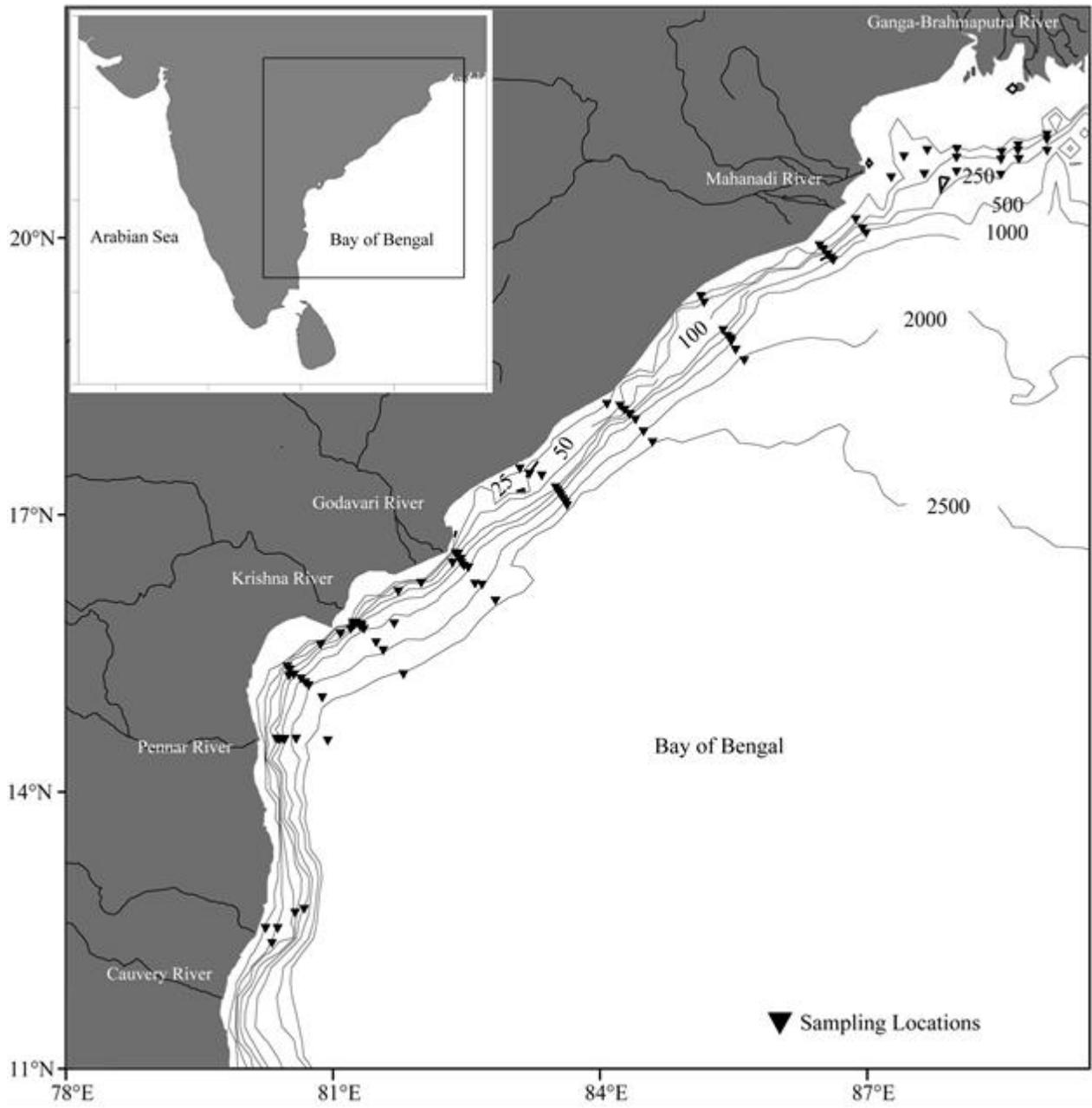


Figure 1

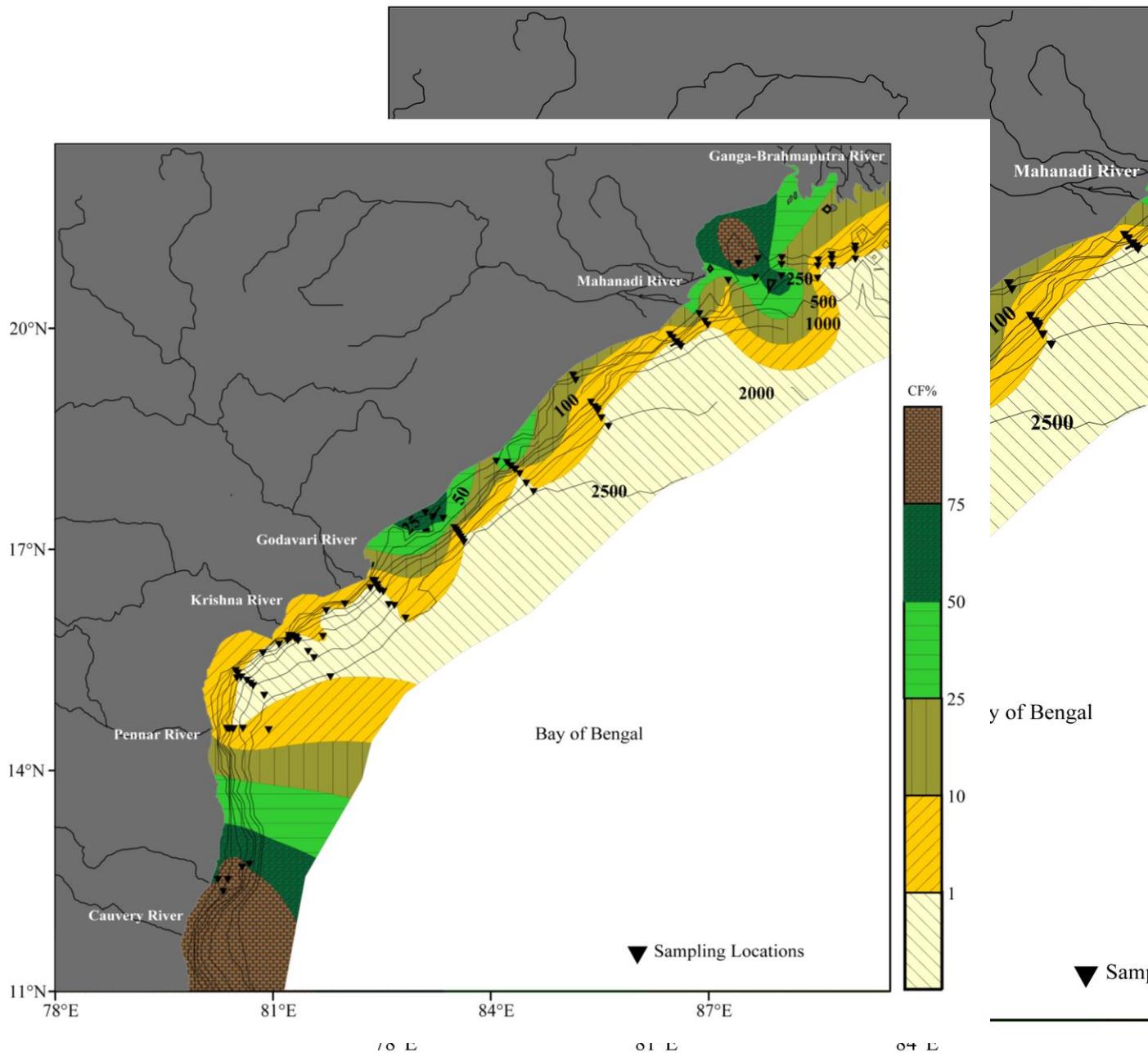
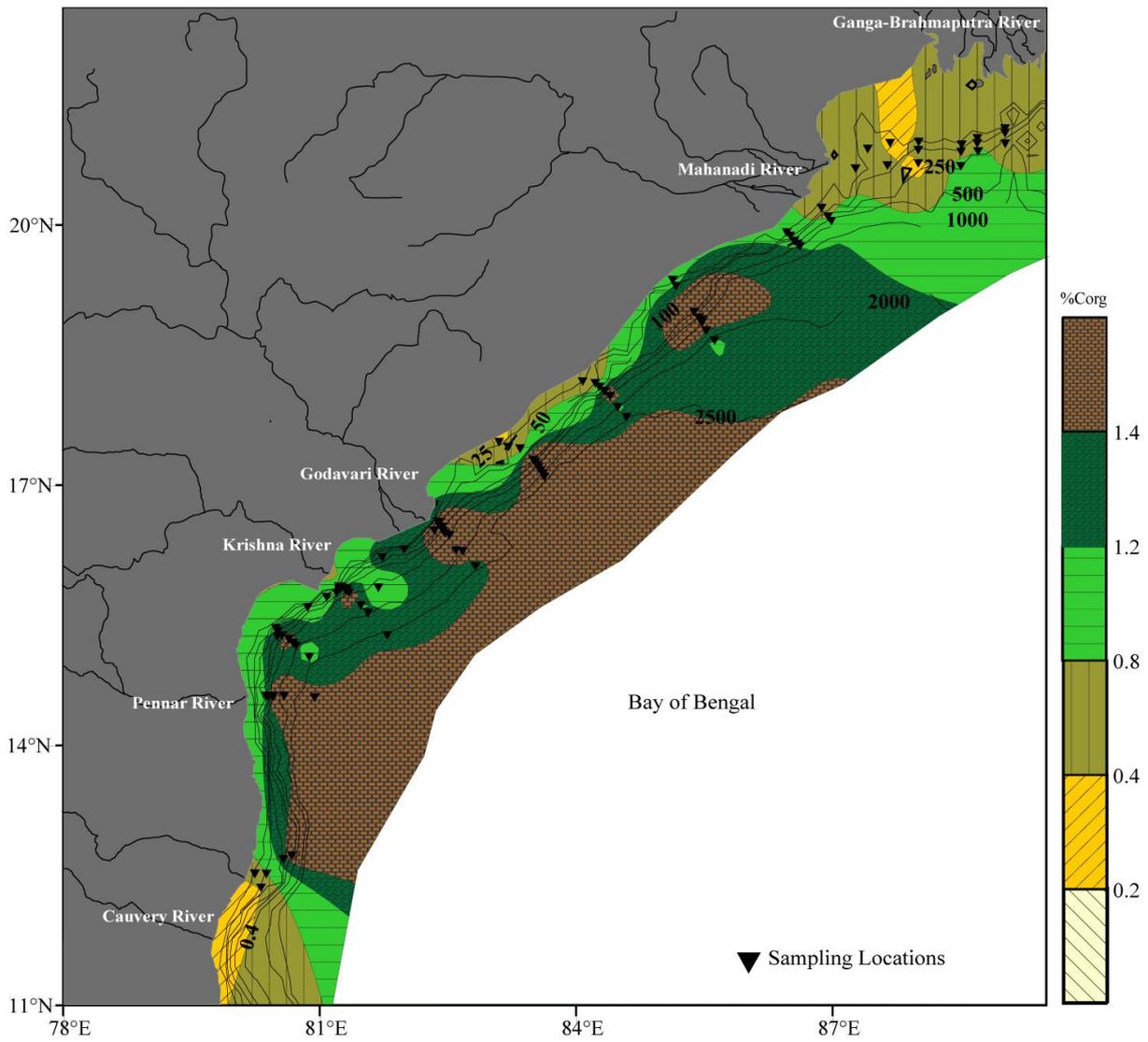


Figure 2



**Figure 3**

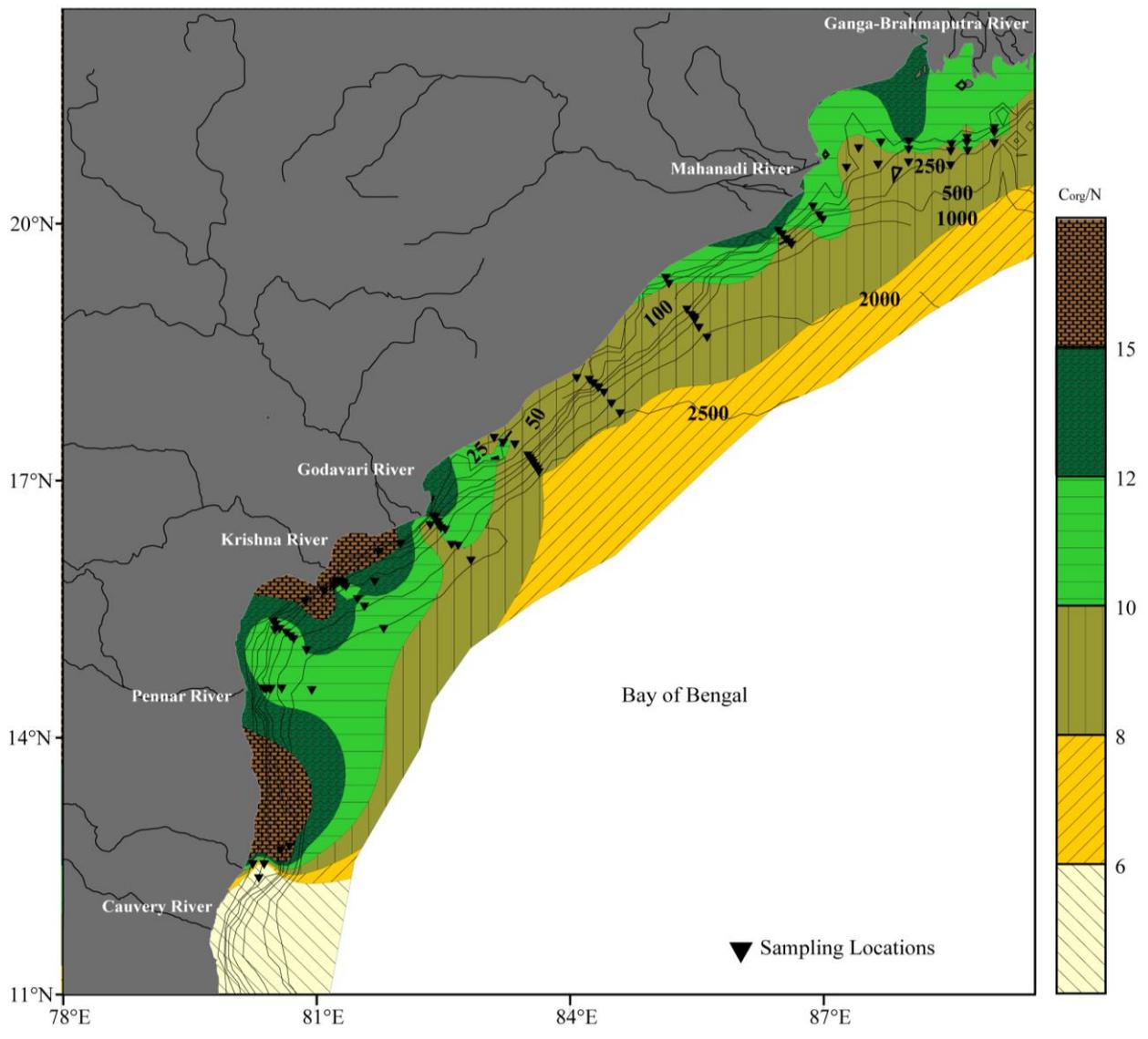


Figure 4

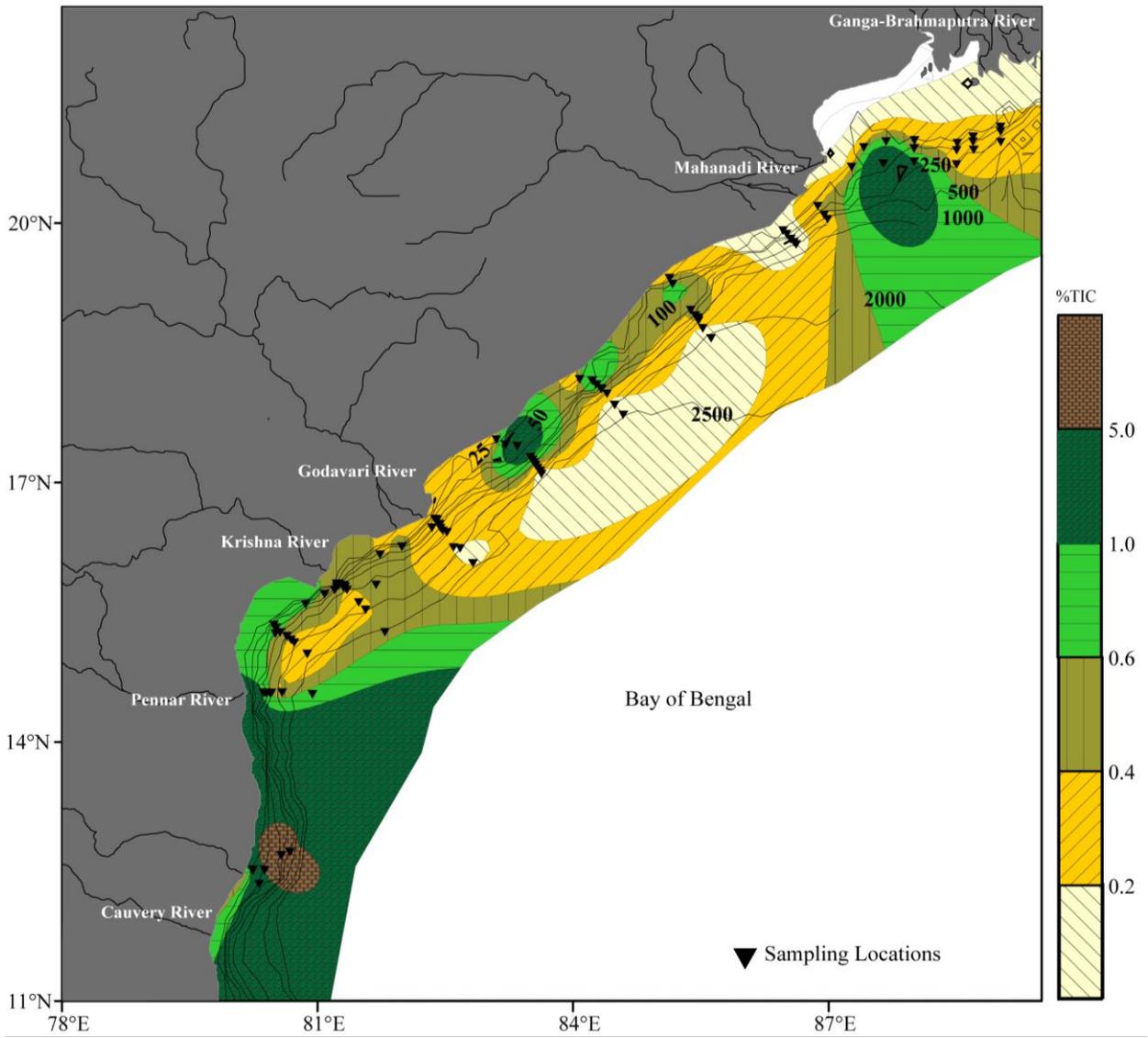


Figure 5

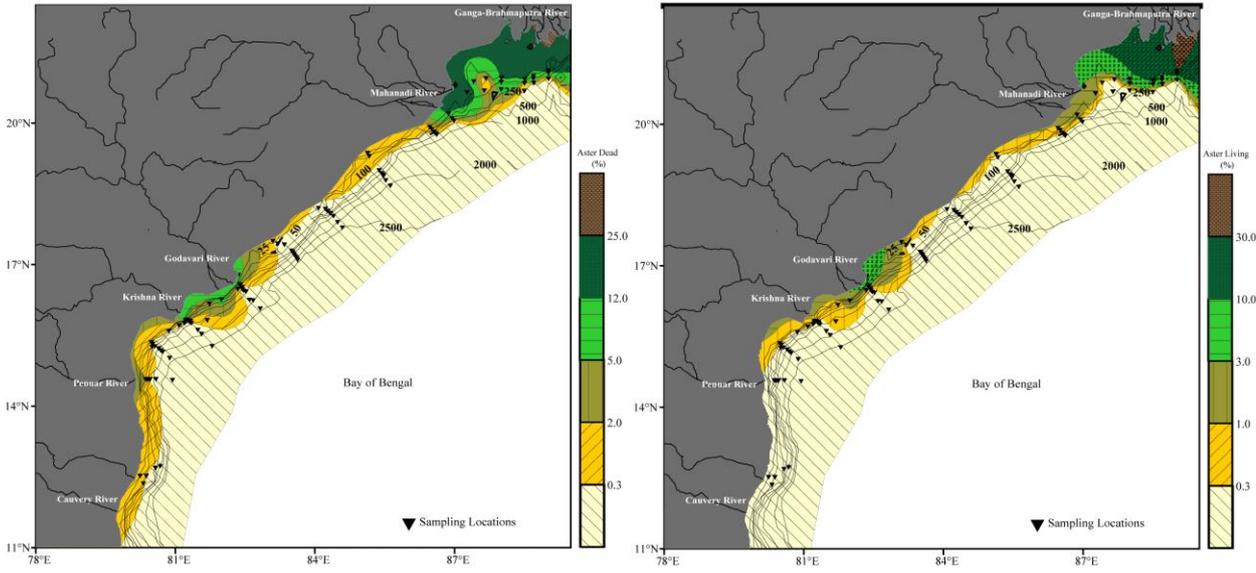


Figure 6

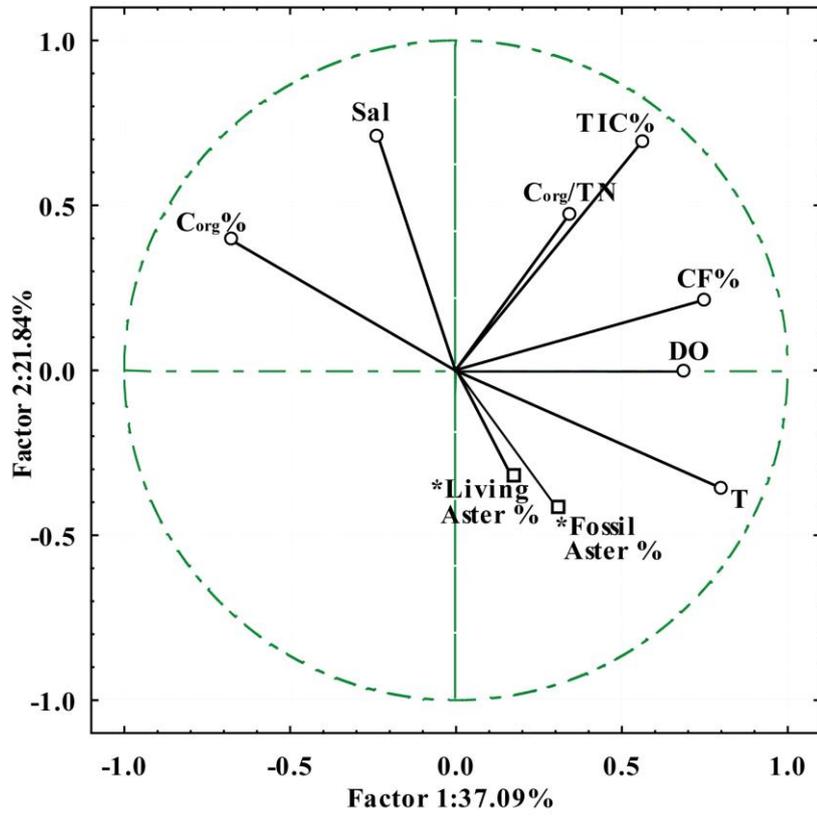


Figure 7

Sl. No.	Author	Year	Location	Depth (m)	Temp (°C)	Sal (psu)
1.	Anil Kumar <i>et al.</i>	2013	Chilka Lake, east coast of India	0.3-4.2	23.6-31.5	30.8-40.9
2.	Anil Kumar and Rao	2014	Chilka Lake, east coast of India	NA	27-32	30-40
3.	Bhatia and Bhalla	1959	Puri, Orissa, east coast of India	Beach sand	NA	NA
4.	Biswas	1973	Continental shelf, South China sea	~9-15	NA	NA
5.	Devi and Patil	2009	East coast of India	NA	NA	NA
6.	Frerichs	1970	Andaman Sea	20-32	26.44-27.01	32.32-33.07
7.	Gandhi and Rajamanickam	2004	Palk Strait, east coast of India	5-7	NA	33.67
8.	Gandhi <i>et al.</i>	2002	Palk Strait	NA	NA	NA
9.	Gandhi <i>et al.</i>	2014	Palk Bay, east coast of India	1-10	35	34.3
10.	Ghose	1966	Digha, Bengal	Beach sand	NA	NA
11.	Ghosh <i>et al.</i>	2014	Off Midnapore, east coast of India	Intertidal region	NA	NA
12.	Jayalakshmi <i>et al.</i>	2001	Chilka Lake, east coast of India	NA	NA	NA
13.	Jayaraju <i>et al.</i>	1998	Pulikat Lake, east coast of India	NA	NA	35.2-35.4
14.	Jayaraju <i>et al.</i>	2011	Uppateru River Estuary, east coast of India	0.7-2.1	34.4-34.8	35.2-36.8
15.	Kumar <i>et al.</i>	2012	Gosthani Estuary, Andhra Pradesh	NA	NA	NA
16.	Manasa <i>et al.</i>	2016	North western Bay of Bengal	28-60	22-27	32-34
17.	Nagendra <i>et al.</i>	2005	Nagapatnam coast, east coast of India	NA	NA	NA
18.	Natsir <i>et al.</i>	2012	Tambelan Islands, Indonesia	34.18, 48.98	NA	NA
19.	Panchang and Nigam	2012	Eastern Bay of Bengal and Andaman Sea	18-40	27.20-27.77	31.78-32.56
20.	Rana	2009	Central east coast of India	20-77	NA	NA
21.	Rao <i>et al.</i>	1990	Nizampatnam Bay, east coast of India	0-15	NA	NA
22.	Rao	1998	Inner Shelf off Karikkattukuppam	NA	NA	31-33
23.	Rao <i>et al.</i>	2000	Chilka Lake, east coast of India	NA	NA	24.06
24.	Rao and Nandhakumar	2012	Inner shelf off Chennai, Bay of Bengal	NA	NA	NA
25.	Rao <i>et al.</i>	2013	Muthupet Lagoon, SE coast of India	0.10-0.82	29-30	28.9-33.6
26.	Rao <i>et al.</i>	2014	Nizampatnam Bay, east coast of India	0.5-3	NA	NA
27.	Subbarao <i>et al.</i>	1979	Visakhapatnam Shelf, east	20	27.5-27.9	32.6-32.8

			Coast of India			
28.	Thilagavathi <i>et al.</i>	2012	Palk strait, east coast of India	0-25	27.5-32.0	27-34.5
29.	Yahya <i>et al.</i>	2014	NW coast of Malacca Straits, Malaysia	NA	29.97	29.52
30.	Present study		Western Bay of Bengal	27-2540	21.7-27.54	32.28-35.35

**Table 1**

Sl. No.	Sample name	Longitude (°E)	Latitude (°N)	Depth (m)	CF (%)	TIC (%)	C <sub>org</sub> (%)	C <sub>org</sub> /TN	Sal. (psu)	Temp. (°C)	DO (ml/L)	pH
1	SC-01	89.0186	21.1137	31	2.35	0.24	0.79	9.95	33.09	27.44	3.81	-
2	SC-02	89.0185	21.0612	49	6.54	0.31	0.75	12.97	33.99	26.10	3.44	-
3	SC-03	89.0212	20.9372	104	0.25	0.32	0.56	8.44	34.80	19.96	0.62	-
4	SC-04	88.6967	20.9990	29	6.35	0.31	0.66	9.28	33.02	27.51	3.87	-
5	SC-05	88.6935	20.9415	44	7.85	0.26	0.76	11.70	33.74	26.48	3.56	-
6	SC-06	88.5113	20.9255	36	5.53	0.29	0.68	10.20	33.37	27.11	3.73	-
7	SC-07	88.5018	20.6781	120	0.59	0.29	1.04	9.40	34.87	18.56	0.43	-
8	SC-08	88.7039	20.8484	94	0.33	0.21	0.88	10.31	34.74	21.04	1.29	-
9	SC-09	88.5035	20.8425	78.5	1.53	0.35	0.61	8.98	34.59	23.05	1.59	-
10	SC-10	88.0078	20.9563	31	19.39	0.43	0.48	13.19	33.09	27.44	3.81	-
11	SC-11	88.0040	20.8640	60	1.95	0.30	0.74	9.84	34.24	25.06	2.79	-
12	SC-12	88.0044	20.7117	83	84.02	1.25	0.16	-	34.64	22.44	1.37	-
13	SC-13	87.6433	20.6870	54	43.79	2.61	0.54	-	34.11	25.63	3.17	-
14	SC-14	87.6750	20.9441	42	85.34	0.72	0.19	-	33.63	26.63	3.62	-
15	SC-15	87.4127	20.8765	36	97.59	0.42	0.74	9.01	33.38	27.07	3.72	-
16	SC-16	87.2698	20.6493	28	6.30	0.28	0.75	9.53	32.87	27.54	3.90	-
17	SC-17	86.8725	20.1959	34	28.04	0.43	0.62	11.53	33.28	27.22	3.75	-
18	SC-18	86.9475	20.0964	54	3.76	0.37	0.75	9.18	34.11	25.63	3.17	-
19	SC-19	86.9875	20.0461	96	0.49	0.21	1.14	11.74	34.75	20.78	0.81	-
20	SC-20	86.5541	19.8114	107	1.17	0.16	1.15	9.96	34.82	19.68	0.57	-
21	SC-21	86.5067	19.8733	47	1.69	0.15	0.87	7.97	33.93	26.25	3.49	-
22	SC-22	86.4645	19.9140	36	2.66	0.16	1.10	14.27	33.38	27.07	3.72	-
23	SC-36	82.3434	16.4757	145	0.20	0.36	1.60	6.72	34.94	21.58	4.60	-
24	SC-37	81.9908	16.2566	44	1.46	0.42	1.22	15.55	34.82	26.35	4.71	-
25	SC-38	81.7330	16.1663	52	0.32	0.38	1.41	15.80	34.84	26.05	4.73	-
26	SC-39	81.2568	15.8289	62	1.83	0.53	0.76	24.30	34.86	25.60	4.74	-
27	SC-40	81.0822	15.7077	53	0.50	0.59	0.97	31.95	34.84	26.01	4.73	-
28	SC-41	80.8602	15.5878	69	0.09	0.64	1.07	15.26	34.87	25.29	4.75	-
29	SC-42	80.3140	12.3538	56	96.45	2.30	0.39	0.00	34.85	25.87	4.73	-
30	SC-43	80.3770	12.5156	52	94.81	5.71	0.85	0.00	34.84	26.05	4.73	-
31	SC-44	80.2415	12.5159	33	71.54	0.53	0.52	14.67	34.80	26.71	4.69	-
32	SC-45	80.5745	12.6842	107	94.24	10.47	1.33	34.53	34.94	23.44	4.70	-
33	SC-46	80.6745	12.7248	190	66.58	5.23	1.53	15.13	34.90	19.52	4.53	-
34	MC-02	80.5852	14.5686	2090	1.51	0.43	1.55	10.70	33.98	10.40	2.71	7.68
35	MC-03	80.4578	14.5670	1476	1.48	0.42	1.79	10.79	34.21	13.90	2.11	7.64
36	MC-04	80.4407	14.5666	979	0.36	0.54	1.28	11.61	34.63	2.01	2.71	-
37	MC-05	80.4062	14.5676	397	1.06	0.60	1.75	10.96	34.87	18.40	4.29	7.58
38	MC-06	80.3925	14.5679	244	1.11	0.66	1.86	9.77	34.11	19.20	4.55	7.55
39	MC-07	80.3705	14.5685	47	3.39	1.20	0.95	12.15	33.95	25.10	4.70	7.91
40	MC-08	80.4850	15.3501	76	1.85	0.81	1.08	11.44	34.70	23.20	4.72	7.70
41	MC-09	80.5165	15.3194	274	0.52	0.64	1.55	11.32	33.90	18.10	4.76	7.60
42	MC-11	80.5600	15.2650	500	0.79	0.60	1.37	11.48	33.67	16.30	3.77	7.58
43	MC-12	80.5036	15.2522	786	0.58	0.59	1.45	10.74	34.37	19.10	1.68	7.57
44	MC-13	80.6394	15.2201	921	0.71	0.48	1.49	10.80	34.11	19.20	1.55	7.55
45	MC-14	80.6881	15.1800	1519	0.74	0.33	1.67	10.03	33.78	13.80	2.17	7.60
46	MC-15	80.7267	15.1467	1940	0.35	0.33	1.13	10.84	35.17	15.80	2.59	7.64
47	MC-16	80.8781	15.0165	2482	0.44	0.17	1.14	12.13	33.17	14.60	2.96	7.53
48	MC-18	81.5645	15.5262	2005	0.30	0.35	1.35	11.47	34.44	14.70	2.65	7.71
49	MC-19	81.4839	15.6118	1463	0.44	0.35	1.16	12.17	34.18	14.20	2.10	7.57
50	MC-20	81.3451	15.7579	1069	0.70	0.36	1.72	9.36	34.70	15.40	1.60	7.61
51	MC-21	81.3235	15.7953	749	0.44	0.43	1.60	10.60	34.67	15.80	1.84	7.62
52	MC-22	81.3048	15.7842	768	0.69	0.41	1.61	9.84	35.18	14.10	1.76	7.60
53	MC-23	81.3064	15.8124	507	0.33	0.51	1.24	11.29	34.65	15.30	3.73	7.53
54	MC-24	81.1995	15.7575	202	0.91	0.50	1.30	12.02	34.93	18.80	4.53	7.58
55	MC-25	81.2353	15.8034	80	1.11	0.50	0.86	11.76	34.52	24.00	4.76	-
56	MC-26	81.2257	15.7941	103	0.42	0.46	1.05	11.70	34.69	22.30	4.72	7.86
57	MC-27	81.6864	15.8164	55	1.45	0.53	0.90	13.53	34.28	25.10	4.73	8.05
58	MC-28	81.2237	15.8296	32	2.86	0.52	0.79	17.18	35.35	24.90	4.68	8.15
59	MC-29	82.3764	16.5780	27	1.31	0.36	1.36	14.12	33.15	25.50	4.67	8.12
60	MC-30	82.3853	16.5723	40	0.70	0.30	1.56	13.70	32.61	25.60	4.70	8.15
61	MC-31	82.4071	16.5732	107	1.10	0.24	1.75	12.36	34.62	23.90	4.70	7.66
62	MC-32	82.4329	16.5188	259	0.57	0.21	1.63	10.84	35.50	18.50	4.56	7.68
63	MC-33	82.4430	16.4724	496	0.45	0.35	1.62	11.58	34.32	18.60	3.80	7.76
64	MC-34	82.4711	16.4429	744	0.67	0.30	1.61	10.34	34.42	14.90	1.86	7.58
65	MC-35	82.5207	16.4240	1006	0.54	0.34	1.63	11.26	34.71	14.60	1.57	7.57
66	MC-36	82.5956	16.2481	1511	0.68	0.17	1.45	9.74	34.79	14.80	2.16	7.56
67	MC-37	82.6742	16.2373	1981	0.67	0.19	1.47	10.08	35.12	2.08	2.63	7.78

68	MC-38	82.8246	16.0649	2495	1.50	0.18	1.36	9.80	34.61	15.20	2.97	7.76
69	MC-39	83.2059	17.4380	55	55.65	1.17	0.48	11.06	34.26	24.90	4.77	8.11
70	MC-40	83.0993	17.4953	29	75.45	0.23	0.36	8.13	32.28	25.20	4.67	8.14
71	MC-41	83.3444	17.4192	73	55.87	2.27	0.64	9.66	34.27	25.00	4.78	7.96
72	MC-42	83.5006	17.2923	280	5.15	0.96	2.19	8.94	34.17	18.50	4.56	7.56
73	MC-43	83.5227	17.2586	520	1.49	0.58	1.97	8.94	34.14	16.70	3.61	7.58
74	MC-44	83.5434	17.2304	763	2.13	0.65	2.09	9.34	33.92	17.30	1.78	7.60
75	MC-45	83.5611	17.2016	1035	1.27	0.46	1.85	8.75	33.24	24.20	1.58	8.07
76	MC-46	83.5846	17.1679	1511	0.67	0.15	1.51	7.75	34.74	13.20	2.16	7.61
77	MC-47	83.6116	17.1344	2030	0.61	0.11	1.36	9.01	34.17	15.50	2.67	7.69
78	MC-48	83.6298	17.0963	2540	1.14	0.11	1.41	8.01	33.82	15.30	3.00	7.67
79	MC-49	84.0772	18.1943	29	13.93	0.24	0.60	9.51	32.80	25.60	4.67	8.10
80	MC-50	84.2254	18.1748	58	71.29	1.41	0.34	9.37	34.18	25.20	4.77	8.04
81	MC-51	84.2706	18.1323	73	14.73	0.91	1.13	8.15	33.02	25.70	4.78	8.15
82	MC-52	84.3251	18.0873	225	0.92	0.21	1.51	8.84	34.70	18.90	4.54	7.66
83	MC-53	84.3338	18.0829	645	0.47	0.28	1.81	7.94	33.91	17.20	2.52	7.56
84	MC-55	84.3977	18.0255	1487	1.17	0.36	1.59	8.52	33.65	16.20	2.13	7.76
85	MC-56	84.4882	17.8963	2098	0.47	0.04	1.08	7.91	34.14	15.10	2.71	7.68
86	MC-57	84.5895	17.7822	2488	1.00	0.08	1.38	8.25	33.83	13.80	2.97	7.68
87	MC-60	85.6194	18.6671	2071	0.39	0.05	1.14	9.11	34.27	16.90	2.70	7.63
88	MC-61	85.5230	18.7829	1538	1.74	0.15	1.31	7.95	34.36	14.30	2.19	7.66
89	MC-62	85.4733	18.8730	1073	0.57	0.26	1.80	7.98	34.65	12.40	1.61	7.65
90	MC-63	85.4640	18.9052	763	2.45	0.63	1.88	8.64	34.26	5.34	1.78	-
91	MC-64	85.4341	18.9307	500	2.55	0.52	1.97	8.91	34.71	14.70	3.79	7.62
92	MC-65	85.3802	18.9942	260	1.77	0.35	2.09	8.26	34.27	18.50	4.56	7.61
93	MC-67	85.1685	19.2956	55	13.10	0.90	1.19	10.08	33.81	24.90	4.77	8.06
94	MC-68	85.1309	19.3648	29	13.21	0.17	1.10	10.96	33.38	25.30	4.67	8.12
95	MC-69	86.5566	19.8170	102	0.44	0.14	0.92	9.42	34.82	21.70	4.66	7.77
96	MC-70	86.5931	19.7796	272	0.99	0.12	1.16	7.89	34.77	16.98	4.50	-
97	MC-71	86.6195	19.7525	507	0.18	0.14	1.20	8.73	34.47	16.30	3.68	7.61

**Table 2**

Sl. No.	Sample Name	Depth (m)	<i>A. trispinosa</i> (Living) (%)	<i>A. trispinosa</i> (Dead) (%)	Sl. No.	Sample Name	Depth (m)	<i>A. trispinosa</i> (Living) (%)	<i>A. trispinosa</i> (Dead) (%)
1.	SC-01	31	31.48	17.31	50.	MC-20	1069	0.00	0.00
2.	SC-02	49	10.47	6.25	51.	MC-21	749	0.00	0.00
3.	SC-03	104	0.00	0.00	52.	MC-22	768	0.00	0.00
4.	SC-04	29	3.38	4.58	53.	MC-23	507	0.00	0.00
5.	SC-05	44	6.95	9.71	54.	MC-24	202	0.00	0.00
6.	SC-06	36	12.85	13.06	55.	MC-25	80	0.00	0.32
7.	SC-07	120	0.00	0.00	56.	MC-26	103	0.00	0.00
8.	SC-08	94	0.00	0.00	57.	MC-27	55	0.84	0.63
9.	SC-09	78.5	0.42	0.00	58.	MC-28	32	1.58	7.95
10.	SC-10	31	6.80	13.25	59.	MC-29	27	7.26	7.94
11.	SC-11	60	1.75	6.86	60.	MC-30	40	0.70	1.83
12.	SC-12	83	0.00	8.63	61.	MC-31	107	0.00	0.00
13.	SC-13	54	0.00	0.27	62.	MC-32	259	0.00	0.00
14.	SC-14	42	0.00	1.27	63.	MC-33	496	0.00	0.00
15.	SC-15	36	0.00	4.38	64.	MC-34	744	0.00	0.00
16.	SC-16	28	1.62	22.68	65.	MC-35	1006	0.00	0.00
17.	SC-17	34	2.04	11.45	66.	MC-36	1511	0.00	0.00
18.	SC-18	54	0.00	3.38	67.	MC-37	1981	0.00	0.00
19.	SC-19	96	0.00	0.00	68.	MC-38	2495	0.00	0.00
20.	SC-20	107	0.00	0.00	69.	MC-39	55	0.00	0.00
21.	SC-21	47	1.25	2.42	70.	MC-40	29	1.86	0.28
22.	SC-22	36	0.65	0.30	71.	MC-41	73	0.00	0.00
23.	SC-36	145	0.00	0.00	72.	MC-42	280	0.00	0.00
24.	SC-37	44	2.35	6.80	73.	MC-43	520	0.00	0.00
25.	SC-38	52	0.00	3.59	74.	MC-44	763	0.00	0.00
26.	SC-39	62	0.00	1.33	75.	MC-45	1035	0.00	0.00
27.	SC-40	53	0.53	0.00	76.	MC-46	1511	0.00	0.00
28.	SC-41	69	0.00	0.00	77.	MC-47	2030	0.00	0.00
29.	SC-42	56	0.00	0.31	78.	MC-48	2540	0.00	0.00
30.	SC-43	52	0.00	0.00	79.	MC-49	29	0.00	0.00
31.	SC-44	33	0.00	1.88	80.	MC-50	58	0.00	0.02
32.	SC-45	107	0.00	0.00	81.	MC-51	73	0.00	0.07
33.	SC-46	190	0.00	0.00	82.	MC-52	225	0.00	0.00
34.	MC-02	2090	0.00	0.00	83.	MC-53	645	0.00	0.00
35.	MC-03	1476	0.00	0.00	84.	MC-55	1487	0.00	0.00
36.	MC-04	979	0.00	0.00	85.	MC-56	2098	0.00	0.00
37.	MC-05	397	0.00	0.00	86.	MC-57	2488	0.00	0.00
38.	MC-06	244	0.00	0.00	87.	MC-60	2071	0.00	0.00
39.	MC-07	47	0.00	2.19	88.	MC-61	1538	0.00	0.00
40.	MC-08	76	0.66	1.88	89.	MC-62	1073	0.00	0.00
41.	MC-09	274	0.00	0.00	90.	MC-63	763	0.00	0.00
42.	MC-11	500	0.00	0.00	91.	MC-64	500	0.00	0.00
43.	MC-12	786	0.00	0.00	92.	MC-65	260	0.00	0.00
44.	MC-13	921	0.00	0.00	93.	MC-67	55	0.11	0.97
45.	MC-14	1519	0.00	0.00	94.	MC-68	29	0.32	0.00
46.	MC-15	1940	0.00	0.00	95.	MC-69	102	0.00	0.25
47.	MC-16	2482	0.00	0.00	96.	MC-70	272	0.00	0.00
48.	MC-18	2005	0.00	0.00	97.	MC-71	507	0.00	0.00
49.	MC-19	1463	0.00	0.00					

Table 3

<b>Parameters</b>	<b>CF%</b>	<b>TIC%</b>	<b>%C<sub>org</sub></b>	<b>C<sub>org</sub>/TN</b>	<b>Salinity</b>	<b>Temp.</b>	<b>DO</b>
Total <i>Asterorotalia</i> %	0.0077	-0.0921	-0.3924*	0.0717	-0.4080*	0.4705*	0.1683
Living <i>Asterorotalia</i> %	-0.0409	-0.0733	-0.2585*	0.0292	-0.3372*	0.3130*	0.0931

**Table 4**