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Temporal distribution of zooplankton communities in coastal waters of the northern Bay of Bengal, Bangladesh

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Abstract

The temporal distribution pattern of zooplankton communities was studied in coastal waters of the northern Bay of Bengal, Bangladesh, during a 1-year period of investigation (May 2014-April 2015). Throughout the investigation, a total of 38 zooplankton species were recorded, in details 22 holo-plankton and 16 mero-plankton species. Copepods (*Acartia danae*, *Acartia tonsa*, *Cyclops biscuspidatus*, and *Canthocalanus pauper*), amphipods (*Grandidierella megnae*), shrimps (*Penaeus indicus* and *Penaeus merguiensis*), Acetes (*Acetes indicus*), and mysids (*Americamysis bahai*) were the dominant zooplankton taxa. The maximum abundance of total zooplankton and species richness was recorded in monsoon season whereas abundance of holo-plankton and species diversity was recorded in winter. Multivariate analyses revealed that the temporal pattern of species distribution of zooplankton communities significantly differed among the four seasons. RELATE analysis signified that temporal variation in species distribution and community structure of zooplankton significantly correlated with ecological condition of water. Moreover, BEST matching analysis indicated that NO2-N along with salinity and pH were the main driving forces for this temporal variation in species distribution and community composition of zooplankton communities. Finally, correlation analysis showed that species richness and diversity significantly correlated with salinity, transparency, TDS, and NO_2-N. These results suggest that zooplankton distribution pattern might be shaped by ecological condition of water in such marine ecosystem and may potentially be used as bioindicators of marine water quality.

Keywords: Channel system; Community structure; Distribution pattern; Multivariate analyses; Northern Bay of Bengal; Zooplankton communities

Introduction

Zooplankton are key components in aquatic food chain and play an important role in the planktonic food web acting as a link between primary producers and higher trophic levels (Liu et al., 2013; Sahu et al., 2013; Abdullah Al et al., 2018). Due to their short life cycles and relatively quick response to natural and anthropogenic environmental perturbation, they have been widely used as bioindicators for water quality and climate change (Bianchi et al., 2003; Uriate and Villate, 2004; Sullivan et al., 2007; Ferdous and Muktadir, 2009; Liu et al., 2013). Additionally, among zooplankton components, several copepods species have been employed as indicators of pollution (i.e. Acartia clause) and increasing temperature (i.e. Acartia tonsa and Acartia hudsonica) (Hirst et al., 1999; Bianchi et al. 2003; Mulyadi 2004; Hooff 2006), and copepod distribution was used as indicator of salinity variation (Thompson et al., 2012; Vineetha et al., 2015; Abu Hena et al., 2016; Fontana et al., 2016).

Indeed, trophic condition of secondary production and ecological succession in aquatic ecosystems are led by zooplankton (Iqbal et al., 2014: Abdullah Al et al., 2018), thanks to their ability to integrate lower with higher trophic levels. Therefore, small variation in their abundance and composition can significantly disrupt normal ecosystem processes. The abundance and composition of zooplankton depend on a range of ecological condition including water temperature, transparency, food availability, and nutrient supplies (Arashkevich et al., 2002; Lo et al., 2004; Sullivan et al., 2007; Abu Hena et al., 2016; Abdullah Al et al., 2018). Furthermore, biodiversity indices are used for describing the ecological health status of aquatic ecosystems: a higher index value indicates a better-quality status (Hooff, 2006; Abu Hena et al., 2016; Abdullah Al et al., 2018).

In the northern Bay of Bengal, especially the south-eastern coastal zone of Bangladesh, several waterways are present, including rivers, open marine channels and estuaries. These waterways support aquatic resources (e.g., fishes, shrimps, mangroves, molluscs, and seaweeds) and contribute to national economy. However, in recent decades, about 950 industries (i.e., ship breaking, chemicals, and oil refineries) arose in this coastal area causing air, water, and soil pollution with aquatic ecosystems biodiversity lost (Iqbal et al., 2014; Khan et al., 2015; Sharif et al., 2017; Abdullah Al et al., 2018). Up to now, only a few studies dealt with zooplankton along with environmental parameters, and with their application to water quality bioassessment in the northern Bay of Bengal, Bangladesh (Iqbal et al., 2014; Khan et al., 2015; Abu Hena et al., 2016; Sharif et al., 2017; Abdullah Al et. al., 2018). Thus, a research on zooplankton along with water parameters is recommended in order to adopt necessary initiatives for ecological health assessment and management of coastal water bodies. However, community-based water quality bioassessment is the most effective method for assessing this goal.

In the present study, a 1-year baseline survey was conducted in coastal waters of the northern Bay of Bengal, Bangladesh. The aims of the study were: (1) to record the taxonomic composition of zooplankton communities; (2) to reveal their distribution patterns; (3) to assess the environmental quality status using distribution patterns of the zooplankton communities in relation to hydrological condition in this ecosystem.

Material and Methods

Study area description

This study was conducted in the Kotubdia channel in south-eastern coast of Bangladesh, northern Bay of Bengal (Fig. 1). The geographical location of the study area is 21°45′ N, 91°48′ E (Garmin GPS60). It is an open marine channel located in the north-western portion of Moheshkhali Island that is connected with Kornafully estuary and separates the Kutubdia Island from the mainland as Cox’s Bazar district, Bangladesh. The semi-diurnal tidal system with two highs and two lows each day provides suitable conditions for the survival of a wide range of aquatic organisms throughout the year (Zafar and Alam, 1997). This channel acts as a mixing zone for pollutants from Riverine waterways and land-based industries, shrimp farms. It receives industrial and domestic effluents via adjacent canals/creeks from the Chakoria Sundarban, Bashkhali, Pekua, and Kutubdia Island, and along the coastal territories throughout the year. Furthermore, the flood land of both bank sides is suitable for natural salt production during the winter season (October to February), and suitable for extensive to semi-intensive shrimp/fish culture. These salt pens and farms take up water during high tide level in the Bay of Bengal by means of this channel and discharge effluents with a range of organic and inorganic compounds during low tide.

Sample collection

Twelve samples were collected, one sample/month, during low tide level using plankton collection net, from May 2014 to April 2015. For summarizing temporal variation, both zooplankton communities and water parameters data were categorized into four seasons i.e., monsoon (May to July), post-monsoon (August to October), winter (November to January), and pre-monsoon (February to April).

The net was vertically fixed with bamboo from engine boat below ~1 m depth from the water surface to avoid wave action. The mesh size of net was 100 µm with 24 cm-wide circular mouth opening fitted with a digital flow meter and a plastic bucket at the end called cod. The net was kept for 30 minutes against water current and the water mass that passed through the net was calculated by means of a flowmeter. Seasonal variation in water discharge was calculated from the volume of water (m^3) filtered through the net where water flow rate was calculated using the following equation:

The volume of water (m^3) = $\{(FR–IR) \times \text{co–efficient}\} \times 2\pi r^2$

where,

FR= final reading,

IR= initial reading,

coefficient= 0.3,

π=3.1416,

r= radius of the opening of the plankton net= 0.12 m.

Therefore, abundance (ind./m^3)= number of species/ vol. of water.

Meteorological variable as rainfall data was collected from online source for the study area. Basic water parameters were measured in situ using appropriate sensors such as water/air temperature (centigrade thermometer), salinity (refractometer: TANAKA New S–100, Japan), hydrogen ion concentration (digital pH meter: HANNA, Japan, model: HI 98107), and transparency (Secchi disk). As for measuring total dissolved solids (TDS), total suspended solids (TSS), 100 ml water was filtered and TDS and TSS were measured based on the outline described in the Standard Methods (APHA, 1989).

One litter of subsurface water (~1 m depth) was collected using water sampler (thermometer attached) and preserved with iodine solution (KI). Then, it was kept in in a cold icebox in dark conditions for laboratory analysis of dissolve oxygen (DO), nitrate-nitrogen (NO_2–N), and phosphate-phosphorus (PO_4–P). The laboratory analysis was done according to the outline described in the Standard Methods for Examination of Water and Wastewater (APHA, 1989).

Species identification and enumeration

After collection, each sample was preserved with 5% formalin and stained with rose bengal for 24 hours according to Gowsomi (2004). Identification was done based on morphological characteristics observed under the light microscope and using published guides and keys such as Conway et al. (2003), Conway (2012), Goddard (2001), Mulyadi (2004), Buckland-Nicks et al. (2002), Brink (2003), Helani (2011), and Martin and Davis (2001).

The enumeration of species was performed by counting them on the whole sample. The species composition was expressed as proportion of the species with respect to the total number of individuals (%) while the abundance was expressed as count of individuals per cubic meters (ind./ m^3).

Data analysis

The species diversity (Shannon-Winner, H'), species evenness (Pielou’s, J'), and species richness (Margalef, D) indices were used to summarize the biodiversity of the zooplankton communities. These measures were computed using PRIMER package (v7.0.13) in the submodule of DIVERSE with the following equations:

$$H' = -\sum_{i=1}^{S} P_i (\ln P_i)$$

$$J' = H' / \ln S$$

$$D = (S-1) / \ln N$$

where,

P_i= proportion of the total counted arising from the ith species,

S= total number of species,

N= total number of individuals.

Multivariate analysis was conducted to summarize the temporal pattern of zooplankton communities and environmental parameters. The temporal pattern of species distribution was analyzed by non-metric multidimensional scaling (nMDS) from square root-transformed species abundance data, while shade plot was used to represent the species composition in terms of relative abundances of species from species abundance data. The species contribution on each sample was computed using SIMPER analysis (similarity percentage). The temporal variation in zooplankton community structure was demonstrated using distance based redundancy analysis (dbRDA) from square root-transformed species abundances data, while temporal variation in environmental parameters was ordinated by principal coordinates (PCO) analysis from log (x+1) transformed/normalized data (Anderson et al., 2008; Clarke and Gorley, 2015). Mental analysis of significant biota-environment correlation was tested using the submodule of RELATE. The Biota-Environment Best Matching analysis (BIOENV) was used to identify the best potential variables for temporal distribution and community structure of zooplankton. The analysis of similarity among the four seasons was performed using submodule of ANOSIM. All these multivariate analyses were conducted with the help of PRIMER v.7.0.13+PERMANOVA according to the methods by Anderson et al. (2008) and Clarke & Gorley (2015).

The temporal variation of water parameters was conducted by a one-way analysis of variation (1-way ANOVA) while Pearson correlation matrix was used to show the significant correlation between community parameters with water parameters from log-transformed data using IBMSPSS v.22.

Results

Hydrological condition of the northern Bay of Bengal

The mean temporal variation of the studied water parameters along with rainfall and discharge rate are reported in Figure 2. Among the analysed water parameters, water transparency, salinity, TDS, and DO were higher in winter and lower in monsoon period. PO_4-P and TSS were higher in monsoon, while air/water temperature and NO_2-N were higher in pre-monsoon. As for rainfall data of this region, the maximum rainfall occurred during monsoon, May to July (i.e. 139-717 mm), and the minimum was in winter, October to January (i.e. 0-10 mm). Water discharge showed a trend similar to that of rainfall (Fig. 2).

One-way ANOVA revealed that air/water temperature, salinity, transparency, TDS, TSS, rainfall, water discharge, and PO_4-P showed significant temporal variation during the study period.

Taxonomic composition and species distribution

A total of 38 species were identified throughout the study period, including 22 holo-plankton and 16 mero-plankton species. Among the recorded species: nine species were copepods; four species belonged to amphipods and shrimps each; three species were molluscs; two species belonged to each of the following taxa: *Acetes*, crabs, annelids, *Lucifer*, and isopods; one species belonged to each of the following groups: fish larvae, echinoderms, lobsters, hydrozoans, mysids, chaetognaths, pantopods, and tanaids (Tab. S1). The list of species with their ecology (groups and types), distribution, average abundance and rank contribution (according to SIMPER) in each season is summarized in Table S1.

Among these 38 species, 17 species (i.e., *Acartia tonsa*, *Acartia danae*, *Acartia clause*, *Temora longicornis*, *Canthocalanus pauper*, *Cyclops biscuspidatus*, *Corycaeus crassiusculua*, *Grandidierella megnae*, *Acetes japonicas*, *Acetes indicus*, *Americamysis bahai*, *Lucifer faxoni*, *Lucifer orientalis*, *Penaeus monodon*, *Penaeus indicus*, *Penaeus merguiensis*, and *Spadella cephaloptera*) were commonly distributed in all four seasons; thus they can be defined as ‘common species’. The following nine species: *Americamysis bahai*, *Acartia tonsa*, *Acartia danae*, *Acetes japonicas*, *Acetes indicus*, *Penaeus indicus*, *Grandidierella megnae*, *Spadella cephaloptera* and *Lucifer orientalis* turned out to be dominant, with a cumulative contribution > 80% within the whole community.

As for the number of species observed in the four seasons, 19 species were recorded in monsoon (May to July), ten in post-monsoon (August to October), 16 in winter (November to January) and 12 species in pre-monsoon (February to April) (Fig. 3a). In terms of species distribution, nMDS analysis showed that zooplankton communities were distributed into seven groups based on 45% similarity level. Clustering analysis revealed that cluster groups 1-4 consisted of most of the commonly distributed species with higher occurrences, while the other three cluster groups 5-7 consisted of rare species with lower occurrences (Fig. 3b). nMDS ordination showed that the trajectories of temporal variation in species distribution differed among the four seasons (Fig. 3c, d). Furthermore, ANOSIM demonstrated that temporal pattern of zooplankton distribution significantly differed among the four seasons ($P<0.001$).

Structural patterns of zooplankton communities

Concerning relative abundance, shade-plotting analysis represented a clear community succession of zooplankton among the four seasons (Fig. 4). In this analysis, 13 species were found predominant in monsoon period (May to July), nine in post-monsoon (August to October), 17 in winter (November to January), and 14 species in pre-monsoon (February to April). At each season, the cumulative contribution of these species was considerably higher than that of the total zooplankton communities.

Among the retrieved nine dominant species, the abundance of *Acartia danae* and *Acartia tonsa* peaked in winter (Fig. 5a, b) whereas that of *Canthocalanus pauper* peaked in post-monsoon (Fig. 5c). Furthermore, the abundance of *Cyclops biscuspidatus*, *Grandidierella megnae*, *Acetes indicus*, and *Penaeus indicus* peaked in pre-monsoon (Fig. 5d-g), while that of *Penaeus merguiensis* and *Americamysis bahai* peaked in monsoon season (Fig. 5h, i).

In terms of total abundance, the highest abundance occurred in the monsoon while abundance of holo-plankton (permanent zooplankton) was in the winter season; the lowest abundance values were in the post-monsoon season (Fig. 6a, b).

The species richness fluctuated throughout the study period, with the highest value recorded in monsoon followed by winter, and the lowest value recorded in pre-monsoon (Fig. 7a); both species evenness and species diversity were lower in monsoon season and gradually increased towards winter (Fig. 7b, c).

Multivariate, dbRDA analysis was applied to evaluate the zooplankton community structure among the four seasons (Fig. 8a, b). The dbRDA axis separated the samples among the four seasons and showed 61.4% total temporal variation (i.e. dbRDA1 showed 39.5% of total variation, while dbRDA2 showed 21.9% of total variation) (Fig. 8a). The vector overlay of the nine dominant species revealed that five species (i.e. *Canthocalanus pauper*, *Acartia danae*, *Cyclops biscuspidatus*, *Grandidierella megnae* and *Acetes indicus*) were pointed toward in pre-monsoon, two species (i.e. *Penaeus merguiensis* and *Americanmysis bahai*) were pointed toward in monsoon and two species (i.e. *Penaeus indicus* and *Acartia tonsa*) were pointed toward in winter (Fig. 8b).

Relationship between environmental parameters and community structure

Multivariate RELATE analysis (coefficient of correlation) showed that zooplankton community structure was significantly correlated with ecological condition of water ($\rho=0.235$, $P=0.049$). Furthermore, BIOENV (biota-environment best matching) analysis indicated that NO2-N was the main factor, either individually or combined with salinity, pH and transparency, for temporal zooplankton distribution and structural patterns in this ecosystem (Tab. 1).

The Principle Coordinate analysis (PCO) demonstrated that there was a clear temporal variation in water parameters (Fig. 8c, d). The PCO axes (i.e. PCO1 and PCO2) separated the samples among the four seasons, and together accounted for 84.6% of the total variation (Fig. 8c). The first axis of PCO (i.e. PCO1 showing 62.8% of temporal variation) separated the samples winter from post-monsoon (right) and pre-monsoon from monsoon (left), while the second axis (i.e. PCO2 showing 21.8% of temporal variation) separated monsoon from post-monsoon (upper) and pre-monsoon from winter (lower).

The vector overlay of PO_4–P, TSS, water discharge, and rainfall pointed toward these parameters in monsoon, whereas the vector overlay of air and water temperature, and of NO_2–N pointed toward these parameters in pre-monsoon; the vector overlay of pH and DO pointed toward these parameters in post-monsoon; the vector overlay of TDS, salinity, and transparency pointed towards these parameters in winter (Fig. 8d).

Among the water parameters, seven showed significant correlation with members of the zooplankton communities (Tab. 2). For example, *Acartia danae* was significantly positively correlated with transparency and TDS while *Acartia tonsa* was correlated with salinity, transparency, TDS, DO, NO_2-N and TSS, and both were negatively correlated with PO_4-P. Furthermore, *Acetes indicus* showed significant positive correlation with salinity, transparency, TDS, NO_2-N, and TSS whereas *Cyclops biscuspidtus* showed significant positive correlation with transparency. However, *Americamysis bahai* showed significantly negative correlation with salinity, transparency, and NO_2-N. Among the community parameters, total species number/species richness and abundance showed s ignificant negative correlation with salinity, transparency, TDS and NO_2-N. Species evenness and diversity showed significantly positive correlation with water salinity, transparency, TDS, and NO_2-N (Tab. 2).

Discussion

In this study performed on samples from the coastal waters of the northern Bay of Bengal, water temperature, salinity, transparency, TDS, NO_2-N, PO_4-P, and TSS showed significant temporal variation among the four seasons during the study period. This variation might be due to maximum rainfall during monsoon season, which could significantly reduce water salinity, as well as to transparency due to freshwater runoff from hills and upland areas. Another major factor accounting for this temporal variation of water parameters can be considered the continuous discharge of household residuals/sewage effluents and land-based industrial pollution. Furthermore, mining and discharge from aquaculture and saltpans might have led to higher TDS and NO_2-N in this coastal area during winter season. However, strong anthropogenic activities have significant effect on environmental degradation by the excessive use of fertilizers, pesticides, insecticides, and hormones in both agriculture and fish farms, which led to water and soil pollution (Islam et al., 2015; Kibria et al., 2016a, b; Islam et al., 2018).

Even though zooplankton distribution and environmental parameters have been previously used to assess water quality and ecological integrity of ecosystems worldwide (Bianchi et al., 2003; Fernandes and Ramaiah, 2009; Ferdous and Muktadir, 2009; Liu et al., 2013; Srichandan et al., 2013, 2014, 2015), they have not been well documented yet in coastal waters of Bangladesh, northern Bay of Bengal. In the present study, 22 holo- plankton and 16 mero-plankton species were recorded. The zooplankton abundance peak was recorded during the monsoon season. According to Zafar and Alam (1997), in this channel the abundance of Acetes (shrimp) is higher in the monsoon than in the other three seasons, and our study confirmed this result. It is noteworthy that in the monsoon season the abundance of Acetes, mysids, crab zoea, and fish larvae overcomes that of the other zooplankton groups. Our study showed similarity with previous investigations conducted on some specific habitats such as Satkira Estuary (Zafar and Mahmood, 1989), Rezukhal Estuary (Iqbal et al., 2014), and Bakkhali sub-tropical estuary (Abu Hena et al., 2016) concerning the winter as season of maximum holo-plankton abundance. Indeed, in those previous analyses the maximum abundance was registered from winter to post-monsoon. However, according to literature data, the total abundance of zooplankton in marine channel quite differs from that of open water or estuarine habitats, with the maximum abundance occurring in monsoon season due to the contribution of the breeding season of some fishes and crustaceans (Ali et al., 1985; Abdullah Al et al., 2018). Furthermore, the study by Fazeli et al. (2013), conducted during a survey in Chabahar Bay in the Oman Sea, reported that the peak of zooplankton abundance was observed during northeast monsoon, when the bulk of nutrients was added to be Bay by runoff. This finding is consistent with our results.

Zooplankton communities showed a clear variation in temporal distribution among the four seasons. In this study, 17 species (14 of holo-plankton and 3 of mero-plankton) were commonly distributed in all the four seasons. The highest number of species occurred in monsoon (19 species) followed by winter (16 species); then, the two remaining seasons (i.e. post-monsoon and pre-monsoon). This result indicates that ecological water conditions in monsoon and winter were the relatively most favourable for zooplankton communities. The distribution of zooplankton in northern to western Bay of Bengal, especially in the India portion, mainly depends on different environmental variables such as water circulation, wave action, tidal fluctuation and availability of nutrients (Prabhaher et al., 2011; Rakhesh and Raman, 2006; Srichandan et al., 2013, 2014, 2015). Furthermore, the nutrients deposited on the bottom by microbial activities are circulated in the monsoon season due to up- and down-welling processes, which can shape the spatiotemporal distribution of zooplankton in shallow coastal habitat (Sahu et al., 2013; Srichandan et al., 2014, 2015; Arashkevich et al., 2002). In the present research, the abundance of five dominant species was significantly correlated with the studied water parameters (i.e., salinity, transparency, TSS, TDS, DO, PO_4-P, and NO_2-N) supporting the results of several previous investigations (Prabhaher et al., 2011; Sahu et al., 2013; Srichandan et al., 2013, 2014, 2015). We found that the abundance of dominant species (Americamysis bahai) was significantly negatively correlated with water salinity and NO_2-N, indicating that these two parameters influence the abundance of this species in this habitat. According to Fernandes and Ramaiah (2009) the spatial variation in zooplankton communities in the northern Bay of Bengal is mainly shaped by temperature and salinity. Moreover, in semi-enclosed waterways copepods distribution was found to depend on temperature (Bianchi et al., 2003; Memon et al., 1971), and water transparency influenced food supply availability (Hirst et al., 1999; Fazeli et al., 2013). In the present study, the maximum species richness and diversity were recorded in winter season when salinity, transparency, and NO_2-N were higher: this finding suggests that these parameters can shape the distribution pattern of zooplankton in marine ecosystem.

It has widely been recognized that multivariate analysis is more useful than univariate analysis for summarizing interaction between biotic communities with environmental parameters, and that it is suitable for predicting potential influencing factors as well (Anderson et al., 2088; Clarke and Gorley, 2015; Abdullah Al et al., 2018). In our study, the multivariate approach of both biotic and abiotic parameters revealed a clear temporal community composition and structural variation in zooplankton communities with relationships to temporal patterns of water condition. Furthermore, mental analysis (i.e. RELATE) and BIOENV indicated that this temporal pattern of zooplankton communities was driven by mainly NO_2-N along with salinity and pH. According to previous literature, seasonal and spatial variations of environmental conditions such as transparency, TDS, TSS, DO, and water nutrients influenced the seasonal cycle of zooplankton, especially composition and distribution (Ramaniah and Nair, 1997; Mohanty et al., 2010). However, our data indicated that distribution and community structure of zooplankton might be shaped by salinity, pH, and NO_2-N.

Community-based parameters such as species richness, evenness, and diversity indices are commonly used for water quality bioassessment: in general, higher indices values indicate better environmental conditions (Abu Hena et al., 2016; Abdullah Al et al., 2018). In the present study, species diversity showed fluctuation throughout the investigation period with biannual peaks, i.e. a first peak in monsoon and a second peak later, in winter. This changing phenomenon indicated that the ecological condition of water was unstable throughout the study period, maybe due to a certain change of water parameters among the four seasons (i.e. heavy rainfall in monsoon period and absence of rainfall in winter plus aquaculture/fish farms water discharge). Considering these findings, the peak in species richness and diversity recorded during monsoon season might be due to the preference of lower salinity and NO_2-N by the dominant groups (*Acetes* and mysids). On the other hand, with high water salinity, winter might be the relatively more suitable season for the dominant zooplankton taxa i.e. copepods. Consistently with the findings of our study, previous paper reported that ecological properties of water (i.e., salinity, transparency and nutrients) have significant influence on planktonic communities (Memon et al., 1971; Bianchi et al., 2003; Prabhaher et al., 2011; Sahu et al., 2013). On this basis, it seems that community patterns of zooplankton communities are mainly driven by ecological condition of water as salinity, pH, and nutrients. Thus, these zooplankton biodiversity parameters might be indeed used for water quality community-based bioassessment.

In summary, the present study provides information on temporal zooplankton distribution and community structure in coastal waters of the northern Bay of Bengal, Bangladesh. A clear temporal variation in species distribution and community composition of zooplankton communities has been observed among the four seasons in this coastal habitat. The abundance of dominant species represents different temporal community succession with respect to water ecological conditions. Multivariate correlation has revealed that community parameters were significantly correlated with ecological condition of water in this ecosystem; additionally, according to BEST matching analysis, this temporal pattern is mainly shaped by NO_2-N along with salinity and pH. However, our study represents a baseline information for further broad scale study in the reference habitat; further studies on a range of marine habitats and over extended time periods are required in order to corroborate our conclusion.

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Figures legends

Fig. 1. Study area showing sampling location in coastal waters of the northern Bay of Bengal, Bangladesh.

Fig. 2. Temporal variation in hydrological variables in coastal waters of the northern Bay of Bengal, Bangladesh during the study period. [Bar, Standard deviation]

Fig. 3. nMDS showing the temporal pattern of species distribution of zooplankton communities in coastal waters of the northern Bay of Bengal, Bangladesh during the study period.

Fig. 4. Temporal species contribution of zooplankton communities (%) in coastal waters of the northern Bay of Bengal, Bangladesh during the study period.

Fig. 5. Temporal variation in abundances of the nine dominant species of zooplankton in coastal waters of the northern Bay of Bengal, Bangladesh during the study period.

Fig. 6. Variation in total abundance (a) and abundance of holo-plankton (b) among the four seasons in coastal waters of the northern Bay of Bengal, Bangladesh during the study period. [Pre-mon, pre-monsoon; post-mon, post-monsoon]

Fig. 7. Variation in species richness (a), species evenness (b), and species diversity (c) of zooplankton among the four seasons in coastal waters of the northern Bay of Bengal, Bangladesh during the study period. [Pre-mon, pre-monsoon; post-mon, post-monsoon]

Fig. 8. Temporal variations of zooplankton community structure showing dbRDA ordination (distance-based ReDundancy Analysis) from square root transformed species data with correlation of the 9 dominant species (a, b) and Principal Coordinates (PCO) on Euclidean distance from log-transformed/normalized hydrological variables data with correlation of PCO axis (c, d).

Table 1. Summary of results from biota-environment (BIO-ENV) analysis showing the 10 best matches of environmental variables with spatial variations in the zooplankton communities in the northern Bay of Bengal during the study period.

Rank	Environmental variables	ρ value	P value
1	NO_2-N	0.565	<0.05
2	Sal, NO_2-N	0.554	<0.05
3	Sal, rainfall	0.515	<0.05
4	Sal, pH, NO_2-N	0.475	<0.05
5	Sal, Trans, NO_2-N	0.466	<0.05
6	Sal, Trans, rainfall	0.454	<0.05
7	Sal, TDS, NO_2-N	0.452	<0.05
8	Sal, Trans, pH, NO_2-N	0.451	<0.05
9	pH, Sal, TSS, NO_2-N	0.438	<0.05
10	Sal, TDS, pH, NO_2-N	0.437	<0.05

ρ, Spearman correlation coefficient value;
P, statistical significance level;
Sal, salinity;
Trans, Transparency;
TDS, Total dissolved solid;
TSS, Total suspended solid.

Table 2. Pearson correlations of environmental parameters with the nine dominant species and community parameters of zooplankton communities during the study period in the Kotubdia channel, in the northern Bay of Bengal.

Parameters	WT	pH	Sal	Trans	TDS	DO	P	N	TSS	rainfall	WD
Acartia danae	-.253	.399	.260	.309	.375	.154	-.127	-.104	-.136	-.069	.001
Acartia tonsa	-.435	.084	**.671***	**.693***	**.656***	**.700***	-.133	.172	**-.763****	**-.812****	**-.656***
Acetes indicus	-.097	.007	**.755****	**.695****	**.699***	.485	-.302	.058	-.519	**-.741****	**-.696***
Americamysis bahai	-.022	.381	**-.853****	**-.742***	**-.637***	-.285	.304	-.396	. 447	.548	**.636***
Canthocalanus pauper	-.005	-.281	.072	.093	-.031	.001	.129	-.142	.127	.168	. 146
Cyclops biscuspidatus	-.284	.079	.258	**.341**	.396	.015	-.542	.030	-.294	-.087	-.174
Grandidierella megnae	**.685***	**-.586***	.393	.155	.010	.056	.090	.336	-.061	-.454	**- .584***
Penaeus indicus	**.667***	-.484	-.064	-.342	-.410	-.405	**.611***	**.673***	.306	-066	-.145
Penaeus merguiensis	.177	.574	-.694*	-.155	-.560	-.084	.322	-.295	.456	.396	.514
S	-.029	.263	**-.699***	**-.704***	**-.579***	-.269	**.586***	-.056	.331	.313	.457
N	.460	.031	-.566	-.757**	**-.691***	-.315	**.737****	.223	.451	.205	.262
D	-.222	.330	**-.681***	**-.609***	-.474	-.222	.457	-.169	.248	.325	.487
J'	-.267	-.214	**.791***	**.822^{1}***	**.740****	.286	-.400	.225	-.439	-.440	-.477
H'	-.472	-.090	**.623***	**.671***	**.658***	.221	-.104	.347	-.406	-.419	-.340

**significant level at 0.01 (P<0.01);
*significant level at 0.05 (P<0.05);
D, Margalef richness index;
H′, Shannon-Winner index;
J′, Pielou's index;
N, total abundance;
S, total species number;
text bold, statistically significant values.
WT, water temperature;
Sal, salinity;
Trans, Transparency;
TDS, Total dissolved solid;
DO, dissolved oxygen;
P, water soluble reactive phosphate;
N, nitrate-nitrogen;
TSS, Total suspended solid;
WD,water discharge.

Figure 1

Figure 2

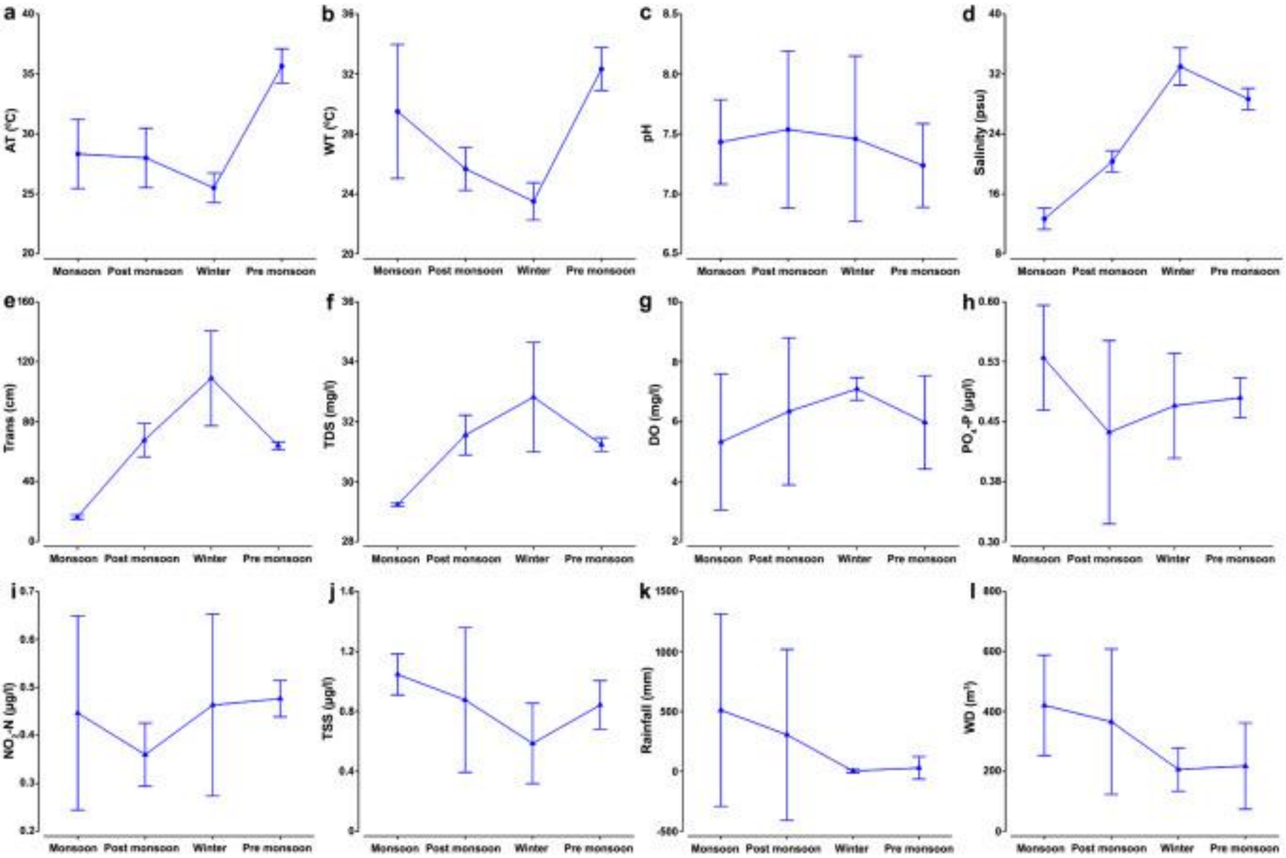


Figure 3

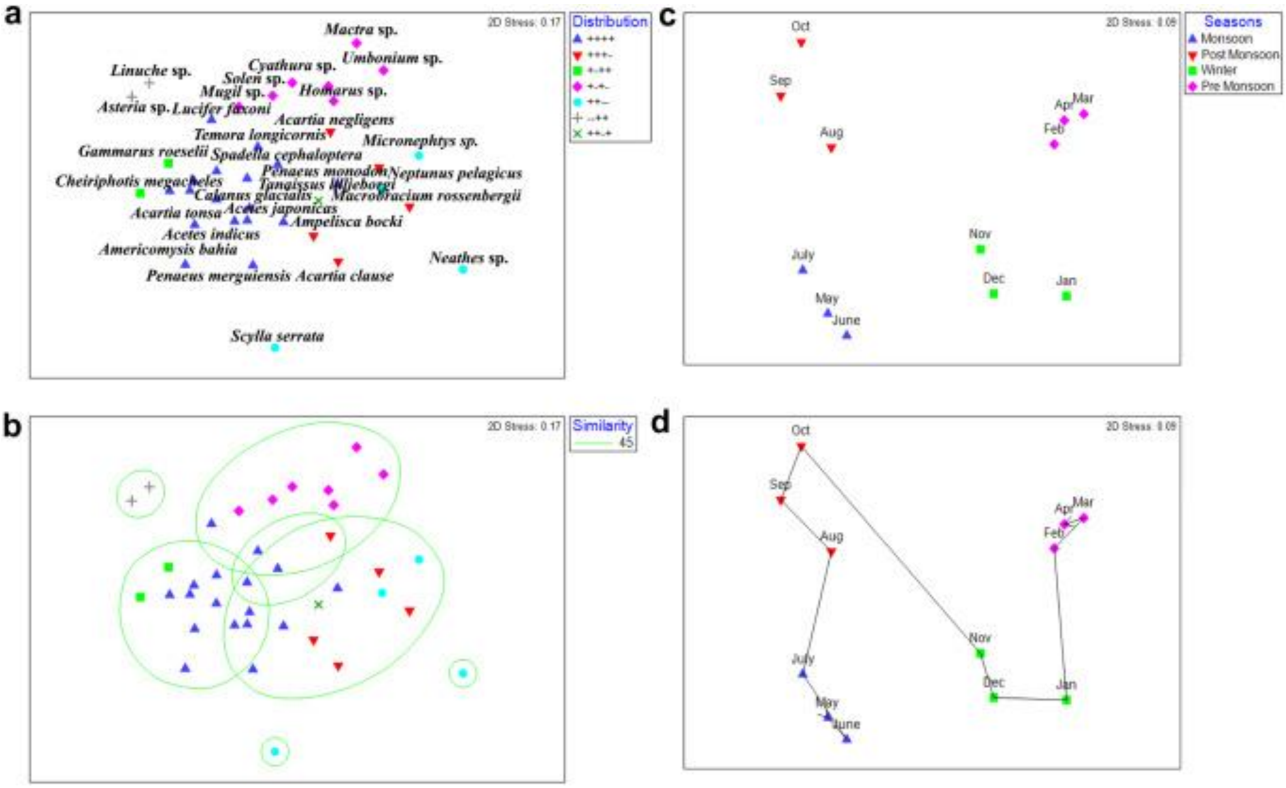

a
2D Stress: 0.17
Distribution
++++
+++-
+-++
+-+-
++--
--++
++-+
Mactra sp.
Umbonium sp.
Linuche sp.
Cyathura sp.
Solen sp.
Mugil sp.
Homarus sp.
Asteria sp.
Lucifer faxoni
Acartia negligens
Temora longicornis
Micronephtys sp.
Gammarus roeselii
Spadella cephaloptera
Penaeus monodon
Neptunus pelagicus
Cheiriphotis megacheles
Tanaissus lilljeborgi
Calanus glacialis
Macrobracium rossenbergii
Acartia tonsa
Acetes japonicas
Ampelisca bocki
Acetes indicus
Americomysis bahia
Neathes sp.
Penaeus merguiensis
Acartia clause
Scylla serrata
b
2D Stress: 0.17
Similarity
45
c
2D Stress: 0.09
Seasons
Monsoon
Post Monsoon
Winter
Pre Monsoon
Oct
Sep
Aug
Apr
Mar
Feb
Nov
July
Dec
Jan
May
June
d
2D Stress: 0.09
Oct
Sep
Aug
Apr
Mar
Feb
Nov
July
Dec
Jan
May
June

Figure 4

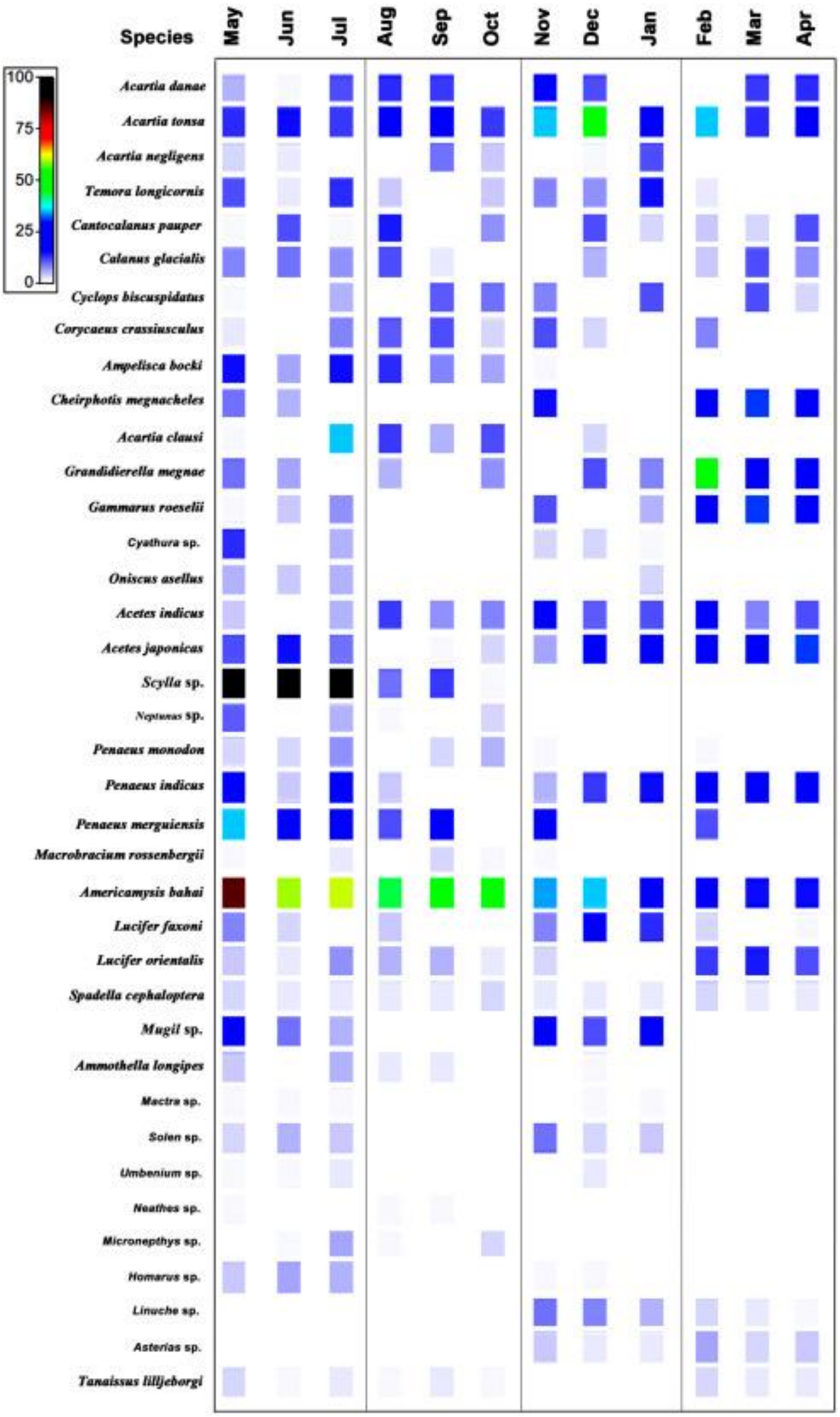
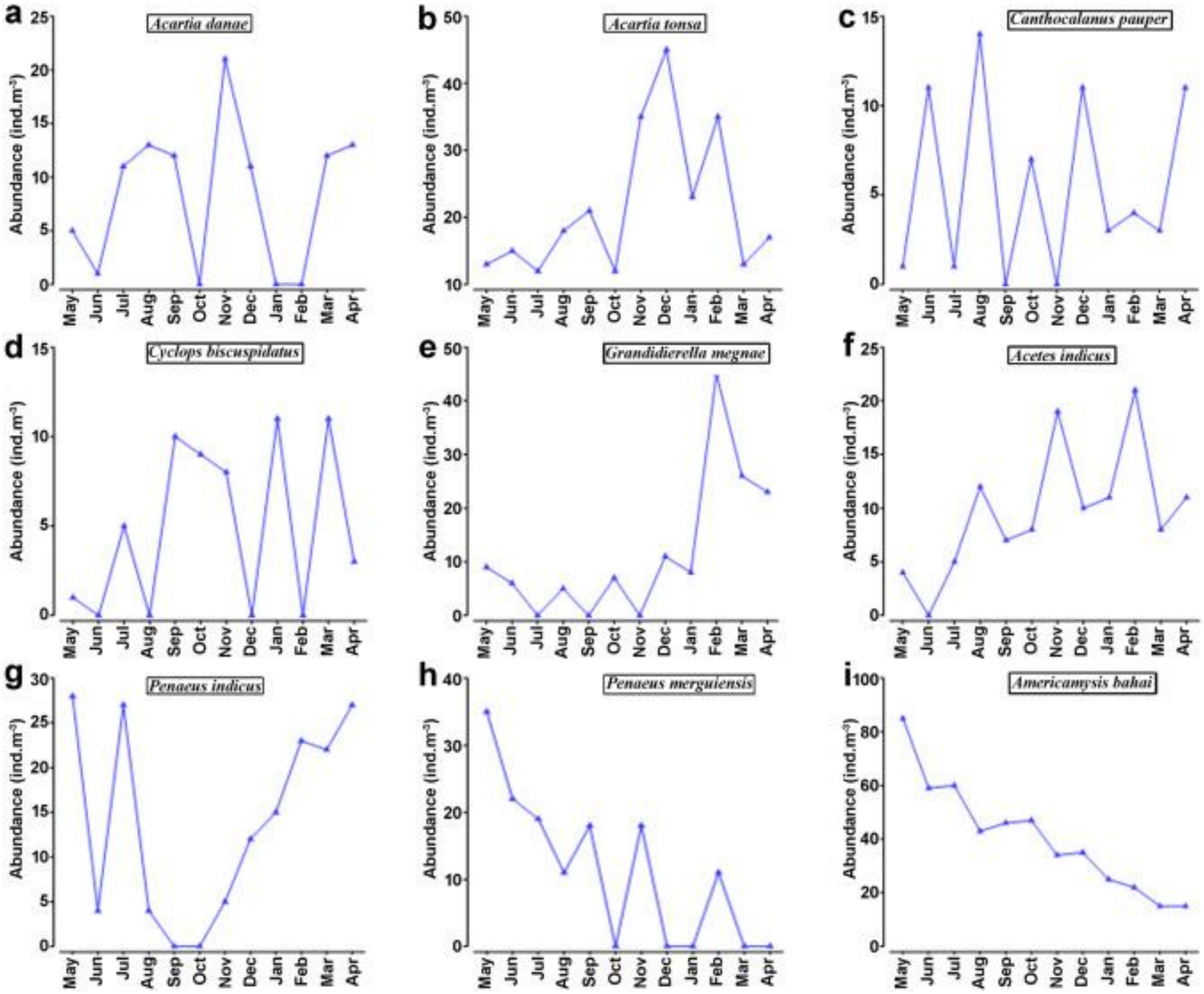

Species
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
100
75
50
25
0
Acartia danae
Acartia tonsa
Acartia negligens
Temora longicornis
Cantocalanus pauper
Calanus glacialis
Cyclops biscuspidatus
Corycaeus crassiusculus
Ampelisca bocki
Cheirphotis megnacheles
Acartia clausi
Grandidierella megnae
Gammarus roeselii
Cyathura sp.
Oniscus asellus
Acetes indicus
Acetes japonicas
Scylla sp.
Neptunus sp.
Penaeus monodon
Penaeus indicus
Penaeus merguiensis
Macrobracium rossenbergii
Americamysis bahai
Lucifer faxoni
Lucifer orientalis
Spadella cephaloptera
Mugil sp.
Ammothella longipes
Mactra sp.
Solen sp.
Umbenium sp.
Neathes sp.
Micronepthys sp.
Homarus sp.
Linuche sp.
Asterias sp.
Tanaissus lilljeborgi

Figure 5



a
Acartia danae
b
Acartia tonsa
c
Canthocalanus pauper
d
Cyclops biscuspidatus
e
Grandidierella megnae
f
Acetes indicus
g
Penaeus indicus
h
Penaeus merguiensis
i
Americamysis bahai
Abundance (ind.m^{-3})
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
0
5
10
15
20
25
30
40
50
60
80
100

Figure 6

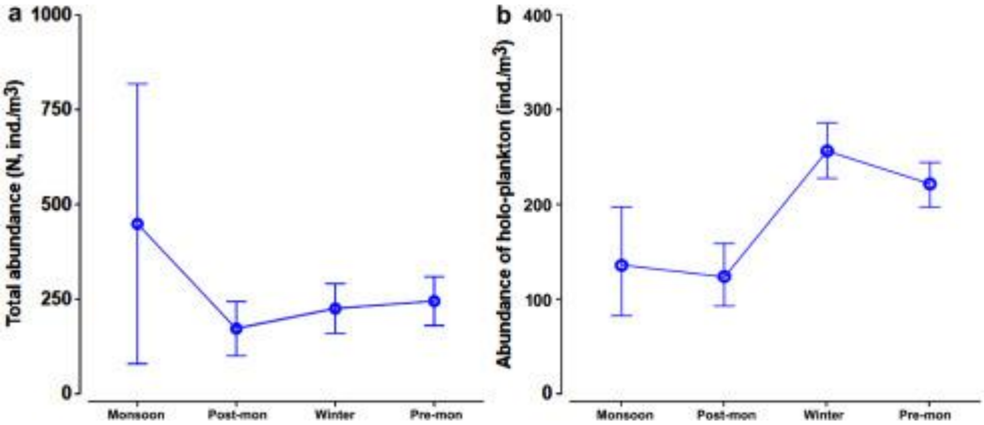


Figure 7

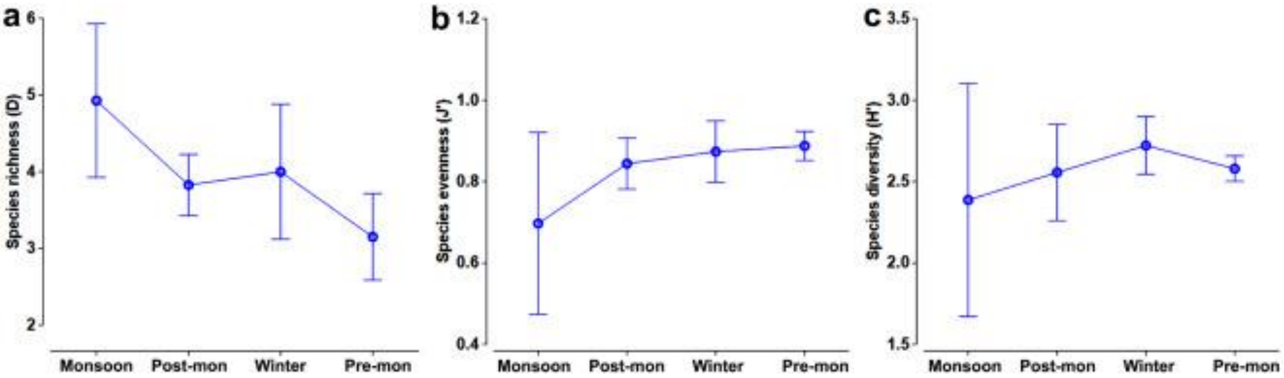
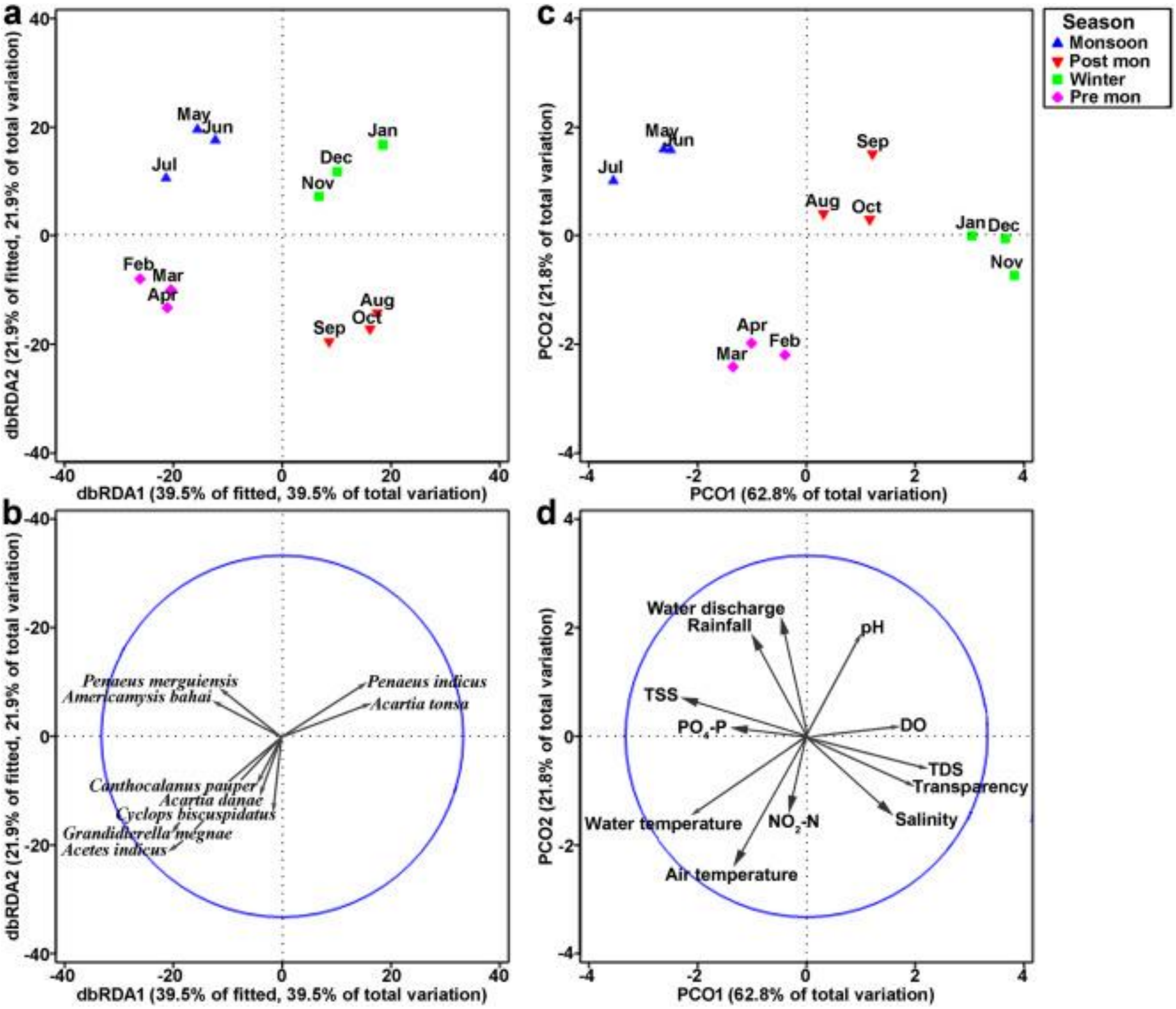


Figure 8


a
c
b
d
Season
▲ Monsoon
▼ Post mon
■ Winter
◆ Pre mon
May
Jun
Jul
Jan
Dec
Nov
Feb
Mar
Apr
Aug
Oct
Sep
dbRDA1 (39.5% of fitted, 39.5% of total variation)
dbRDA2 (21.9% of fitted, 21.9% of total variation)
PCO1 (62.8% of total variation)
PCO2 (21.8% of total variation)
40
20
0
-20
-40
4
2
-2
-4
Penaeus merguiensis
Americamysis bahai
Penaeus indicus
Acartia tonsa
Canthocalanus pauper
Acartia danae
Cyclops biscuspidatus
Grandidierella megnae
Acetes indicus
Water discharge
Rainfall
pH
TSS
PO$_4$-P
DO
TDS
Transparency
Salinity
Water temperature
NO$_2$-N
Air temperature