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ORIGINAL ARTICLE

Effects of tropical cyclone Amphan on the copepods of the Ganges estuary

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ABSTRACT
Tropical cyclones are increasingly affecting estuarine communities. The effects of category-5 tropical cyclone Amphan (landfall on 20 May 2020 near the Ganges estuary mouth) on the copepod community of the Ganges estuary were studied. Copepod assemblages were sampled before (February–December 2019), shortly after (31 May–12 June 2020) and post- (September–November 2020) Amphan periods. It was hypothesized that shortly after Amphan a relatively homogeneous community consisting of a few estuarine specialists would succeed but that would soon be replaced by a heterogeneous one; however, those specialists would continue their dominance. Shortly after Amphan species richness declined but the recovery process was completed within months, led by *Paracalanus parvus*, *Bestiolina similis*, *Acartia spinicauda*, *Acartiella tortaniformis* and *Oithona brevicornis*. Spatial homogeneity of the community that prevailed in pre- and shortly after Amphan was lost in post-Amphan. The unilateral dominance of B. similis observed in the pre-Amphan period was challenged by *P. parvus*, *A. spinicauda*, *A. tortaniformis* and *O. brevicornis* after Amphan. Shortly after Amphan *A. spinicauda* proliferated and co-dominated the estuary with *A. tortaniformis* but the latter replaced the former within a few months. The copepod community experienced rearrangements in species composition, abundance and dominance hierarchy; therefore, its regular monitoring is recommended..

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Introduction

Stochastic disruptions of coastal-marine ecosystems are often the results of discrete events that are extreme in nature (Sasaki et al. 2015). Tropical cyclones (TCs) also known as hurricanes and typhoons are increasingly affecting the lives and livelihoods of biological communities that inhabit within and beside coastal-marine ecosystems such as estuaries (Paerl et al. 2001; Phlips et al. 2020; Paul et al. 2020a, 2020b). With the advances in weather forecasting, tracking TCs before their landfall has become more predictable than was possible in the 20th century (Madsen and Jakobsen 2004; Mohanty et al. 2019); therefore, the estuarine scientific community is able to conduct assessment of disruptions caused by a TC or successive TCs (Steinke and Ward 1989; Paerl et al. 2001; Mukherjee et al. 2012; Beyrend-Dur et al. 2013; Bhattacharya et al. 2014; Kumar et al. 2017; Paul et al. 2020a). The impacts of TCs that hit the eastern coasts of North America have received significant attention in the estuarine literature because biogeochemical cycles and ecological communities of a few estuaries there are regularly monitored (Gong et al. 2007; Wetz and Paerl 2008; Paerl et al. 2018; Phlips et al. 2020; Wachnicka et al. 2020). For most estuaries of developing countries such assessments are difficult because they are not monitored at regular intervals. A few studies conducted in India, South Africa, Taiwan and China suggest that mechanical disruptions following a TC may lead plankton communities to experience various rearrangements in their species composition, abundance and dominance (Forbes and Cyrus 1992; Beyrend-Dur et al. 2013; Bhattacharya et al. 2014; Kumar et al. 2017; Paul et al. 2020b; Feng et al. 2022).

The coasts of the Bay of Bengal (BoB) are TC prone and an average of 3–4 TCs annually hit the region often in late pre-monsoon (April and May) and in early post-monsoon (October and November) (Alam et al. 2003). The Ganges River of India forms a macro-tidal river-estuary that penetrates about 200 km inside the BoB coast but its salinity front seldom penetrates beyond 90 km (Mukhopadhyay et al. 2006). Near the Namkhana of West Bengal, the Ganges estuary (GE) bifurcates and the offshoot known as the Muriganga takes a curved route before it meets the BoB (Mukhopadhyay et al. 2006). The Muriganga being close to the BoB coast faces the brunt of storm surges, depressions and TCs (Bhattacharya et al. 2014; Paul et al. 2020a,

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2020b). About 36 species of copepods are reported from the Muriganga and other river estuaries of the Indian Sundarbans (Bhattacharya et al. 2015; Paul et al. 2019). Copepod species such as *Bestiolina similis*, *Acartiella tortaniformis*, *Pseudodiaptomus serricaudatus*, *Paracalanus parvus* and *Acartia spinicauda* persist throughout the year in the Muriganga and are considered as estuarine specialists which adapt quickly to the extreme changes of the estuarine environment that follow a TC or successive TCs (Paul et al. 2020a, 2020b). Competition among those species is generally intense because their spatial niches are segregated only by a stretch of a few hundred metres of the Muriganga (Paul et al. 2019). Shortly after the TCs Aila, Fani and Bulbul the copepod community of the Muriganga temporarily lost many of its component species and an overall decrease in the copepod abundance was observed by Bhattacharya et al. (2014) and Paul et al. (2020a, 2020b). The intensity of TCs is increasing in the BoB; therefore, prolonged disruptions of the lower food web of the estuaries in the region may be more likely in the future (Bhattacharya et al. 2014; Mandal and Hosaka 2020; Paul et al. 2020b). Indian estuaries are not institutionally monitored on a regular basis; therefore, consequences of TC mediated changes of their biological communities and environments are mostly unknown. For such reasons the ‘Cyclone Ecology’ research programme of Indian estuaries was established by the authors in May 2019 in the Muriganga stretch of the GE. The programme intends to study impacts of different categories of TCs on the lower food web (taking copepods as model organisms) of an estuary along with the environmental changes that occur following a TC or successive TCs by adopting a before–after sampling design (Paul et al. 2020a, 2020b).

The Amphan was a category-5 TC which had a 1-minute sustained windspeed of 270 km/hour and a 3-minute windspeed of 240 km/hour (Khan et al. 2021). On 20 May 2019 Amphan made landfall near Bakkhali region, which is a few kilometres from the CE programme sites on the Muriganga stretch of the GE. At the time of landfall TC Amphan had a speed of 150–160 km/hour and gusts up to 185–190 km/hour. The storm surge (4.6 m recorded at the nearby Sagar Island weather station) and torrential rainfall (~250 mm in the Indian Sundarbans within few hours before–after landfall) associated with TC Amphan flooded most of the areas close to the Muriganga (Halder et al. 2021; Kumar et al. 2021). Considering those changes that followed shortly after TC Amphan the impacts were assessed on the copepod community of the Muriganga. It was hypothesized that within a few weeks of TC Amphan a relatively homogeneous community made up primarily by a few estuarine specialist copepod species would succeed; however, that within a few months a homogeneous community would be replaced by a more heterogeneous one but the dominance of those estuarine specialists would continue. The study aimed to understand the short- to medium-term vulnerability and resilience of the copepod community following a category-5 TC in a tropical river estuary.

Materials and methods

Study site

The Muriganga has a moderately developed mangrove vegetation and an intensely cultivated hinterland on the sides of the channel. Under the CE programme, plankton resources of S1, S2 and S3 sites which are about 500 m from each other in north–south direction on the Muriganga are regularly monitored in stable and/or perturbed states of the estuary (Paul et al. 2019, 2020a, 2020b). The site S1 (21°44′53.8"N, 88° 12′46.2″ E) is towards the upstream region of the Muriganga, site S3 (21°44′55.4"N, 88°12′36.8"E) is towards the downstream and near Taitan Island which has a semi-intense mangrove patch and site S2 (21° 44′55.7"N, 88°12′40.0"E) is equidistant from S1 and S3 and close to a dense mangrove patch of Half-Fish Island, which was recently declared a reserve by the Forest Department of West Bengal, India (Figure 1).

Before-after sampling design

The TC Amphan made landfall on 20 May 2020 and caused massive damage to infrastructure including roads to the Indian Sundarbans. The COVID-19 pandemic related lockdown made it even more difficult to mobilize scientific resources quickly after TC Amphan. The Muriganga stretch (Namkhana region of West Bengal) remained inaccessible for a week so the sampling begun on 31 May 2020. At first, samplings were conducted on a weekly basis from 31 May–12 June 2020. Those samples were assumed as the samples of shortly after Amphan period. After a pause, further samplings were conducted at monthly intervals from September–November 2020. Those samples were assumed as the samples of the post-Amphan period. Seasonal samplings conducted from S1, S2 and S3 sites of the Muriganga from February 2019 were assumed as the samples of the pre-Amphan period.

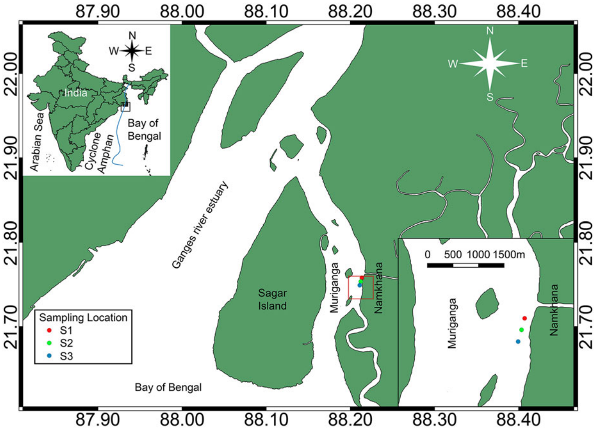

Figure 1. Map of the study area, track of tropical cyclone Amphan and sampling sites (S1, S2 and S3) on the Muriganga stretch of the Ganges estuary of India (modified after Paul et al. 2020b).

Measurement of abiotic parameters

All the samples were collected at high tide in the dark from a motor boat and on each occasion of sampling from S1, S2 and S3, salinity, water temperature (°C) and pH levels of the Muriganga were measured (in triplicate) by a handheld multi-parameter probe (YSI-1030, USA) from subsurface water.

Copepod sampling

For collection of copepod (>200 µm) assemblages, at each sampling site, 100 l of estuarine water was collected through a 10 l plastic bucket and sieved through a 200 µm plankton mesh after minor modification of the protocol adopted by Paul et al. (2019, 2020a, 2020b). Copepod assemblages were collected in triplicate and 5 ml of 4% buffered formalin was added to the copepod samples for preservation. Samples were then transported to the laboratory where multiple aliquot samples of 1 ml each were drawn. Each aliquot was placed on a Sedgewick Rafter counting cell and examined under a stereo microscope (Bestscope-BS30T, China). Copepod individuals (adults only) were identified to species level following the taxonomic literature of Kasturirangan (1963) and their abundances were expressed as individual(s) per cubic metre (i.e. ind.m^{-3}).

Data structure, presentation and analysis

Analyses were performed using CRAN-R 4.1.1 (R Core Team 2021) and PRIMER-7.0 (Clarke and Gorley 2015). Results of statistical tests were presented with corresponding t, W, F, K-W chi-square and P values and degrees of freedom (DF). Site-specific relative abundance of the copepods was calculated for the pre-, shortly after and post-Amphan periods. For analysing dominant or co-dominant status of a few frequently caught species, index of dominance was calculated following the formula adopted by Bhattacharya et al. (2014) i.e. $Yi = (Ni/N) * Fi$ where Yi is the dominance of species i, Ni is the number of individuals of species i at all sites (i.e. S1, S2 and S3), N is the number of all species sampled at all sites, and Fi is the frequency of sites at which species i occurs. Species with a Yi value greater than 0.02 were considered dominant species of the habitat (Bhattacharya et al. 2014). Such was calculated for the pre-, shortly after Amphan and post-Amphan periods. Diversity indices such as Shannon and Simpson were calculated for biological data collected in all the sampling occasions by using the Vegan package (version 2.6–4). Site-specific data were pooled together to draw comparisons of total abundance, diversity (Shannon index) and dominance (Simpson) of the copepod community between the pre-, shortly after and post-Amphan periods. For the comparative assessments of the total abundance (i.e. count data) and dominance (Simpson index; Shapiro test: $W = 0.86$, $P < 0.0001$) datasets between the pre-, shortly after and post-Amphan periods, Kruskal–Wallis tests were conducted as those datasets were not normally distributed; however, in the case of diversity data (i.e. Shannon index; Shapiro test: $W = 0.95$, $P = 0.145$) an ANOVA was conducted. If the results of Kruskal–Wallis tests and ANOVA were found to be significant then further post-hoc tests were conducted.

Ordination analysis (on species abundance data after square root transformation) was conducted through Non-metric Multidimensional Scaling (NMDS) using the Bray–Curtis measure of dissimilarity (Vegan package version 2.5.6). Inference on dimensionality of NMDS ($K = 2$ were considered) was taken only after examining the stress scores, Shepard diagrams, non-metric and linear fit R^2 scores (see details in Annexure 1). NMDS biplots were drawn. Permutational Multivariate Analyses of Variance (PERMANOVA) were conducted (i.e. Adonis test, permutations = 999, method = Bray–Curtis, package: Vegan version: 2.5.6) to evaluate variability of the copepod assemblages of pre-Amphan, shortly after Amphan and post-Amphan periods. For PERMANOVA an assumption of homogeneity of multi-variate dispersion was tested by conducting analysis of variance (ANOVA). Similarity percentage analysis (i.e. SIMPER) was conducted for the assessment of similarity and dissimilarity of the copepod assemblages sampled in the pre-Amphan, shortly after Amphan and post-Amphan periods.

Results

Abiotic variability of the Muriganga before–after TC Amphan

In 2019, the highest salinity (19.30) was measured in May and the lowest (8.60) was measured in August (Table I). The highest water temperature (31.20°C) was measured in May 2019 and it dropped to the lowest (20.40°C) in December 2019 (Table I). The highest pH (8.64) was measured in December and the lowest pH (7.10) was measured in May 2019 (Table I). Shortly after Amphan, meso- to polyhaline (16.20–19.30) salinity, warm water temperature and alkaline pH conditions of the Muriganga were evident (Table I). Salinity (4.80–7.70) in the post-Amphan period dropped in the Muriganga but the warm water temperature and alkaline pH conditions persisted (Table I).

Community structure before–after Amphan

Species richness in the pre-, shortly after and post-Amphan periods were up to 26, 22 and 25, respectively (Table II). *Bestiolina similis*, *Paracalanus parvus*, *Acartia spinicauda*, *Acartiella tortaniformis* and *Oithona brevicornis* were highly abundant whereas *Euchaeta marina*, *Eucalanus crassus*, *Labidocera euchaeta* and *Oithona similis* were among the rare species (Table II). During the pre-Amphan period the median of the total abundance of the sampled copepods was 35,970 ind./m^3 (ranged 13,333–88,000 ind./m^3), shortly after Amphan the median was 44,433 ind./m^3 (ranged 4100–68,200 ind./m^3) and in the post-Amphan period the median was 63,783 ind./m^3 (36,100–100,800 ind./m^3). Kruskal–Wallis test revealed that total abundance of the copepod community did not change significantly (K-W chi-squared = 5.4, df = 2, $P = 0.07$) from the pre-Amphan to shortly after to post-Amphan periods. Site-specific changes of the total abundances of the copepod community during the pre-Amphan, shortly after and post-Amphan periods are described in Figure 2. Compared with the pre-Amphan period the relative abundances of *Bestiolina similis* were less at S2 and S3 shortly after Amphan and post-Amphan periods (Table II). *Acartia spinicauda* was more frequent in the shortly after Amphan than the pre- and post-Amphan periods, as were *Acrocalanus gracilis* and *Acartia sewelli* (Table II). Abundances of *Bestiolina similis*, *Acartia spinicauda*, *Acartiella tortaniformis* did rise shortly after Amana but *Acartia tonsa* was absent from S1 and S2 shortly after Amphan (Table II). Shortly after Amphan, abundance of *Oithona brevicornis* did rise but *Oithona similis* was absent from all the sites (Table II). Shortly after Amphan copepod *Pseudodiaptamus binghami* was absent (Table II). Relative abundance of *Acrocalanus gibber* was higher shortly after Amphan than in the pre- and post-Amphan periods (Table II). Relative abundance of *Pseudodiaptamus serricaudatus* was considerably less (was even absent at S1 and S2) shortly after Amphan compared with its relative abundances in pre- and post-Amphan periods (Table II). During the pre-Amphan period the mean of the Shannon diversity index was 2.30 (range 1.65–2.94), shortly after Amphan that was 1.99 (range 1.09–2.59) and in the post-Amphan period that was 2.56 (range 2.27–2.80). The Shannon diversity index varied significantly (F value = 5.83, df = 2, $P = 0.007$) from the pre-Amphan to shorty after to post-Amphan periods. In term of diversity significant variation ($P = 0.005$) was observed between shortly after and post-Amphan periods but such was not the case in pre-Amphan to post-Amphan and per-Amphan to shortly after Amphan periods. Site-specific changes of the

Table I. Salinity, water temperature (°C) and pH of the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

		Salinity			Water temperature			pH		
Period	Sampling date	S1	S2	S3	S1	S2	S3	S1	S2	S3
Pre-Amphan	25.02.2019	13.27	13.93	14.03	23.40	23.30	23.00	7.90	7.80	7.60
	14.05.2019	19.30	19.20	19.20	31.20	31.20	31.30	7.10	7.10	7.20
	24.08.2019	8.90	8.85	8.60	27.10	27.32	27.27	8.10	8.11	8.14
	18.11.2019	9.80	10.10	10.20	23.20	23.20	23.30	8.40	8.60	8.60
	28.12.2019	10.00	10.90	10.90	20.40	20.70	20.70	8.64	8.42	8.53
Shortly after Amphan	31.05.2020	17.80	17.50	18.50	30.10	30.80	29.90	8.31	8.22	8.25
	05.06.2020	18.30	18.20	19.30	29.60	29.90	29.90	8.41	8.56	8.39
	12.06.2020	16.20	16.20	16.30	28.30	28.30	28.40	8.33	8.34	8.51
Post-Amphan	09.09.2020	5.10	5.30	5.10	29.70	29.60	29.70	7.81	7.80	7.76
	03.10.2020	5.10	5.10	4.80	30.20	30.20	30.25	7.00	7.66	7.88
	21.11.2020	7.50	7.65	7.70	26.90	26.80	26.80	7.50	7.48	7.54

Table II. Relative abundance (%) of copepod species on the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

	S1			S2			S3		
Copepod species	PRA	SAA	POA	PRA	SAA	POA	PRA	SAA	POA
Paracalanus parvas	12.86	10.98	10.16	10.60	07.55	10.68	09.53	08.90	10.16
Paracalanus aculeatus	04.77	01.87	04.06	04.79	04.73	01.37	04.14	04.52	02.56
Paracalanus indicus	00.47	03.75	03.20	01.18	04.91	02.90	01.02	04.52	02.56
Paracalanus dubia	02.03	01.87	00.00	02.13	01.32	05.60	04.40	01.26	04.35
Acrocalanus gibber	00.00	05.27	01.87	00.00	03.12	00.75	00.00	02.12	00.00
Acrocalanus gracilis	01.69	05.36	03.36	02.75	07.76	02.90	00.86	04.38	03.64
Acrocalanus longicornis	01.86	03.61	00.00	00.74	01.32	02.90	00.90	02.32	02.53
Bestiolina similis	21.30	21.86	20.24	21.73	22.50	17.43	19.45	19.60	14.90
Parvocalanus crassirostris	03.26	01.87	04.97	02.47	01.32	01.37	01.53	03.79	03.28
Acartia spinicauda	08.70	14.33	12.82	09.83	17.68	09.87	10.31	16.28	10.55
Acartia sewelli	00.00	05.53	01.44	00.00	03.78	00.75	00.00	02.26	01.82
Acartia tonsa	02.33	00.00	00.00	01.40	00.00	01.37	01.17	01.26	01.82
Acatia tropica	04.59	00.00	00.00	04.56	00.00	03.82	06.63	00.00	05.45
Acartiella tortaniformis	16.65	16.33	17.63	11.31	12.28	14.69	13.13	13.28	12.01
Pseudodiaptamus serricaudatus	02.94	00.00	05.39	06.84	00.00	02.74	08.87	01.26	05.84
Pseudodiaptamus binghami	02.50	00.00	02.19	02.49	00.00	00.75	02.90	00.00	00.72
Canthocalanus pauper	00.00	00.00	02.19	02.10	00.00	03.66	02.55	02.06	01.82
Eucalanus subcrassus	00.47	00.00	01.44	03.03	00.00	02.90	01.15	00.00	02.18
Eucalanus crassus	01.55	00.00	00.00	01.41	00.00	00.00	00.86	00.00	01.10
Euchaeta marina	00.00	00.00	00.00	00.00	02.08	00.00	00.00	00.00	00.00
Labidocera euchaeta	01.08	00.00	00.00	01.40	00.00	00.00	00.86	00.00	00.00
Labidocera acuta	01.55	01.74	00.00	01.76	00.00	02.90	01.17	02.12	00.74
Temora turbinata	00.00	00.00	02.19	01.24	00.00	01.37	00.76	01.26	01.82
Corycaeus danae	01.08	00.00	01.44	01.03	02.28	02.88	00.86	01.00	01.10
Oncea venusta	03.16	00.00	00.00	00.00	00.00	00.00	00.00	01.26	02.53
Oithona similis	00.47	00.00	00.00	00.36	00.00	01.37	00.61	00.00	00.00
Oithona brevicornis	04.68	05.62	05.39	04.85	07.37	05.00	06.35	06.52	06.53

PRA = Pre-Amphan; SAA = Shortly after Amphan; POA = Post-Amphan

Shannon diversity index of the copepod community during the pre-Amphan, shortly after and post-Amphan periods are described in Figure 2. *Bestiolina similis* maintained its dominant status throughout the pre-Amphan period (Table III). Shortly after Amphan *Acartia spinicauda* and *P. parvus* dominated the Muriganga but *Bestiolina similis* soon regained its dominant position (Table III). Species such as *Acartiella tortaniformis*, *Acartia spinicauda* and *Oithona brevicornis* co-dominated the Muriganga along with *Bestiolina similis* in the shortly after Amphan and post-Amphan periods. During the pre-Amphan period the median of the dominance index was 0.87 (range 0.77–0.94), shortly after Amphan the median was 0.85 (range 0.66–0.91) and in the post-Amphan period the median was 0.9 (range 0.87–0.92). The Simpson index varied significantly (K-W chi-squared = 7.15, df = 2, $P = 0.03$) from the pre-Amphan to shorty after to post-Amphan periods. In term of dominance significant variation ($P = 0.03$) was observed between shortly after and post-Amphan periods but this was not the cases for the pre-Amphan to post-Amphan and per-Amphan to shortly after Amphan periods. Site-specific changes of the Simpson index of the copepod community during the pre-Amphan, shortly after and post-Amphan periods are described in Figure 2.

Spatial–temporal variability of community before-after Amphan

Spatial variability of the copepod community in the pre-Amphan period was not significant (PERMANOVA: df = 2, sum of square = 0.12, Pseudo-F = 0.74, $R^2 = 0.05$, $P = 0.69$; homogeneity of multivariate dispersion test ANOVA: df = 2, F = 0.12, $P = 0.88$) so was shortly after Amphan (PERMANOVA: df = 2, sum of square = 0.16, Pseudo-F = 0.58, $R^2 = 0.16$, $P = 0.79$; homogeneity of multivariate dispersion test ANOVA: df = 2, F = 0.48, $P = 0.63$) (see Figure 3). The copepod community exhibited significant spatial variability in the post-Amphan period (PERMANOVA: df = 2, sum of square = 0.14, Pseudo-F = 4.73, $R^2 = 0.61$, $P = 0.004$; homogeneity of multivariate dispersion test ANOVA: df = 2, F = 0.09, $P = 0.91$) (see Figure 3).

Temporally the composition of the copepod community varied significantly among the pre-, shortly after and post-Amphan periods (PERMANOVA: df = 2, sum of square = 0.81, Pseudo-F = 4.89, $R^2 = 0.24$, $P = 0.001$; the assumption of homogeneity of multivariate dispersion was not violated (ANOVA: df = 2, F = 0.08, $P = 0.87$)) (Figure 4). During the pre-Amphan period, the average similarities of the copepod community sampled from S1, S2 and S3 sites were 52.55%,

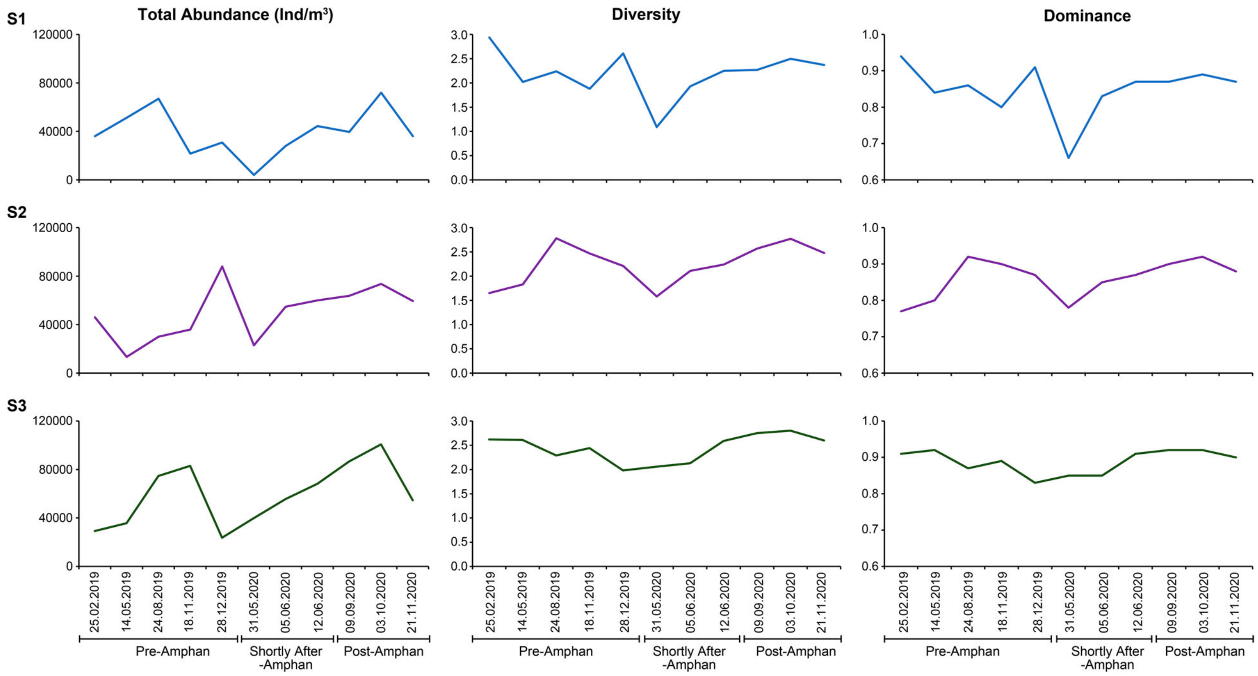

Figure 2. Temporal variability of the total abundance (ind./m^3), Shannon diversity index and Simpson dominance index of the copepod community sampled from the S1, S2 and S3 sites of the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

53.98% and 57.13%, respectively and were primarily driven by *Bestiolina similis*, *Paracalanus parvus* and *Acartia spinicauda* (Table IV). The dissimilarity between S1 and S2 was 43.26%, S1 and S3 was 43.88%, S2 and S3 was 39.46%. Dissimilarities were chiefly contributed by *Acartiella tortaniformis*, *Acartia tropica* and *Oithona brevicornis* (Table V). Shortly after Amphan similarities of the copepod community among S1, S2 and S3 were 34.55%, 50.13% and 60.68%, respectively and primarily driven by *Bestiolina similis*, *Acartia spinicauda*, *Acartiella tortaniformis* and a few other species (Table IV). The dissimilarity of the copepod community between S1 and S2 was 50.20%, S1 and S3 was 48.65%, S2 and S3 was 37.62% and these were driven mainly by *Acartia spinicauda*, *Acartiella tortaniformis* and *Oithona brevicornis* (Table V). During the post-Amphan period similarities of the copepod community at S1, S2 and S3 were 80.34%, 78.02% and 81.54%, respectively and *Bestiolina similis*, *P. parvus*, *Acartia spinicauda* and *Acartiella tortaniformis* were among the primary contributors (Table IV). The dissimilarity between S1 and S2 was 29.83%, S1 and S3 was 29.87%, S2 and S3 was 23.09% and were largely contributed by *Paracalanus dubia*, *Acartia tropica*, *Acrocalanus longicornis*, *Oncea venusta* and *Labidocera acuta* (Table V).

Table III. Index of dominance of a few abundant species of copepods on the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

Sampling period	Sampling date	*Bestiolina similis*	*Acartiella tortaniformis*	*Acartia spinicauda*	*Paracalanus parvas*	*Oithona brevicornis*
Pre-Amphan	25.02.2019	0.12	0.01	0.06	0.08	0.06
	14.05.2019	0.23	0.18	0.13	0.11	0.04
	24.08.2019	0.13	0.06	0.04	0.11	0.02
	18.11.2019	0.22	0.15	0.09	0.11	0.08
	28.12.2019	0.29	0.28	0.11	0.07	0.02
Shortly after Amphan	31.05.2020	0.03	0.03	0.12	0.17	0.00
	05.06.2020	0.22	0.14	0.21	0.07	0.08
	12.06.2020	0.19	0.14	0.12	0.11	0.08
Post-Amphan	09.09.2020	0.17	0.14	0.10	0.08	0.07
	03.10.2020	0.16	0.13	0.11	0.07	0.05
	21.11.2020	0.03	0.37	0.01	0.26	0.16

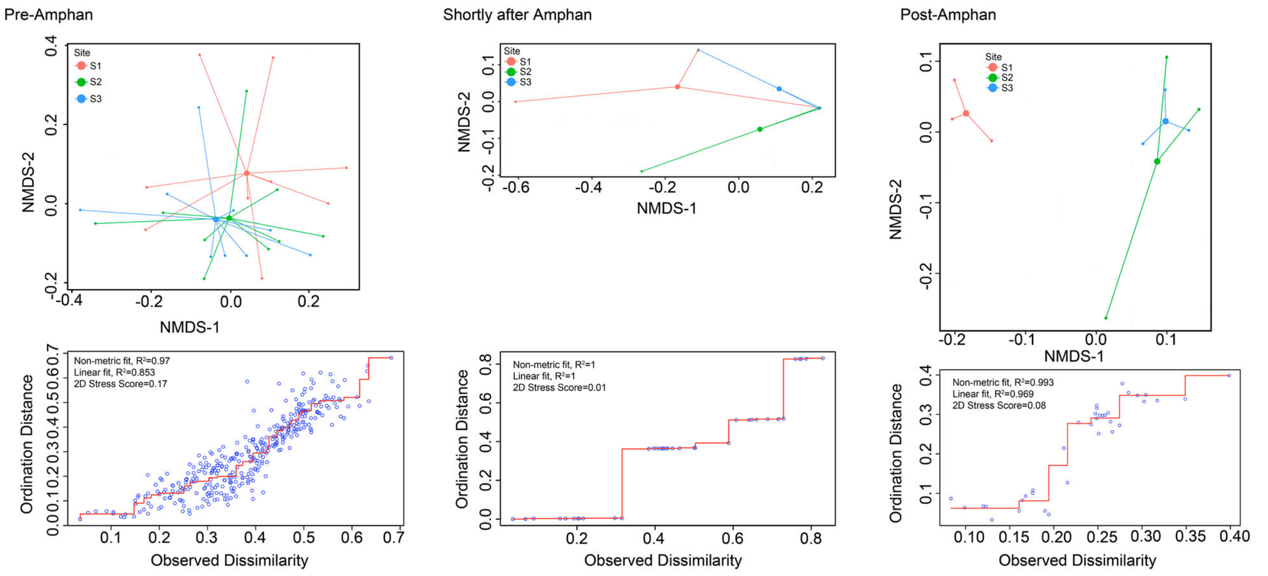

Figure 3. Spatial variability of the copepod community sampled during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods from the S1, S2 and S3 sites on the Muriganga stretch of the Ganges estuary of India.

Discussion

Abiotic variability of the Muriganga

The results demonstrated that in the short to medium term (i.e. within a few weeks to a few months from the landfall of TC Amphan) the copepod community of the Muriganga had rebuilt their community and a few estuarine specialist copepod species dominated throughout the period. Shortly after Amphan the Muriganga turned to a warm, polyhaline and alkaline (pH > 8) habitat and these conditions lasted for a few weeks. That is, however, not unusual for the Muriganga stretch of the GE specially in the late pre-monsoon to early monsoon because evaporation rates remain high in that period due to high ambient temperatures (Mukhopadhyay et al. 2006). The Muriganga may remain saline even after receiving post-TC rains for a few days because salinity of the Muriganga is dependent more on tidal inflow of marine waters of the adjacent BoB than on precipitation (Choudhury et al. 2015; Das et al. 2016; Paul et al. 2020b). During and even after a few days of a TC, strong onshore winds enhance the landward saltwater intrusion in the coastal wetlands and estuaries of the USA (Michener et al. 1997). For the Muriganga such was observed shortly after TC Phailin in October 2013 (Das et al. 2016), TC Fani in May 2019 (Paul et al. 2020b) and a similar condition persisted even after TC Amphan in May 2020. Shortly after TC Amphan, alkalinity of the Muriganga was high. This is possibly due to the intrusion and dominance of seawater over riverine flow of the GE (Das et al. 2016); however, in the post-Amphan period the pH level of the Muriganga dropped compared with the pH level measured shortly after Amphan. The Muriganga usually remains alkaline and its pH profile has a negative correlation with seasonal rainfall and positive correlation with

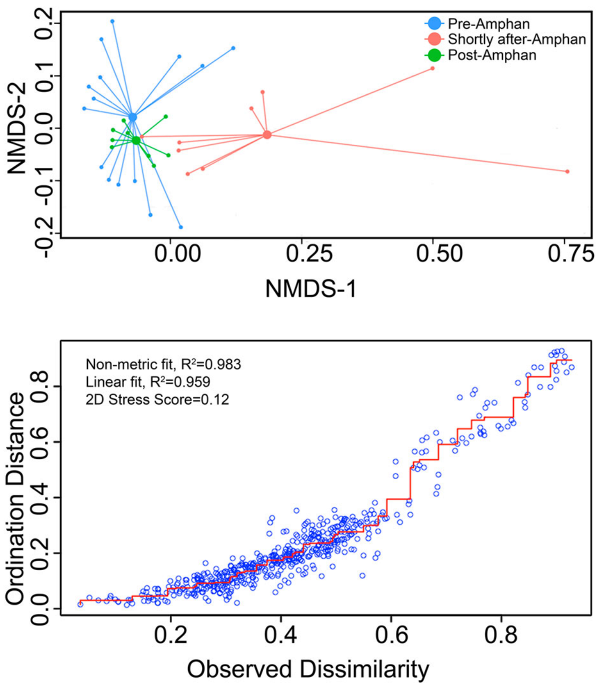

Figure 4. Temporal variability of the copepod community sampled from the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

Table IV. Similarities of the copepod community of S1, S2 and S3 sites on the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

Pre-Amphan (February–December 2019)					
S1		S2		S3	
Species	Average similarity: 52.55%	Species	Average similarity: 53.98%	Species	Average similarity: 57.13%
B. similis	20.54	*B. similis*	19.14	*B. similis*	18.77
A. tortaniformis	18.27	*P. parvas*	13.11	*P. parvas*	14.37
P. parvas	14.93	*A. spinicauda*	12.98	*A. spinicauda*	11.87
A. spinicauda	12.28	*P. serricaudatus*	11.67	*P. serricaudatus*	11.40
Acatia tropica	06.38	*P. aculeatus*	08.29	*O. brevicornis*	09.41
Shortly after Amphan (31 May–12 June 2020)					
S1		S2		S3	
Species	Average similarity: 34.55%	Species	Average similarity: 50.13%	Species	Average similarity: 60.68%
B. similis	33.84	*B. similis*	28.47	*B. similis*	20.78
A. gibber	12.59	*A. spinicauda*	24.51	*A. spinicauda*	18.59
A. tortaniformis	12.32	*A. gracilis*	15.92	*A. tortaniformis*	17.74
A. spinicauda	11.06	*A. tortaniformis*	07.84	*P. parvas*	13.51
Acartia sewelli	08.93	-	-	-	-
Post-Amphan (September–November 2020)					
S1		S2		S3	
Species	Average similarity: 80.34%	Species	Average similarity: 78.02%	Species	Average similarity: 81.54%
B. similis	14.15	*B. similis*	13.02	*B. similis*	10.07
A. tortaniformis	13.02	*A. tortaniformis*	12.05	*A. tortaniformis*	09.30
A. spinicauda	10.93	*A. spinicauda*	09.60	*P. parvus*	08.98
P. parvus	09.98	*P. parvus*	08.91	*A. spinicauda*	08.55
P. serricaudatus	06.20	*P. dubia*	07.11	*O. brevicornis*	06.56

salinity (Mukhopadhyay et al. 2006; Choudhury et al. 2015; Das et al. 2016). During the Post-Amphan period a considerable decline in salinity level of the Muriganga was evident because the system received a lot of rain in 2020 as there was a delay in the onset of the monsoon in India (specifically, in southern West Bengal) and the rainy days carried on well into November 2020.

Copepod community before–after Amphan

The results suggested that the copepod community structure (measured through richness, abundance, Shannon diversity and Simpson index of dominance) did change to some degree in the Muriganga but those changes of the community lasted only for a few weeks. Such a temporary decline in the species richness of the copepod community structure was observed in the Indian Sundarbans after TCs Aila, Fani and Bulbul, and also in the Chilika lagoon of Orissa, India after TC Hudhud (Bhattacharya et al. 2014; Paul et al. 2020a; Srichandan et al. 2021). Species such as *Bestiolina similis*, *Paraclanus parvus*, *Acartia spinicauda*, *Acartiella tortaniformis* and *O. brevicornis* were abundant after TC Amphan. This was also observed after TCs Aila, Fani and Bulbul disrupted the GE in 2009 and 2019, respectively (Bhattacharya et al. 2014; Paul et al. 2020a, 2020b). After TC Hudhud in 2014, a major shift in the zooplankton community of the Chilika lagoon was seen, which was primarily caused by copepods of the genera *Acartia*, *Acrocalanus*, *Euterpina*, *Oithona* and *Pseudodiaptomus* under the influence of exaggerated variability of salinity, turbidity and phytoplankton density (Srichandan et al. 2021). *Bestiolina similis* is an estuarine specialist that could survive even under extreme and abrupt changes of estuarine environment as observed by Paul et al. (2020b) after TC Fani in the Muriganga stretch of the GE. In the Indian Sundarbans *Bestiolina similis* maintained its dominant status in the copepod community after TCs Aila, Fani and Bulbul (Bhattacharya et al. 2014; Paul et al. 2020a, 2020b) and even in the pre-Amphan period but shortly after TC Amphan and later in the post-Amphan period it lost its dominant position in the copepod community on various occasions to *Paraclanus parvus*, *Acartia spinicauda*, *Acartiella tortaniformis* and *O. brevicornis*. Bhattacharya et al. (2014) observed proliferation of *Acartia spinicauda* in the Indian Sundarbans after TC Aila in 2009. The calanoid copepods of Taiwan's Danshuei River estuary declined considerably after successive typhoons during 2008–2009, which led to a sudden proliferation of *Acartia spinicauda* followed by a temporary replacement of *Pseudodiaptomus annandalei* which otherwise dominates the estuary (Beyrend-Dur et al. 2013). A sudden proliferation of *Acartia*

Table V. Dissimilarities of the copepod community of S1, S2 and S3 sites on the Muriganga stretch of the Ganges estuary of India during the pre-Amphan (February–December 2019), shortly after Amphan (31 May–12 June 2020) and post-Amphan (September–November 2020) periods.

Pre-Amphan (February–December 2019)					
S1 & S2		S1 & S3		S2 & S3	
Species	Average dissimilarity: 43.26%	Species	Average dissimilarity: 43.88%	Species	Average dissimilarity: 39.46%
A. tortaniformis	7.38	*A. tortaniformis*	7.23	*A. tortaniformis*	8.66
B. similis	6.42	*A. tropica*	6.52	*A. tropica*	6.75
O. brevicornis	5.74	*P. serricaudatus*	6.41	*P. aculeatus*	5.91
P. serricaudatus	5.33	*O. brevicornis*	6.23	*P. dubia*	5.55
P. parvas	5.15	*B. similis*	5.93	*B. similis*	5.49
Shortly after Amphan (31 May–12 June 2020)					
S1 & S2		S1 & S3		S2 & S3	
Species	Average dissimilarity: 50.20%	Species	Average dissimilarity: 48.65%	Species	Average dissimilarity: 37.62%
A. spinicauda	10.61	*A. spinicauda*	9.54	*A. tortaniformis*	7.88
A. tortaniformis	9.50	*A. tortaniformis*	7.66	*O. brevicornis*	7.45
A. gracilis	8.40	*O. brevicornis*	7.54	*P. parvas*	7.31
B. similis	8.22	*B. similis*	7.36	*P. aculeatus*	6.45
O. brevicornis	7.86	*P. parvas*	6.85	*A. gibber*	6.11
Post-Amphan (September–November 2020)					
S1 & S2		S1 & S3		S2 & S3	
Species	Average dissimilarity: 29.83%	Species	Average dissimilarity: 29.87%	Species	Average dissimilarity: 23.09%
P. dubia	11.27	*A. tropica*	11.06	*O. venusta*	8.47
A. longicornis	7.86	*P. dubia*	9.76	*P. serricaudatus*	7.00
L. acuta	7.86	*A. longicornis*	7.34	*L. acuta*	6.31
A. tropica	7.45	*O. venusta*	7.34	*A. tropica*	5.83
P. crassirostris	4.92	*A. tonsa*	6.39	*P. crassirostris*	5.25

spinicauda was also observed shortly after the TC Amphan and it temporarily replaced the dominant *Bestiolina similis*. After TC Aila the *Oithona brevicornis* population was highly abundant in the estuaries of the Indian Sundarbans (Bhattacharya et al. 2014) but that was not observed shortly after TC Amphan, rather it was months after TC Amphan when *Oithona brevicornis* population proliferated in the Muriganga and co-dominated the estuary along with *Acartiella tortaniformis* and *Paracalanus parvus*. When the Muriganga remains unperturbed by any TC for months *Paracalanus parvus* and *Bestiolina similis* intensely compete with each other for a spatial niche (Paul et al. 2019). Shortly after Amphan *Paracalanus parvus* population proliferated in the Muriganga and co-dominated the estuary along with *Acartiella tortaniformis*; however, such proliferation of *Paracalanus parvus* was also observed shortly after TCs Fani and Bulbul in May and November of 2019 (Paul et al. 2020a).

After TC Hudhud in 2014 the zooplankton community of the Chilika lagoon of Orissa, India was dominated by the nauplii and copepodites stages as the phytoplankton density of the lagoon increased in response to the upsurge in the nutrient level of the habitat (Srichandan et al. 2021). Results of environmental and biological variabilities observed after TC Amphan have some similarities with the work of Bhattacharya et al. (2014) who found considerable changes in biotic communities and their environments after TC Aila in 2009 which ravaged the estuaries of the Indian Sundarbans. After TC Amphan the copepod *Oithona brevicornis* population slowly proliferated; however, its proliferation did not resemble the overwhelming proliferation of the same species observed by Bhattacharya et al. (2014) who studied the changes of the zooplankton community in the Indian Sundarbans after TC Aila in 2009. A delayed recolonization of *Oithona brevicornis* was also observed after TCs Fani and Bulbul in 2019 (Paul et al. 2020a). Overall, the results demonstrated many rearrangements which had occurred in the composition, abundance and dominance of the copepod community after the Muriganga stretch of the GE was disrupted by TC Amphan.

The copepod community of the Muriganga exhibited a significant spatial variability in the post-Amphan period which was absent shortly after Amphan and in the pre-Amphan period. Similar conditions were observed in the Chilika lagoon of India by Kumar et al. (2017) and Srichandan et al. (2021) after TC Phailin in 2013 and TC Hudhud in 2014, respectively. The post-Amphan similarities of the copepod community were higher than those of the pre-Amphan and shortly after Amphan periods but irrespective of time copepod species such as *Bestiolina similis* and *Acartia spinicauda* were among the chief contributors of those similarities. Dissimilarities of the copepod community were less in the post-Amphan period compared with the pre- and shortly after Amphan periods. Shortly after Amphan dissimilarities of the community at S1 and S2 sites were higher than the pre-Amphan period but the dissimilarities at S3 site was less than the pre-Amphan period. Hurricane Ike in 2008 and Hurricane Harvey in 2017 struck the Gulf of Mexico of USA and on both these occasions the pelagic communities including zooplankton were severely perturbed; however, zooplankton recovered fast and their recovery time was related more with the severity of the flood that followed a TC rather than the storm surge (Liu et al. 2021). Liu et al. (2021) further suggested that 'aftermaths of the two hurricanes exhibited distinct spatial arrangements of zooplankton assemblages associated with hydrographic factors largely signifying the relative impact of floodwater discharge and storm surge on pelagic communities'. The aftermath of a TC or TCs may cause decreases in the abundance, biomass and species composition of zooplankton (including) in estuaries but most changes are temporary due to the short life cycle and potential replenishment from adjacent coastal waters, particularly for the study area with a short residence and sheared residual circulation driving coastal ocean water upstream near the seafloor (Rayson et al. 2015; Paul et al. 2020a, 2020b). That is highly plausible for the copepod community of the inter-connected river estuaries of the Indian Sundarbans including the Muriganga stretch of the GE which receives coastal water from the adjacent BoB (Bhattacharya et al. 2014; Paul et al. 2020a, 2020b). Liu et al. (2021) suggested the differences in the short- and long-term comparisons of zooplankton abundance after a TC or TCs reveal the intense effect of physical removal (i.e. scouring) by TCs on estuarine pelagic communities. Studies conducted on open systems suggested that tidal advection of seawater carrying coastal and oceanic species replenishes zooplankton communities sooner than in estuarine lakes (Forbes and Cyrus 1992; Beyrend-Dur et al. 2013; Kumar et al. 2017; Liu et al. 2021); therefore copepods of river estuaries generally recover fast after being disrupted by a TC or successive TCs (Paul et al. 2020a, 2020b) as observed previously in the Muriganga after it was hit by TCs Fani and BulBul in 2019. If the number of TCs increases or if future TCs that may hit the Indian Sundarbans become more intense than before, or both of these circumstances occur, then the vulnerability of the copepod community cannot be ruled out because the recovery time may not be available between successive TCs (Paul et al. 2020a).

Conceiving a cyclone research programme for Indian estuaries

The intensity of TCs is increasing in the BoB region which has become a global hotspot of TCs (Golder et al. 2021). Looking forward as far as 2050, annual incidences of cyclonic disturbances may vary from 5–13 and on average there may be one severe cyclonic storm per year and that is most likely in the post-monsoon (Sen et al. 2021); therefore, the estuarine communities of India are likely to be stressed for longer time periods in future than they used to be in the past from TC-mediated disruptions (Kumar et al. 2017; Paul et al. 2020a, 2020b; Srichandan et al. 2021). Regular TCs may strain coastal communities which may trigger cascading effects in the estuarine food chains (Joseph et al. 2011; Mukherjee et al. 2012; Mangesh et al. 2016; Paul et al. 2020a; Mishra et al. 2021; Srichandan et al. 2021). Considering such possibilities, in future regular monitoring of Indian estuaries before and after a cyclonic disruption is strongly recommended. By establishing collaborations among coastal institutions (both public and private) a pan India monitoring programme of estuaries shall be initiated in the United Nation Ocean Decade (2021–2030). The 'Cyclone Ecology' programme could be the initiation of a pan India programme where various types of estuaries (open/closed, backwater, lagoon, mangrove dominated, urban) from different regions of India may be included by adopting uniform sampling designs, methods and best practises for providing more in depth perspectives of resilience and vulnerabilities of estuarine resources of India.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Declaration

Conflicts of interest

All authors declare that they have no conflict of interest on connection with this study.

Ethical approval

Biological samples were collected in accordance with the ethical standards of University of Calcutta, India.

Author contributions

Conceptualization: Sourav Paul; Methodology: Bhaskar Deb Bhattacharya, Samya Karan, Sourav Paul; Formal analysis and investigation: Sourav Paul, Bhaskar Deb Bhattacharya, Samya Karan; Writing – Sourav Paul; Writing – review and editing: Sourav Paul, Bhaskar Deb Bhattacharya, Samya Karan; Funding acquisition: Sourav Paul; Resources: Sourav Paul; Supervision: Sourav Paul.

Sampling and field studies

All necessary permits for sampling and observational field studies have been obtained by the authors from the competent authorities and are mentioned in the acknowledgements, if applicable. The study is compliant with CBD and Nagoya protocols.

Data availability

The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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