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Community structure of microzooplankton in a tropical estuary (Uppanar) and a mangrove (Pichavaram) from the south-east coast of India

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Original Article

Abstract

In the marine and estuarine waters of Cuddalore, the southeast coast of India microzooplankton have previously been sparingly investigated. Micro-zooplankton community structure (species composition, abundance, diversity, richness, evenness) of an estuary and mangroves of the Cuddalore and Pichavaram areas, southeast India were investigated in detail. Monthly samples were taken from April 2000 to March 2002, from four fixed stations. Micro-zooplankton taxon composition and abundance showed seasonal variations being highest in summer (45 to 50 ind./l in April to August 2000; 60 to 67.5 ind./l in April to June 2001) and lowest during the monsoon (6 to 16 ind./l in September to December 2000; 7 to 19 ind./l in October to December 2001). The total abundance of microzooplankton was in the range of 10.3-65.0 ind./l in Cuddalore areas (Stations 1 and 2) and 5.2 - 67.5 ind./l in Pichavaram mangroves (Stations 3 and 4). Over the study period, tintinnids dominated the microzooplankton community in terms of both abundance and species diversity. The remaining taxa included Radiolaria, Foraminifera, Rotifera, ciliates other than tintinnids, and metazoans. A total of 62 and 74 species of microzooplankton were recorded from Cuddalore and Pichavaram mangroves respectively. Canonical Correspondence Analysis (CCA) was applied to discriminate environmental factors associated with the microzooplankton community at the species level. The results of the study provide a basis for rational sustainable exploitation of Cuddalore waters and future research on its living resources. Furthermore, a comparison of results with studies from around the world showed a very strong, significant relationship between abundance and sampling methods, underlining the need for standardized protocols.

Keywords: *Microzooplankton, tintinnids, rotifers, community structure, physico-chemical parameters, tropical estuary and mangroves*

Introduction

Microzooplankton (20-200 μm) form a considerable portion of the zooplankton biomass in marine and estuarine environments (Porter *et al.,* 1985). They play an important role in transferring the production of pico- and nanoplankton (Porter *et al.*, 1985; Gifford, 1991; Dolan *et al.*, 2006) including bacteria to meso- and macro-carnivores (Rajkumar and Kumaraguru Vasagam, 2006; Rajkumar *et al.,* 2009). They are also a significant food source for various invertebrate and vertebrate predators (Fukami *et al.,* 1999; Jyothibabu *et al.,* 2006; Rahman 2015a, 2015b). Microzooplankton are also the important primary grazers of phytoplankton production in many open ocean systems (Liu *et al.,* 2002; Landry and Calbet, 2004; Rajkumar and Rahman, 2016) and nutrient regenerators (Verity, 1985; Rahman *et al.,* 2008). The species composition and community structure of microzooplankton are affected by environmental factors such as temperature, salinity, turbidity, water flow etc. However, the variability of microzooplankton is often difficult to relate to environmental factors because of complex multifactorial influences (Rahman and Verdegem, 2007). This is particularly true for estuarine and mangrove environments, because of their dynamicity and heterogeneity. Estuarine plankton is likely to be influenced by future climate change in complex ways, fundamentally changing grazing pressures within the food web with large implications for ecosystem services and biogeochemistry (Caron and Hutchins, 2013). Studies in the tropics on the taxonomic composition and abundance of microplankton have largely been conducted in the Ganges estuary bordered by the Sundarban mangroves of north-eastern India (Biswas *et al.*, 2013; Rakshit *et al.*, 2014, 2015, 2016a, 2016b, 2017b), with a different monsoonal system. Furthermore, work is in progress to develop tintinnid community composition as a tool for monitoring water quality (Rakshit *et al.*, 2017a). However, the relationship between the seasonal variation of different microzooplankton and environmental factors particularly temperature, salinity and water flow is not fully understood. A clear understanding of seasonal variations of different microzooplankton and environmental factors is needed for future long-term ecological monitoring and management of estuarine and mangrove ecosystems (Rajkumar *et al.,* 2014). Our study sites in the Pichavaram mangroves were different from those of Godhantaraman (1994, 2001, 2002a). These mangroves, in the Uppanar estuary, form part of one of the important tropical estuaries on the southeast coast of India with great complexity of environmental conditions. Like many other tropical estuaries in Asia, this estuary is characterized by a very strong monsoon regime, due to the active northeast monsoon, which brings heavy rainfall (ca. 1000 mm) for the three months, October to December. For the remainder of the year (January-September), the climate is warmer and these ninemonths are divided into three different seasons, namely post-monsoon: January-March; summer: April-June; and pre-monsoon: July-September.

The objectives of the present study in Cuddalore marine, Uppanar estuarine and Pichavaram mangrove waters were based on the following: (a) knowledge of microzooplankton community structure of tropical estuaries is limited; (b) microzooplankton communities of Cuddalore marine and Uppanar estuarine waters have not been previously studied; and (c) although salinity is one of the most important factors that control the distribution of microzooplankton in all estuaries, its precise role at the presently studied site remains unknown. The abundance and diversity of microzooplankton were investigated through regular observations for two years in these areas. The work has also been driven by several hypotheses at two scales, local and worldwide. At the local scale, our study has tested the hypotheses that seasonal changes were associated with changes in microplankton abundance, species diversity, evenness and richness at each of the four stations. Our study has also tested whether station geographical position (Station no.) affected microplankton abundance and diversity. On the worldwide scale, to test the hypothesis that microplankton abundance shows consistent geographical distribution, and to test the hypothesis that abundance is related to sampling method (difference in mesh size filtration, and filtration vs. sedimentation), we collated maximum abundance in about 56 surveys carried out in different areas around the world.

Material and methods

Study area

The Uppanar estuary is formed by the confluence of Gadilam and Paravanar rivers with the Bay of Bengal. This open-type estuary has an average depth of 2.5 m, and is 30 m wide near the mouth and 20 m wide in the upstream part. The tidal effect extends 6 km upstream (Ashok Prabu *et al.,* 2008a). Station 1 is situated near Cuddalore old town, 1 km away from the Uppanar-mouth (marine zone) (Lat. 11° 42′ 14.42′′ N; Long. 79° 47′ 54.61′′ E) (Fig. 1). It is 5.0 m in depth, with a sandy-bottom and had salinity around 31. Station 2 is in the polluted Uppanar estuary located by the Rasapettai boat jetty (Lat. 11° 42′ 03.75′′ N; Long. 79° 46′ 28.49′′ E). It is 2.5 m deep with a muddy bottom and had a salinity of around 25.

In the mangrove forest at Pichavaram, (Lat. 11° 29′ N: Long. 79° 46′′ E) two different sampling sites were chosen (Stations 3 and 4). Station 3, received neritic water from the adjacent Bay of Bengal through a mouth called 'Chinnavaikal' (marine zone) and the depth of the water column was about 2.0 m, (this mouth has now been closed by the 2004 Tsunami); Station 4, Kanankeluthi Canal, is located near the old cottage of Tamil Nadu Tourism Corporation. During extreme low tides of certain months, the muddy bottom is exposed. The depth of this station is about 0.5 m during the high tide. The major freshwater source to this station is the Khan Sahib Canal during the monsoon and the excess drainage water is received through the irrigation canals from paddy fields. The tides are semi-diurnal and vary in amplitude from 15 to 100 cm during different seasons, reaching maximum during monsoon and post-monsoon and minimum during summer (Ashok Prabu *et al.,* 2008b). The rise and fall of the tidal waters are through

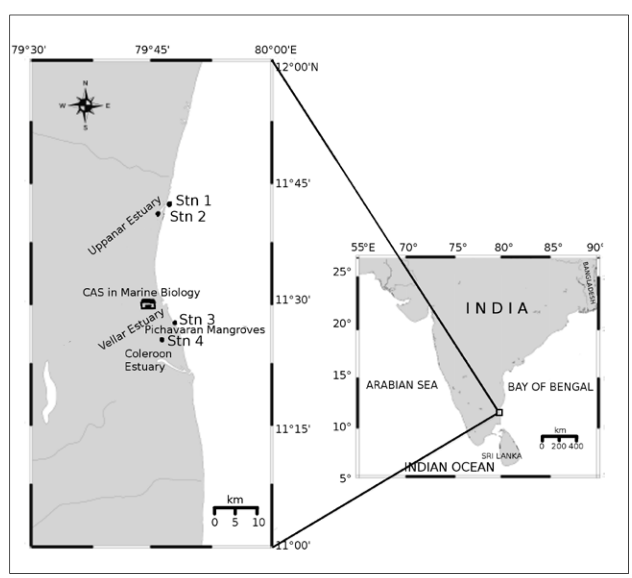

Fig. 1. Map showing the study area and locations

direct connection with the sea at the Chinnavaikal mouth and the two adjacent estuaries. The depths of the waterways range from about 0.3 to 3 m. Monthly samplings were made during forenoon at all 4 stations.

Sampling

Microzooplankton samples were collected monthly over two years from surface water. At every station, sampling was carried out using two complementary methods. The first method was used to take large semi-quantitative samples for identification, and recording of presence, particularly of the larger microplankton. Samples were taken by horizontal hauls of a conical net (mouth area 0.25 m^2) made up of bolting silk (mesh size 54 μm) towed behind a boat for 10 min, during high tide. The net was towed horizontally in the surface water for about 650 m. The second method was used for the quantitative analysis of the microplankton. One litre of surface water was sampled in a plastic bottle, fixed with a 5% buffered formaldehyde-seawater solution and kept refrigerated at 3.0 °C in darkness until microscopic examination. The preserved samples were concentrated by settling to a final volume of 25 ml, from which 10 ml was counted according to the method of Utermöhl (1958), under an inverted microscope at magnifications mostly of 100x and 400x. Three major microzooplankton categories, *i.e.*, species of tintinnids, rotifers and copepod nauplii, were enumerated. Identification was carried out based on Kofoid and Campbell (1929, 1939), Hada (1938), Marshall (1969) for tintinnids Kasturirangan (1963) for copepods to Sharma and Michael (1980) and Sharma (1991) for rotifers, while Jersabek and Leitner (2022) are used to re-check rotifer identifications. Besides these 3 major groups, naked ciliates, radiolarians, foraminiferans, veligers and some metazoan larval forms were also enumerated and grouped into "others".

Statistical analyses

From counts made on the bottle samples, biodiversity indices such as species diversity, evenness and richness were calculated following Shannon and Weaver (1949), Pielou (1966) and Gleason (1922). The relationships between environmental variables and the most dominant species (selected by their dominance index Y) have been explored using Canonical Correspondence Analysis using raw data for physicochemical variables and log (x+1) transformation for plankton abundances (ter Braak, 1986). A Monte Carlo permutation test (unrestricted) was used to determine the significance of species-environment relationships for all the collections at Stations 1, 2, 3 and 4 separately. Some hypotheses have been tested by using Student's t-test (R Core Team, 2022).

Results

Physicochemical parameters

The physicochemical parameters in two study areas (Cuddalore and Pichavaram), published in Ashok Prabu *et al.* (2008a, 2008b), are presented in Table 1. Seasonal variations in all physicochemical parameters such as rainfall, temperature, salinity, pH, dissolved oxygen and nutrients like nitrate, nitrite, inorganic phosphate and reactive silicate were studied from two study areas in the Uppanar Estuary, Cuddalore and Pichavaram mangroves, Southeast coast of India from April 2000 to March 2002 (Ashok Prabu *et al.*, 2008a, 2008b).

Marine and estuarine systems

Sixty-two species of microzooplankton were recorded from the marine and estuarine waters. Twenty-eight species of agglomerated

Table 1. Physico-chemical parameters of the two study areas from April 2000 – March 2002

Parameter	Cuddalore–marine and estuarine				Pichavaram mangroves			
	Station 1		Station 2		Station 3		Station 4	
	Range	Mean ± Standard deviation	Range	Mean ± Standard deviation	Range	Mean ± Standard deviation	Range	Mean ± Standard deviation
Rainfall per month (mm)	15.0 – 280.0	101.5±88	15.0 – 280	101.6±88	10.0 – 297	97.7±93.5	10.0 – 297.6	97.7±93.5
Air Temperature (°C)	28.0 – 40.5	34.0±3.8	28.0 – 38.0	32.4±3.1	28.0 – 38.0	33.4±3.9	27.0 – 36.5	32.0±3.5
Surface water temp. (°C)	26.5 – 38.0	32.3±3.7	26.0 – 36.0	31.0±3.2	26.0 – 37.0	31.7±3.6	26.0 – 35.0	30.7±3.5
Salinity	12.0 – 38.0	29.1±6.4	6.0 – 33.0	19.0±8.7	7.0 – 33.0	20.79±8.37	3.0 – 25.0	14.2±6.8
pH	7.4 – 8.2	7.8±0.2	7.1 – 8.2	7.6±0.4	7.2 – 8.2	7.6±0.3	7.2 – 8.2	7.6±0.4
Dissolved oxygen (ml/l)	1.9 – 3.5	2.8±0.4	2.6 – 4.5	3.4±0.6	2.4 – 5.0	3.5±0.8	2.5 – 5.0	3.6±0.8
Nitrate (μm)	8.2 – 24.3	14.8±5.3	8.8 – 25.7	15.8±5.8	9.5 – 30.1	17.5±6.7	9.6– 32.1	18.8±7.4
Nitrite (μm)	1.01– 3.7	2.1±0.9	1.13– 4.2	2.4±1.0	1.1 – 5.7	2.6±1.5	1.1– 6.0	2.8±1.6
Phosphate (μm)	0.6 – 2.2	1.2±0.6	0.2 – 3.0	1.3±0.7	0.8 – 2.0	1.3±0.5	0.7 – 2.4	1.3±0.5
Silicate (μm)	27.0 – 162.0	84.4±46.6	29.0 – 168.0	88.9±48.2	22.1 – 85.2	46.0±23.3	22.7 – 89.8	46.5±23.8

Table 2. List of dominant and common microzooplankton species recorded from the Bay of Bengal, estuarine waters, neritic and estuarine mangrove waters from April 2000 to March 2002 at stations 1, 2, 3 and 4 (Species number is used in CCA, ni is the species abundance, fi is the frequency of species, Y is the Dominance Index).

Species Name	Station 1				Station 2				Station 3				Station 4			
	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y
Protozoan ciliates – Tintinnids																
a) Agglomerated																
Codonellopsis orthoceros [1]	19	0.013	0.417	0.0054	57	-	-	-	18	0.028	0.417	0.0116	58	-	-	-
C. ostenfeldi (syn: *C. morchella?)* [1]	28	0.008	0.292	0.0023	25	0.011	0.25	0.0028	69	-	-	-	40	0.001	0.125	0.0001
C. schabi [1]	57	-	-	-	50	0.001	0.042	-	-	-	-	-	-	-	-	-
C. tessellata (syn: C. orthoceros) [2]	37	0.006	0.167	0.001	14	0.027	0.583	0.0159	-	-	-	-	-	-	-	-
Codonellopsis sp.	26	0.01	0.333	0.0032	34	0.009	0.125	0.0011	38	0.007	0.167	0.0011	10	0.033	1	0.0325
Dictyocysta seshaiyai [3]	58	-	-	-	51	0.001	0.042	-	6	0.049	1	0.049	41	0.001	0.083	0.0001
Dictyocysta sp.	41	0.004	0.167	0.0006	19	0.015	0.292	0.0042	60	0.001	0.042	–	33	0.001	0.208	0.0003
Leprotintinnus nordqvisti [1]	16	0.013	0.542	0.0072	18	0.014	0.417	0.0057	-	-	-	-	-	-	-	-
L. simplex [1]	44	0.003	0.167	0.0005	45	0.002	0.083	0.0002	-	-	-	-	-	-	-	-
Leprotintinnus sp.	-	-	-	-	-	-	-	-	11	0.045	0.833	0.0378	13	0.023	0.542	0.0123
Tintinnidium incertum [1]	-	-	-	-	-	-	-	-	34	0.006	0.25	0.0016	49	-	-	-
T. primitivum [1]	24	0.015	0.25	0.0038	53	-	-	-	22	0.014	0.5	0.0071	50	-	-	-
Tintinnopsis amphora [1]	6	0.066	1	0.0657	11	0.036	0.667	0.0239	51	0.003	0.083	0.0003	51	-	-	-
T. bermudensis [4,7]	52	0.002	0.083	0.0001	54	-	-	-	45	0.003	0.125	0.0004	52	-	-	-
T. beroidea [1]	36	0.006	0.208	0.0012	35	0.006	0.167	0.001	1	0.088	1	0.0884	7	0.079	1	0.0791
T. cylindrica [1]	2	0.085	1	0.0852	1	0.101	1	0.1013	4	0.058	0.958	0.0559	4	0.083	1	0.0828
T. dadayi [1]	-	-	-	-	-	-	-	-	19	0.016	0.625	0.0103	57	-	-	-
T. directa [1]	50	0.003	0.083	0.0002	55	-	-	-	52	0.002	0.083	0.0002	19	0.01	0.25	0.0026
T. glans (syn: *T. parva*) [2]	18	0.016	0.375	0.0062	15	0.022	0.542	0.012	37	0.007	0.167	0.0012	53	-	-	-
T. gracilis [1]	15	0.017	0.458	0.0077	5	0.063	1	0.0632	25	0.011	0.292	0.0031	24	0.007	0.25	0.0018
T. karajacensis [1]	-	-	-	-	-	-	-	-	35	0.005	0.25	0.0013	27	0.004	0.333	0.0013
T. kofoidi (syn: *T. cylindrica)* [1]	47	0.002	0.167	0.0003	46	0.001	0.042	-	67	-	-	-	42	-	0.083	-
T. lohmanni [1]	54	-	-	-	26	0.008	0.25	0.002	68	-	-	-	44	-	0.083	-
T. minuta [1]	35	0.008	0.167	0.0013	23	0.012	0.292	0.0035	65	-	0.042	-	17	0.009	0.375	0.0034
T. mortensenii [1]	22	0.013	0.333	0.0044	33	0.005	0.208	0.0011	32	0.005	0.333	0.0018	31	0.005	0.125	0.0006
T. nucula [1]	30	0.008	0.25	0.002	56	-	-	-	66	-	-	-	28	0.003	0.375	0.0011
T. parvula (syn: T. fusus?) [1]	-	-	-	-	-	-	-	-	56	0.001	0.083	0.0001	8	0.058	0.958	0.056
T. radix [1}	46	0.003	0.125	0.0004	41	0.004	0.125	0.0005	31	0.007	0.25	0.0018	54	-	-	-
T. sacculus [1]	-	-	-	-	-	-	-	-	40	0.005	0.208	0.0011	56	-	-	-
T. tocantinensis [1]	3	0.084	1	0.084	8	0.045	0.792	0.0355	2	0.073	1	0.0734	3	0.092	1	0.0923
T. tubulosa [1]	1	0.095	1	0.0945	3	0.091	1	0.091	5	0.051	1	0.0511	5	0.082	1	0.0818
T. uruguayensis [1]	55	-	-	-	52	0.001	0.042	-	12	0.038	0.958	0.036	55	-	-	-
S. steinii [1]	56	-	-	-	49	0.001	0.042	-	-	-	-	-	-	-	-	-
Stenosemella ventricosa [1]	31	0.009	0.208	0.0018	29	0.008	0.208	0.0016	-	-	-	-	-	-	-	-
Stenosemella sp.[1]	-	-	-	-	-	-	-	-	61	0.001	0.042	-	59	-	-	-

Species Name	Station 1				Station 2				Station 3				Station 4			
	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y
b) Non-agglomerated																
Amphorellopsis acuta [1]	17	0.014	0.5	0.0071	24	0.01	0.333	0.0032	23	0.011	0.458	0.0051	22	0.005	0.417	0.0022
Coxliella ampla [1]	11	0.03	0.583	0.0175	32	0.007	0.167	0.0012	24	0.007	0.458	0.0034	60	-	-	-
C. annulata [1]	53	0.001	0.083	0.0001	58	-	-	-	-	-	-	-	-	-	-	-
Dadayiella bulbosa [1]	27	0.008	0.333	0.0028	30	0.006	0.208	0.0014	30	0.007	0.292	0.0022	61	-	-	-
Eutintinnus sp. [1]	-	-	-	-	-	-	-	-	26	0.008	0.333	0.0027	26	0.004	0.375	0.0017
Favella brevis [1]	45	0.006	0.083	0.0005	42	0.004	0.083	0.0003	47	0.002	0.167	0.0003	39	0.002	0.083	0.0001
F. ehrenbergii [1]	-	-	-	-	-	-	-	-	70	-	-	-	62	-	-	-
F. philippinensis [11]	5	0.068	1	0.0676	2	0.092	1	0.0924	3	0.061	1	0.061	1	0.127	1	0.1275
Favella sp. [1]	32	0.006	0.25	0.0016	38	0.005	0.167	0.0009	13	0.03	0.75	0.0223	23	0.008	0.25	0.0019
Helicostomella longa [1]	-	-	-	-	-	-	-	-	28	0.007	0.333	0.0023	63	-	-	-
Rhabdonella sp. [1]	-	-	-	-	-	-	-	-	49	0.002	0.167	0.0003	64	-	-	-
Foraminifera																
Globigerina sp. [1]	23	0.009	0.458	0.0044	16	0.019	0.583	0.011	-	-	-	-	-	-	-	-
Rotifera																
Anuraeopsis fissa [1]	-	-	-	-	-	-	-	-	71	-	-	-	16	0.013	0.625	0.0083
Brachionus angularis [1]	8	0.041	0.75	0.0307	7	0.047	0.875	0.0407	7	0.048	1	0.0476	6	0.085	0.958	0.0815
B. bidentata (syn: *B. bidentatus)* [1]	59	-	-	-	43	0.004	0.083	0.0003	58	0.001	0.042	-	43	0.001	0.042	-
B. calyciflorus [1]	-	-	-	-	-	-	-	-	8	0.042	1	0.0421	46	-	0.083	-
B. caudatus [1]	34	0.006	0.25	0.0014	59	-	-	-	57	0.001	0.042	0.0001	25	0.005	0.333	0.0017
B. falcatus [1]	4	0.082	1	0.0818	39	0.004	0.167	0.0007	73	-	-	-	48	-	0.042	-
B. forficula [1]	61	-	-	-	47	0.001	0.042	-	43	0.003	0.25	0.0007	65	-	-	-
B. plicatilis [1]	7	0.065	1	0.0652	4	0.089	1	0.0892	9	0.045	0.917	0.0412	2	0.096	1	0.0959
B. quadridentatus [1]	-	-	-	-	-	-	-	-	59	0.001	0.042	-	38	0.001	0.125	0.0001
B. rubens [1]	33	0.007	0.208	0.0014	60	-	-	-	72	-	-	-	21	0.005	0.458	0.0024
B. urceolaris [1]	60	-	-	-	6	0.059	1	0.059	62	0.001	0.042	-	45	0.001	0.042	-
Euchlanis sp. [5]	29	0.008	0.25	0.0021	61	-	-	-	39	0.004	0.25	0.0011	66	-	-	-
Keratella procurva [5]	-	-	-	-	-	-	-	-	10	0.041	1	0.0407	67	-	-	-
K. quadrata [5]	-	-	-	-	-	-	-	-	53	0.002	0.083	0.0001	36	0.001	0.208	0.0002
Keratella sp. [5]	-	-	-	-	-	-	-	-	63	0.001	0.042	-	9	0.054	0.958	0.0517
Monostyla bulla (syn: *Lecane bulla bulla)* [6]	40	0.003	0.208	0.0007	62	-	-	-	74	-	-	-	18	0.004	0.667	0.0028
Monostyla sp. (syn: *Lecane)* [6]	49	0.002	0.125	0.0002	40	0.004	0.167	0.0007	29	0.007	0.333	0.0023	37	0.001	0.167	0.0002
Lecane luna [6]	62	-	-	-	22	0.009	0.375	0.0035	36	0.006	0.208	0.0012	68	-	-	-
L. ungulata [6]	-	-	-	-	-	-	-	-	41	0.005	0.208	0.001	69	-	-	-
Lecane sp. [6]	63	-	-	-	48	0.001	0.042	-	64	0.001	0.042	-	70	-	-	-
Platyias patulus [6]	14	0.018	0.542	0.0099	20	0.011	0.375	0.004	75	-	-	-	47	-	0.042	-
Testudinella sp. [6]	48	0.002	0.125	0.0003	63	-	-	-	50	0.003	0.125	0.0003	71	-	-	-
Radiolaria																
Acantharia sp. 1	25	0.008	0.417	0.0035	37	0.004	0.208	0.0009	-	-	-	-	-	-	-	-

Species Name	Station 1				Station 2				Station 3				Station 4			
	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y	Sp. No	ni	fi	Y
Acantharia sp. 2	-	-	-	-	-	-	-	-	33	0.005	0.292	0.0016	73	-	-	-
Globigerina rubescens [6]	-	-	-	-	-	-	-	-	44	0.003	0.167	0.0005	72	-	-	-
Globigerina sp. [6]	-	-	-	-	-	-	-	-	16	0.023	0.792	0.0179	34	0.002	0.125	0.0002
Ciliates other than tintinnids																
Didinium sp. [1]	42	0.003	0.208	0.0006	28	0.006	0.292	0.0018	46	0.003	0.125	0.0004	20	0.007	0.333	0.0024
Mesodinium sp. [1]	21	0.01	0.5	0.005	21	0.009	0.417	0.0038	54	0.001	0.125	0.0001	75	-	-	-
Strombidium sp. [1]	-	-	-	-	-	-	-	-	21	0.013	0.583	0.0077	74	-	-	-
Other metazoans																
Bivalvia veligers	20	0.009	0.583	0.0053	10	0.025	1	0.0249	14	0.022	1	0.022	11	0.028	1	0.0275
Cirripedia nauplii	38	0.004	0.25	0.0009	27	0.005	0.375	0.0019	42	0.003	0.292	0.0008	35	0.001	0.208	0.0002
Copepoda nauplii	10	0.029	0.958	0.0278	12	0.026	0.917	0.0235	20	0.013	0.75	0.0094	14	0.011	0.958	0.0109
Crab zoea	12	0.019	0.833	0.0157	31	0.004	0.333	0.0013	55	0.001	0.083	0.0001	30	0.003	0.208	0.0007
Gastropoda veligers	9	0.03	0.958	0.0289	9	0.031	1	0.031	15	0.021	1	0.0213	12	0.025	0.875	0.0221
Oikopleura sp. *[1]*	13	0.017	0.917	0.0152	17	0.009	0.958	0.0083	48	0.002	0.208	0.0003	32	0.001	0.375	0.0004
Pluteus larvae	51	0.001	0.167	0.0002	44	0.002	0.167	0.0003	-	-	-	-	-	-	-	-
Polychaeta larvae	39	0.003	0.25	0.0007	13	0.019	1	0.0192	17	0.015	0.958	0.014	15	0.011	0.958	0.0108
Protozoea	43	0.002	0.25	0.0006	36	0.004	0.25	0.001	27	0.005	0.5	0.0024	29	0.003	0.25	0.0008

References: [1] – WoRMS (2019); [2] – Alder (2019); [3] – Krishnamurthy et al. (1979); [4] - Godhantaraman (2002b); [5] - Jersabek and Leitner (2019); [6] – ITIS (2019);

tintinnids, seven species of non-agglomerated tintinnids sensu Wasik *et al.* (1996) and (Godhantaraman, 1994), one species of Radiolaria, one species of Foraminifera, 14 species of Rotifera, two species of non-tintinnid ciliates and nine species of other metazoans (Table 2). Among the tintinnids, were recorded 28 agglomerated and seven non-agglomerated species. Most of the microzooplankton species showed a distinct seasonal pattern. Species including *Tintinnopsis amphora*, *T. cylindrica*, *T. tubulosa*, *T. tocantinensis*, *Favella philippinensis*, *Brachionus falcatus*, *B. plicatilis*, bivalve veligers, gastropod veligers, copepod nauplii, crab zoea and *Oikopleura* sp., however, were found commonly and abundantly over the entire period of study (Table 2, Fig. 2). Among the rotifers, the genus *Synchaeta* was not observed. At Station 1, *T. cylindrica, Coxiella ampla, F. philippinensis, B. angularis,* gastropod veligers, copepod nauplii, and crab zoea were found in summer. *Codonellopsis* sp., *C. tessellata, F. brevis,* protozoea and *Oikopleura* larvae were found early in the monsoon period. At station 2, species including *T. amphora, T. tubulosa, Codonellopsis* sp., *C. tessellata, F. philippinensis, B. plicatilis, B. urceolaris,* bivalve veligers, copepod nauplii, protozoea, polychaete larvae and *Pluteus* larvae were found in summer. *Tintinnopsis tocantinensis, T. cylindrica, T. gracilis* and *Oikopleura* larvae were observed in the post-pre-monsoon period.

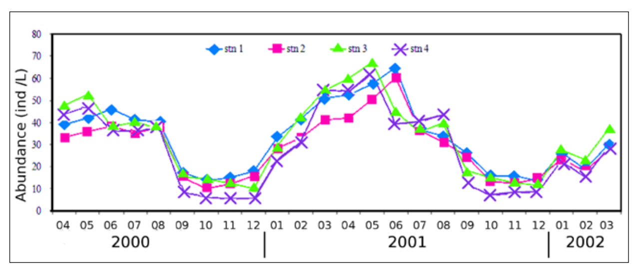

Fig. 2. Species compositions and variations in microzooplankton in Cuddalore marine, estuarine and Pichavaram mangrove waters at stations 1, 2, 3 and 4 from April 2000 to March 2002

At stations 1 and 2, microzooplankton abundance varied from 13.8 to 65 ind.1^{-1} and 10.3 to 60.3 ind.1^{-1} during monsoon and summer respectively (Fig. 3). Tintinnids formed the dominant group followed by rotifers, metazoans, non-tintinnid ciliates, radiolarians and foraminiferans at stations 1 and 2. The ranges of species diversity, richness and evenness at Stations 1 and 2 were: 3.27-4.64, 0.73-2.17 and 0.89-0.96 respectively (Fig. 4). The microzooplankton dominance and abundance patterns at Stations 1 and 2 are given in Fig. 2. Station 1 was dominated by the species *T. cylindrica* (5 ind./l - Jun-01), *T. tocantinensis* (6 ind./l - Jun-01), *T. tubulosa* (7 ind./l - May-01), *B. falcatus* (5 ind./l - May-01) and others (43 ind./l - Jun-01). Station 2 was dominated by the tintinnids *T. cylindrica* (6 ind./l - Aug-00), *T. tubulosa* (6 ind./l - Jun-01) and *F. philippinensis* (5 ind./l - May-01) as well as the rotifer *B. plicatilis* (5 ind./l - Jun-01) and others

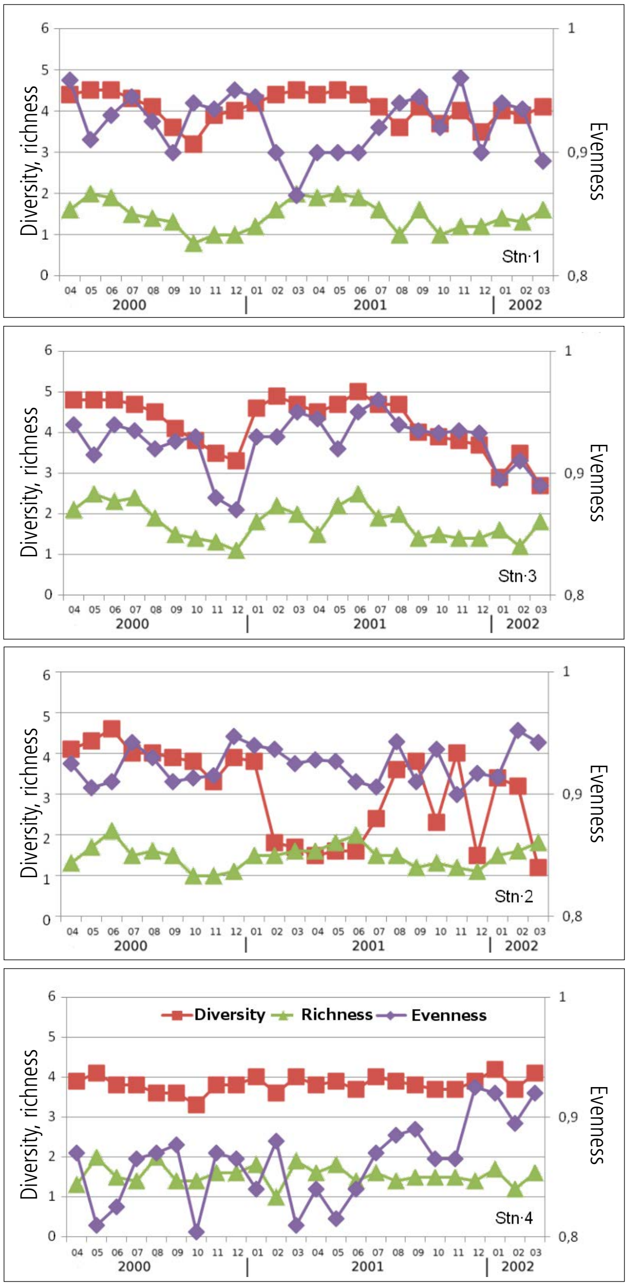

Fig. 3. Microzooplankton abundance in Cuddalore marine, estuarine and Pichavaram mangrove waters from April 2000 to March 2002

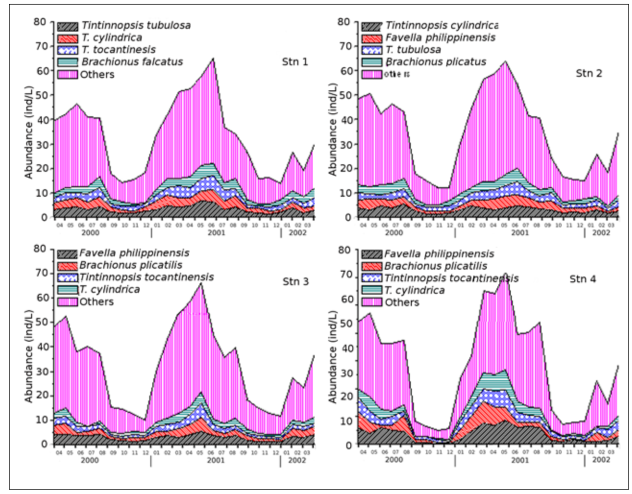

Fig. 4. Shannon–Weaver diversity index H', Margalef's richness d and Evenness J' of microzooplankton in Cuddalore marine, estuarine and Pichavaram mangrove waters at Stations 1, 2, 3 and 4 during April 2000 to March 2002

(46 ind./l - May-01). These species were found in summer and *T. cylindrica* was found particularly in the pre-monsoon season.

CCA was carried out on the monthly collections, microzooplankton distribution and species abundance. Nineteen taxa were retained for the CCA analyses. These are shown in Table 2. In station 1, the first CCA axis initially separates nitrate, silicate, phosphate, rainfall, nitrite and dissolved oxygen along with 7 monthly collections (Aug-01, Dec-00, Oct-01, Dec-01, Sep-00, Oct-00 and Aug-00) (Fig. 5a). At Station 1, the first axis of CCA had an eigenvalue of 0.04 (Table 3). In the second CCA axis, the only environmental factor was pH along with 7 monthly collections (Jul-01, Jul-00, Apr-01, May-01, Jun-01, Feb-02 and Mar-02). The third CCA axis was further separated by temperature (air and surface water) and salinity along with 4 monthly collections (May-00, Jan-01, Jan-02 and Mar-01) (Fig. 5a). The fourth CCA axis was heavily impacted in summer (Jun-00 and Apr-00), post-monsoon (Feb-01), monsoon (Nov-00 and Nov-01) and pre-monsoon (Sep-01). Most of the microzooplankton species condensed on the second CCA axis (Fig. 5a). *Brachionus angularis* and *T. cylindrica* were associated with surface water temperature. *Brachionus plicatilis* were associated with dissolved oxygen. *Tintinnopsis tubulosa*, *T. tocantinensis*, *B. falcatus* and *F. philippinensis* were associated with pH. *Tintinnopsis amphora* and crab zoea were associated with nitrate. CCA separated the 19 retained species into four major groups at the 91% level. Group I was composed of species that occurred during summer/post-monsoon. Low-salinity species collected just during post-monsoon/pre-monsoon formed Group II, and Groups III and IV consisted of euryhaline species during summer and the pre-monsoon season respectively. At Station 2, the first axis of CCA had an eigenvalue of 0.026 (Table 3). For the monthly collections, microzooplankton distribution and species abundance pattern is given in Figure 5b. The first CCA axis was initially separated nitrate, silicate, phosphate, nitrite and dissolved oxygen along with 8 monthly collections, Aug-2000, Dec-2000, Jan-2002, Jul-2000, Jun-2000, Jan-2001, Feb-2002 and Mar-2002. The second CCA axis was markedly associated in summer (Jun-2001 and Apr-2001), post-monsoon (Mar-2001) and monsoon (Oct-2000 and Nov-2000). The third CCA axis, separated temperature (air and surface water), salinity and pH, along with the 5 monthly collections, May-2001, Jul-2001, Feb-2001, Aug-2000 and Apr-2000 (Fig. 5b). The fourth CCA axis

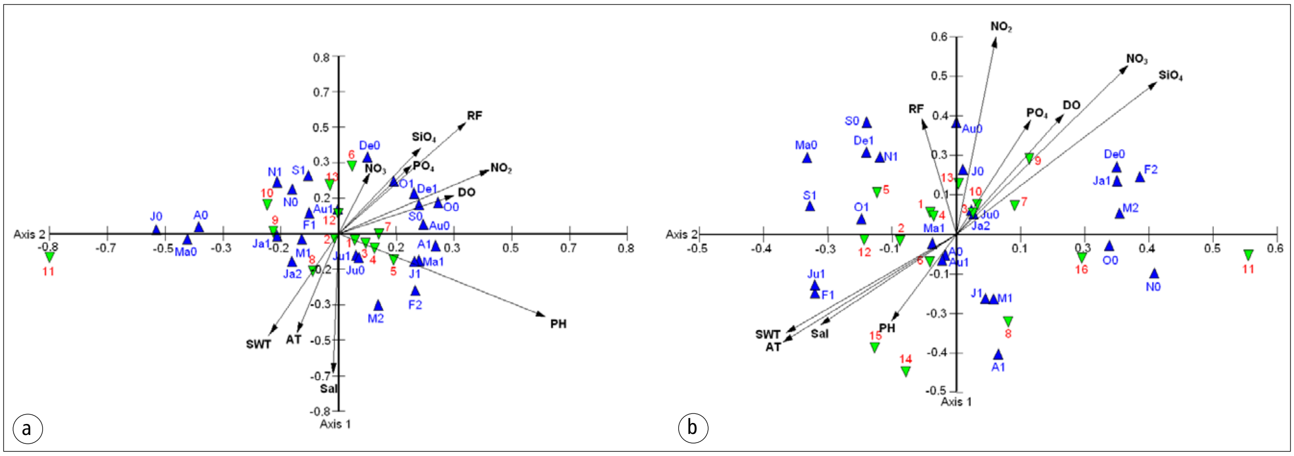

Fig. 5. Canonical Correspondence Analysis scatter tri-plot for microzooplankton. Monthly sampling, environmental variables and microzooplankton species at Stations 1 and 2. A. Station 1; B. Station 2; Numbers by triangles refer to species in Table 2. RF, rainfall; PO4, phosphate; NO3, nitrate; NO2, nitrite; SiO4, silicate; DO, dissolved oxygen; Sal, salinity; SWT, surface water temperature; AT, atmospheric temperature; Ja1, January-2001; Ja2, January-2002; F1, February-2001; F2, February-2002; M1, March-2001; M2, March-2002; A0, April-2000; A1, April-2001; Ma0, May-2000; Ma1, May-2001; J0, June-2000; J1, June-2001; Ju0, July-2000; Ju1, July-2001; Au0, August-2000; Au1, August-2001; S0, September-2000; S1, Setember-2001; O0, October-2000; O1, October-2001; N0, November-2000; N1, November-2001; De0, December-2000; De1, December-2001.

separated only one environmental factor, rainfall, along with the 6 monthly collections Oct-2001, Sep-2001, May-2000, Sep-2000, Dec-2001 and Nov-2001. Most of the microzooplankton species were concentrated on the first (Fig. 5b) and third CCA axis (not indicated). *Tintinnopsis cylindrica* and *B. plicatilis* were associated with rainfall, *B. urceolaris* was associated with temperature (air and surface water) and salinity, *T. tubulosa*, gastropod veliger and bivalve veliger were affected by dissolved oxygen and nitrate, polychaete larvae were associated with nitrite, *T. tubulosa* and bivalve veliger were associated with phosphate, and *B. angularis* was associated with silicate.

Correlation between species at Station 2 was separated into three major groups at the 92% level. The groups formed by this analysis showed considerable similarity concerning fluctuations in number. Group I composed of species that occurred during post-monsoon/summer. Low-salinity species collected just in the summer/pre-monsoon period formed Group II and Group III consisted of euryhaline species during summer and pre-monsoon.

Neritic mangrove and freshwater systems

Seventy-four species of microzooplankton were recorded from the neritic mangrove regions and freshwater areas. Twenty-nine species of agglomerated tintinnids, 9 species of non-agglomerated tintinnids, 1 species of Radiolaria, 2 species of Foraminifera, 22 species of Rotifera, 3 species of ciliates other than tintinnids and 8 species of other metazoans (Table 2). These 29 species of agglomerated forms belonged to the genera *Tintinnidium*, *Leptrotintinnus*, *Tintinnopsis*, *Stenosemella*, *Codonellopsis* and *Dictyocysta*. The non-agglomerated forms comprised 9 species with 7 genera *Coxiella*, *Helicostomella*, *Favella*, *Rhabdonella*,

Table 3. Results of the CCA: Eigenvalues, species-environment correlations and percentage variance at the Bay of Bengal, estuarine and two mangrove waters, southeast coast of India microzooplankton abundance data; the weighted correlation coefficient between environmental variables and CCA axes.

Axes	1	2	3	4
Station 1				
Eigenvalues	0.04	0.015	0.012	0.006
Species–environment correlations	0.813	0.817	0.826	0.56
Cumulative percentage variance				
of species	21.497	29.856	36.123	39.184
of species–environment	48.228	66.98	81.04	87.908
Correlation coefficient				
Rainfall	0.225	0.515	-0.1	0.023
Air Temperature	-0.073	-0.459	-0.407	0.079
Surface water Temperature	-0.121	-0.465	-0.478	0.057
Salinity	-0.009	-0.649	-0.064	0.147
pH	0.366	-0.386	-0.222	-0.002
Dissolved oxygen	0.204	0.178	0.111	0.148
Nitrite	0.266	0.294	0.34	0.212
Nitrate	0.055	0.28	0.437	-0.004
Phosphate	0.129	0.317	0.378	-0.013
Silicate	0.145	0.397	0.299	-0.052
Station 2				
Eigenvalues	0.026	0.024	0.017	0.013
Species–environment correlations	0.82	0.742	0.815	0.798
Cumulative percentage variance				
of species data	12.337	23.328	31.144	37.158
of species-environment	25.269	47.782	63.79	76.108
Correlation coefficient				
Rainfall	-0.056	0.299	0.21	0.298
Air Temperature	-0.287	-0.279	-0.33	-0.089
Surface water Temperature	-0.282	-0.254	-0.308	-0.111

Axes	1	2	3	4
Salinity	-0.225	-0.234	-0.431	-0.069
pH	-0.107	-0.225	-0.322	-0.172
Dissolved oxygen	0.178	0.312	0.172	0.456
Nitrite	0.066	0.511	0.27	0.303
Nitrate	0.285	0.436	0.207	0.273
Phosphate	0.124	0.295	-0.184	0.327
Silicate	0.334	0.395	0.146	0.149
Station 3				
Eigenvalues	0.043	0.035	0.024	0.011
Species–environment correlations	0.902	0.963	0.849	0.826
Cumulative percentage variance				
of species data	20.269	36.388	47.708	52.999
of species-environment	31.92	57.304	75.132	83.464
Correlation coefficient				
Rainfall	0.397	0.046	0.531	0.206
Air Temperature	-0.77	-0.25	-0.034	-0.026
Surface water Temperature	-0.733	-0.315	-0.023	0.056
Salinity	-0.495	-0.372	-0.471	-0.146
pH	-0.572	-0.101	-0.434	0.186
Dissolved oxygen	0.518	0.207	0.569	-0.025
Nitrite	0.64	0.251	0.476	0.138
Nitrate	0.718	0.167	0.412	0.193
Phosphate	0.593	0.122	0.485	0.062
Silicate	0.569	0.205	0.563	0.149
Station 4				
Eigen values	0.063	0.024	0.019	0.008
Species–environment correlations	0.914	0.729	0.89	0.761
Cumulative percentage variance				
of species data	28.408	39.033	47.412	50.952
of species-environment	47.601	65.405	79.445	85.376
Correlation coefficient				
Rainfall	-0.317	0.151	0.479	0.245
Air Temperature	-0.608	-0.23	-0.347	-0.067
Surface water Temperature	-0.588	-0.182	-0.324	-0.008
Salinity	-0.196	-0.458	-0.486	-0.144
pH	-0.021	-0.399	-0.34	-0.377
Dissolved oxygen	-0.046	0.488	0.368	0.268
Nitrite	0.115	0.309	0.564	0.048
Nitrate	0.325	0.28	0.413	0.009
Phosphate	-0.073	0.259	0.613	0.179
Silicate	0.044	0.35	0.472	0.064

Amphorellopsis, *Dadayiella* and *Eutintinnus*. Most of the microzooplankton species occurred with a distinct seasonal pattern. Species as *T. cylindrica*, *D. seshaiyai*, *F. philippinensis*, *B. angularis*, *B. plicatilis*, *K. procurva*, bivalve veligers, gastropod veligers, copepod nauplii and polychaete larvae were found commonly and abundantly over the entire period of study. At station 3, species including *Tintinnidium incertum*, *T. cylindrica, C. orthoceros*, *D. seshaiyai, F. philippinensis, Globigerina* sp., *B. calyciflorus,* gastropod veligers, copepod nauplii, cirripede nauplii, protozoans, crab zoea and polychaete larvae were found particularly in summer. Typical species in the post-pre-monsoon period included *Leptrotintinnus* sp., *B. angularis*, *B. plicatilis*, *T. tubulosa* and *Favella* sp. (Table 2). At station 4, species including *Leptrotintinnus* sp., *T. cylindrica, T. parvula, F. philippinensis* and cirripede nauplii were found particularly in summer. Typical species in the post-pre-monsoon period included *T. lohmanni*, *D. seshaiyai, A. acuta, Globigerina* sp., *Anuraeopsis fissa*, *B. falcatus*, *B. plicatilis*, *K. quadrata*, bivalve veligers, gastropod veligers, copepod nauplii, Protozoea, polychaete larvae, *Oikopleura* larvae, *T. beroidea, T. directa, T. karajacensis, T. nucula, Codonellopsis* sp., *Favella* sp., *Eutintinnus* sp., *B. angularis*, *B. caudatus*, *Keratella* sp., *P. patulus*, *Monostyla* sp. and crab zoea. *Dictyocysta* sp. was found only during the monsoon (Table 2). Microzooplankton abundance varied from 10.1 to 67.5 ind./l and 5.2 to 62.2 ind./l at Stations 3 and 4 during the monsoon and summer (Fig. 3). Also at these stations, tintinnids formed the most dominant group followed by declining order of dominance by rotifers, metazoans, naked ciliates, foraminiferans and radiolarians. The ranges of species diversity, richness and evenness at stations 3 and 4 were: 3.34-5.03, 0.94-2.46 and 0.80-0.96 respectively (Fig. 4). At Stations 3 and 4, the species abundances were almost the same but the order of dominance was different (Fig. 2). At station 3, *T. cylindrica* (4.2 ind./l - May-2001), *T. tocantinensis* (6.15 ind./l - May-2001), *F. philippinensis* (5.2 ind./l - May-2001), *B. plicatilis* (5.75 ind./l - May-2001), and others (46.2 ind./l - May-2001) were observed. These species were found particularly in summer and also abundantly over the entire period of study. At Station 4, there occurred *T. cylindrica* (7.5 ind./l - May-2001), *T. tocantinensis* (6 ind./l - May-2001), *F. philippinensis* (8.5 ind./l - May-2001), *B. plicatilis* (7.8 ind./l - March-2001), and others (35.2 ind./l - May-2001). These species were found in summer and *B. plicatilis* was found particularly in the post-monsoon season.

At Station 3, the first axis of CCA had an eigenvalue of 0.043 (Table 3). For the monthly collections, the microzooplankton distribution and species abundance pattern are given in Fig. 6a. The first CCA axis initially separated nitrate, silicate, phosphate, nitrite, dissolved oxygen and rainfall along with 8 monthly collections (Nov-2001, Oct-2000, Sep-2000, Mar-2001, Dec-2000, Jan-2001, Jul-2001 and Nov-2000). The second CCA axis markedly separates the monsoon (Oct-2001 and Dec-2001) from the post-monsoon (Jan-2002, Feb-2002 and Mar-2002) periods. The third CCA axis, further separated temperature (air and surface water), salinity and pH along with 8 monthly collections (Jun-2000, Aug-2001, Jul-2000, Apr-2001, Apr-2000, Jun-2001, May-2001 and May-2000) (Fig. 6a). The fourth CCA axis also markedly separated pre-monsoon (Sep-2001 and Aug-2000) from post-monsoon (Feb-2001) periods. Most of

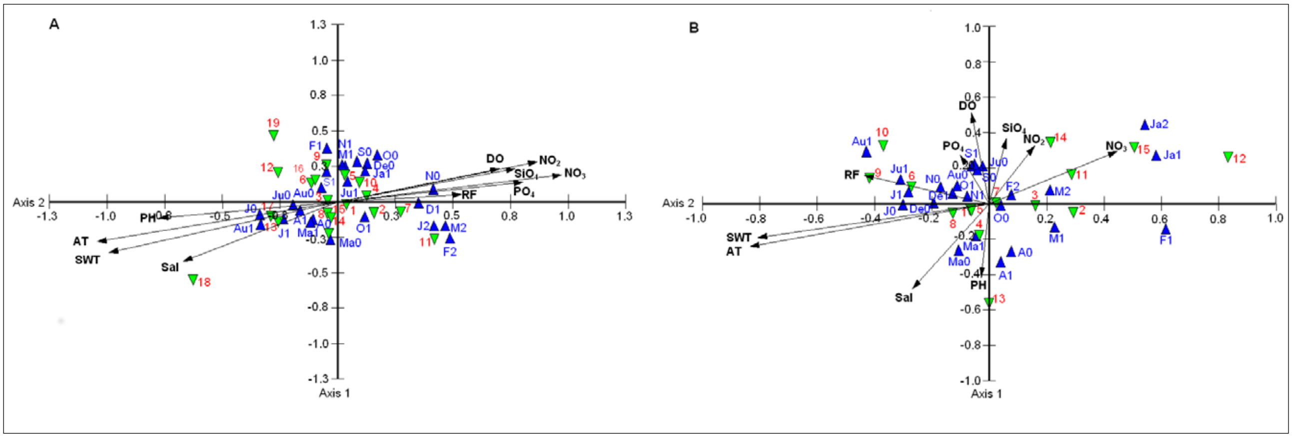

Fig. 6. Canonical Correspondence Analysis scatter tri-plot for microzooplankton. Monthly sampling, environmental variables and microzooplankton species at Stations 3 and 4. A. Station 3; B. Station 4; Numbers by triangles refer to species in Table 2. RF, rainfall; PO4, phosphate; NO3, nitrate; NO2, nitrite; SiO4, silicate; DO, dissolved oxygen; Sal, salinity; SWT, surface water temperature; AT, atmospheric temperature; Ja1, January-2001; Ja2, January-2002; F1, February-2001; F2, February-2002; M1, March-2001; M2, March-2002; A0, April-2000; A1, April-2001; Ma0, May-2000; Ma1, May-2001; J0, June-2000; J1, June-2001; Ju0, July-2000; Ju1, July-2001; Au0, August-2000; Au1, August-2001; S0, September-2000; S1, Setember-2001; O0, October-2000; O1, October-2001; N0, November-2000; N1, November-2001; De1, December-2000; De1, December-2001

the microzooplankton species scored importantly on the third and fourth CCA axes (not indicated). *Tintinnopsis beroidea* and *T. cylindrica* were associated with rainfall, dissolved oxygen, nitrate, nitrite, phosphate and silicate, polychaete larvae were associated with atmospheric temperature and pH, polychaete larvae and *Favella* sp. were associated with surface water temperature, *C. orthoceros*, *B. calyciflorus*, bivalve veliger, *F. philippinensis* and *Favella* sp. were associated with salinity.

At station 3, the correlation between species separated them into four major groups at the 95% level. Groups formed by this analysis showed considerable similarity concerning fluctuations in number. Group I composed of species that occurred during summer/post-monsoon. Low-salinity species collected just post-monsoon and in summer formed Group II, while Groups III and IV consisted of euryhaline species during summer, pre-monsoon and post-monsoon periods.

At Station 4, the first axis of CCA had an eigenvalue of 0.063 (Table 3). In the monthly collections, microzooplankton distribution and species abundance pattern are given in Fig. 6b. Scoring importantly on both the first and the second CCA axes were nitrate, silicate and nitrite along with the 4 monthly collections, Feb-2002, Mar-2002, Jan-2002 and Jan-2001. The second CCA axis scored highly for the monsoon (Oct-2000), summer (Apr-2000 and Apr-2001) and the post-monsoon (Feb-2001 and Mar-2001). The third CCA axis further scored importantly for temperature (both air and surface water), salinity and pH along with 4 monthly collections (Jun-2000, Dec-2000, May-2001 and May-2000) (Fig. 6b). The fourth CCA axis further scored most for rainfall, phosphate and dissolved oxygen along with 11 monthly collections (Aug-2001, Jun-2001, Dec-2001, Nov-2001, Oct-2001, Nov-2000, Jul-2001, Aug-2000, Sep-2001, Jul-2000 and Sep-2000). Most of the microzooplankton species were concentrated on the first CCA axis (Fig. 6b). *Brachionus angularis* and *Keratella* sp. were associated with rainfall, while *F. philippinensis*, *T. tubulosa* and *T. parvula* were associated with temperature (both air and surface water), both *T. tubulosa* and *F. philippinensis* were associated with salinity, and *T. cylindrica* was associated with pH. *Tintinnopsis beroidea*, bivalve veliger, polychaete larvae and copepod nauplii were associated with high nutrient content (nitrate, nitrite and silicate). At Station 4, the CCA applied to the 43 most abundant species and separated them into three major groups at the 87% level. The groups formed by this analysis showed considerable similarity concerning fluctuations in number. Group I composed of species that occurred during summer. Low-salinity species collected in summer and the pre-monsoon formed Group II while Group III consisted of euryhaline species during post-monsoon, summer and pre-monsoon periods.

Table 4. Comparison of diversity, richness and evenness among the four stations.

	Mean (± SD) (n = 24)		
Station	Shannon diversity	Margalef richness	Evenness
1	4.08a (± 0.37)	1.46a (± 0.37)	0.923a (± 0.024)
2	3.05b (± 1.11)	1.48a (± 0.29)	0.924a (± 0.015)
3	4.19a (± 0.67)	1.79b (± 0.42)	0.926a (± 0.022)
4	3.82c (± 0.20)	1.55a (± 0.24)	0.863b (± 0.035)

Mean values with different superscripts are significantly different ($P < 0.05$, unpaired t-test).

The Table 4 compares the 24-month means of Shannon-Weaver diversity, Margalef richness and evenness across all four stations. Diversity was highest at Stations 3 and 1, followed by Station

4 and then Station 2. Richness was also highest at Station 3, followed by Stations 4, 2 and 1, amongst which there was no significant difference. Evenness was highest and remarkably similar at Stations 3, 2 and 1, but markedly and significantly lower at Station 4. This comparatively low evenness at Station 4 lasted throughout the study period, except for the last four months, December 2001 to March 2002. It may have reflected the mixing of waters of the two very different origins at this shallow estuarine station.

Discussion

Comparison with other studies

The Vellar-Coleroon estuarine complex has already been well studied for micro- and other plankton (Rajkumar *et al.,* 2014). In the previous investigations, emphasis was given to the tintinnids (Krishnamurthy and Santhanam, 1975; Krishnamurthy *et al.*, 1979; Godhantaraman, 1994, 2002a). In this manuscript, the distributions of four major groups are described: 1) tintinnid ciliates; 2) rotifers; 3) copepod nauplii; 4) other microzooplankton. As shown in Fig. 3, the total abundance of microzooplankton was highest in summer, as commonly observed in many other marine coastal and estuarine waters (Kamiyama and Tsujino, 1996; Mangesh *et al.,* 1996; Godhantaraman and Uye, 2001). This highest abundance of tintinnids in the summer months might be attributed to the highest temperature and salinity and high reproductive capacity and food supply as also reported by Verity (1985), Sanders (1987) and Godhantaraman (2001, 2002a). The abundance of microzooplankton was lowest during the monsoon months, when the water column was markedly stratified, to a large extent associated with heavy rainfall, overcast sky and cool conditions. Low temperature, low salinity and poor availability of food drastically affect the life cycles of many tintinnids in particular affecting their abundance and growth (Godhantaraman, 1994, 2001, 2002a). Moreover, many tintinnids disappeared during high river discharge (Godhantaraman, 1994, 2001, 2002a). In the present study, the most dominant genus was *Tintinnopsis*. They significantly contributed to the total abundance of tintinnids, as reported in many coastal and oceanic waters with different temperatures and salinity (Godhantaraman, 2001, 2002a; Ashok Prabu *et al.,* 2005; Dolan *et al.,* 2006). *Tintinnopsis cylindrica*, *T. tocantinensis*, *T. tubulosa*, *Codonellopsis* sp. *F. philippinensis*, *B. angularis*, *B. plicatilis*, bivalve veliger, gastropod veliger, copepod nauplii and polychaete larvae were observed over the entire study period indicating that these taxa are euryhaline and eurythermal. Species from the genus *Tintinnopsis*, *Favella*, *Codonellopsis*, *Amphorellopsis*, *Globigerina*, *Brachionus* and *Didinium* occurred in high numbers in both study areas during all seasons except the monsoon season, indicating their thermophilic nature. A few tintinnid species (*Dictyocysta* sp.) were particularly abundant during the monsoon season, suggesting that these species are adapted to the low salinity. The seasonal occurrence of tintinnid species may be closely associated with the species-specific environmental conditions that are required for encystment or excystment (Godhantaraman, 1994, 2001, 2002a). The genera *Coxiella* and *Dadayiella* were abundant in the estuary. The high numbers and variety of tintinnid species in the marine, estuary and neritic mangrove area might be partly because of the advection of species from the adjacent Bay of Bengal, but this advection is probably limited in the mangroves due to the distance from the sea. Godhantaraman (1994, 2001, 2002a) observed that the number of tintinnid species increased consistently towards the Parangipettai coast and Pichavaram mangroves, where the salinity was high (c.f. Table 2). The maximum abundance of tintinnids recorded was 65 and 67.5 ind./1, lower than the maximum abundance of tintinnids found in other studies using sedimentation. In the present study overall, the contribution by rotifers was second to that by tintinnids, in terms of both abundance and diversity. In marine, estuarine and mangrove areas, where salinity was relatively low, the diversity and abundance of rotifers were, higher than those of tintinnids reflecting rotifers' preference for less saline or fluvial conditions (Godhantaraman, 2001, 2002a). Rotifers respond rapidly to the changing environmental conditions characteristic of these areas by asexual (parthenogenic) reproduction (Sanders, 1987), and they were predominantly found during summer at all four stations, as previously found by Govindasamy and Kannan (1991).

The foraminiferan, *Globigerina* sp. and the non-tintinnid ciliates, *Strombidium* sp., *Didinium* sp. and *Mesodinium* sp., were found at all the stations during summer, which could indicate that these species can survive at high temperature and salinity (Sharma and Daneshian, 1998). The contribution of veligers (both bivalve and gastropod), cirripede nauplii, Protozoea, crab zoea, polychaete larvae, Pluteus larvae, *Oikopleura* larvaceans, were very low. This is surprising since the marine, estuarine and mangrove water system is a habitat for a large population of adult copepods, bivalves and gastropods (Krishnamurthy *et al.,* 1974). The presence of higher numbers of meroplanktonic fish larvae indicates that the estuarine waters serve as breeding and nursery grounds for a variety of fishes as reported earlier by Chandrasekaran and Natarajan (1993) and Tiwari and Nair (1993) from Pichavaram mangroves and Dharmatar creek. One of the characteristic features of the present observation was the relatively large occurrence of copepod nauplii, which could be attributed to the high density of older stage copepods (Uye *et al.,* 2000). Another reason could be the minor contribution made by rotifers, which is often specific to brackish-water environments (Godhantaraman, 2001).

The highest microzooplankton diversity was recorded during summer, which coincided with the peaks in microzooplankton numbers. The low diversity during the monsoon period might be due to the high freshwater discharge. The low diversity and low abundance of tintinnids we found in the mangroves could be due to shallowness combined with higher turbidity of the water (Godhantaraman, 1994, 2001, 2002a). According to Prince Jeyaseelan and Krishnamurthy (1980), seston content in the mangrove waters goes up to 1000 mg/1, which could lead to reduced microzooplankton abundance, due to the effects of sediments. The high levels of suspended sediment may cause changes in primary production and thereby indirectly affect both the structure and the physiology of the microzooplankton communities. During the monsoon, the water column was markedly stratified. Under these situations the encystment process of tintinnids may be impaired, while many neritic species may be advected to the adjacent sea (Kršinić, 1995), to avoid salinity fluctuations. Further, the life of many planktonic organisms in the waterways would be affected during the monsoon because of high turbidity, and many of them might thus have disappeared from the system (Kannan and Krishnamurthy, 1979).

Local indicator species

Plankton indicator species need to be sufficiently abundant to be easily found during plankton monitoring. For this reason, we have retained those species with high dominance index Y, which is closely related to abundance. Considering the two dominant rotifer species, *Brachionus plicatilis* and *B. falcatus*; the *B. plicatilis* shows high dominance at all stations (Y values at Stations1, 2, 3, 4: 0.07, 0.09, 0.04, 0.10 respectively) and at all times of the year. Therefore, it is not a good indicator species in the present study area. The *B. falcatus*, on the other hand, showed high dominance almost only at Stn 1 (Y values at Stations 1, 2, 3, 4: 0.08, 0.0007, 0.0000, 0.0000, respectively), but at all times of the year. Therefore, it is an excellent indicator species for Station1 waters at all times of the year. Overall, Station 1 was the most saline station, but over the years there was considerable overlap in salinities amongst the different stations, so other unknown factors in addition to salinity are likely to have been responsible for the strong association of *B. falcatus* with Station 1. Considering agglomerated tintinnids, *T. cylindrica* presents high mean dominance amongst all stations (Y values at Stations 1, 2, 3, 4: 0.09, 0.10, 0.06, 0.08 respectively), with highest abundance relative to all microplankton from February to August and lowest values from October to December. Therefore *T. cylindrica* is an indicator species for the inter-monsoon at all four stations. *T. tocantinensis* also presents high mean dominance amongst all stations (*Y* values at Stns 1, 2, 3, 4: 0.08, 0.04, 0.07, 0.09 respectively), with the highest abundance relative to all microplankton from February to August and lowest values from October to December (but never completely absent). Therefore *T. cylindrica* is an indicator species for the inter-monsoon at all four Stations. *T. tubulosa* showed a distribution in dominance rather similar to that of both *T. cylindrica* and *T. tocantinensis*. During the study period, the association of these three *Tintinnopsis* species may be considered an indicator of inter-monsoon conditions.

Testing of hypotheses

Our work has allowed the hypotheses proposed in Section 1 to be tested during the study period and in the study area. The hypothesis that changes in microplankton abundance were associated with seasonal changes is strongly supported by our results; over both years and at all four stations. The highest levels (35-65 ind/L) occurred from March to June and the lowest levels (4-20 ind./l) from September (2000) or October (2001) to December. The hypothesis that geographical position (Station no.) affected microplankton abundance was supported for some times of the year only; at each time of year, abundance level was similar at all four stations, except that Stn 2 (Cuddalore estuarine) showed lower abundance levels on average by 11 (+/-2) (95% confidence limits) ind./l than the other three stations in March (2001, but not 2002) and April to May (2000 and 2001) ($P = 4 \times 10^{-9}$). Furthermore, Stn4 (Coleroon Estuary) showed abundance levels lower on average by 8.0 (+/-1.4) ind./l than the other stations from September to December (2000 and 2001) ($P = 2 \times 10^{-11}$). The lower abundance levels found at Station 2 relative to Station 1 and Station 4 relative to Station 3, pairs of stations only 3 to 5 km apart could be associated with the considerably lower salinity values during parts of the study period at Stations 2 and 4, compared to those at Stations 1 and 3. The hypothesis that diversity H' varied systematically was confirmed, with values at the outermost stations, Station 1 (oceanic) and Station 3 (mangroves), systematically higher than at the estuarine station, Station 2, while Station 4, in the Coleroon Estuary showed the lowest value of H'. Richness R' was not shown to vary significantly amongst Station 1, 2 and 4, but it was significantly higher at Station 3 (mangroves). Evenness E' showed no systematic significant difference amongst Station 1, 2 and 3, but it was significantly lower at Stn4 (Coleroon Estuary). Variations of H', R' and E' over the two-year study period at the different stations are difficult to interpret, and no clear hypothesis of seasonal variation is supported.

Worldwide comparison of microplankton abundance

Table 5 showed the maximum abundance of microplankton

Table 5. Comparison of maximum microzooplankton abundance (ind. L^{-1}) found in studies among various localities worldwide.

Locations	Latitude	Maximum Abundance (ind.1^{-1})	Remarks	Mesh size used (μm) or sedimentation (S)	References
Damariscotta River estuary, USA	44°N	540,000	A	S	(Sanders, 1987)
Damariscotta River estuary, USA	44°N	~7000	B	S	(Sanders, 1987)
Nervión Estuary, Basque Country, Spain	43°N	540,000	C	S	(Urrutxurtu *et al.,* 2003)
Nervión Estuary, Basque Country, Spain	43°N	300,000	C	S	(Urrutxurtu, 2004)
Nervión Estuary, Basque Country, Spain	43°N	7,400	B	S	(Urrutxurtu, 2004)
Bay of Naples, S.W. coast of Italy	41°N	298,500	C	S	(Modigh and Castaldo, 2002)
Bay of Naples, S.W. coast of Italy	41°N	30,500	B	S	(Modigh and Castaldo, 2002)
Narragansett Bay, E. coast, USA	42°N	270,000	B	S	(Verity, 1987)
Irish Sea	53-55°N	60,000	D	S	(Edwards and Burkill, 1995)
Tokyo Bay, Japan	35°N	60,000	E	S	(Nakane *et al.,* 2008)
Karboub, Tunisia	33°N	50,350	C, F	S	(Kchaou *et al.,* 2009)
Damariscotta estuary, E. coast, U.S.A.	44°N	44,100	G	S	(Revelante and Gilmartin, 1987)
Hooghly (Ganges) Estuary, N.E. India	21-23°N	42,000	B	S	(Rakshit *et al.,* 2017b)
Parangipettai coastal waters, S.E. India	11°N	37,520	E	S	(Ashok Prabu *et al.,* 2005)
Jiaozhou Bay, Yellow Sea coast, China	36°N	32,000	C	S	(Yu *et al.,* 2011)
Strangford Lough, Irish Sea, N. Ireland	54°N	26,000	H	S	(Jenkinson, 1983)
Strangford Lough, Irish Sea, N. Ireland	54°N	4,000	B	S	(Jenkinson, 1983)
Hiroshima Bay, Japan	34°N	25,400	I	S	(Kamiyama, 1994)
Long Island Bay, New York, USA	41°N	12,600	B	S	(Capriulo and Carpenter, 1983)
Bahia Blanca estuary, Argentina	39°S	12,400	B	S	(Barría de Cao *et al.,* 2005)
Bahia Blanca estuary, Argentina	39°S	11,300	B	S	(Barría de Cao, 1992)
North Lebanon waters	34°N	6012	H	S	(Abboud-Abi Saab, 2002)
North Lebanon waters	34°N	39	B	S	(Abboud-Abi Saab, 2002)
Seto Inland Sea of Japan	34°N	5700	B	S	(Kamiyama and Tsujino, 1996)
Tabia, Tunisia	37°N	5600	C, J	S	(Kchaou *et al.,* 2009)
Offshore, Central and Eastern Arabian Sea	10-21°N	5000	G, K	S	(Gauns *et al.,* 1996)
Kaštela Bay, Central Adriatic, Croatia	44°N	4300	B	S	(Bojani *et al.,* 2012)
Jiaozhou Bay, Yellow Sea coast, China	36°N	3970	B	S	(Feng *et al.,* 2018)
Prydz Bay, Antarctica	64-68°S	2770	K	S	(Liang *et al.,* 2018)
Prydz Bay, Antarctica	64-68°S	1031	B	S	(Liang *et al.,* 2018)
Kalpakkam coastal waters, S.E. India	12-13°N	2300	B	S	(Rakshit *et al.,* 2017a)
Seto Inland Sea, Japan	34°N	2190	E	S	(Uye *et al.,* 1996)
Harbor of Gabès, Tunisia	34°N	2100	C, L	S	(Kchaou *et al.,* 2009)
Sundarban mangroves, Ganges, N.E. India	21-23°N	1600	C	S	(Biswas *et al.,* 2013)
Port Erin Bay, Isle of Man, Irish Sea	54°N	1500	B	S	(Graziano, 1989)
Hooghly (Ganges) Estuary, N.E. India	21-23°N	1300	B	S	(Rakshit *et al.,* 2014)
Chesapeake Bay, E. coast, USA	37-39°N	>1000	C	S	(Coats and Heisler, 1989)
Solent estuary, S. England	51°N	1000		S	(Burkill, 1982)
Eastern Adriatic Bays, Croatia	42-44°N	967	B	S	Kršini, 1987a)
Ushuaia Bay, S. Argentina (polluted area)	54°S	627	C	S	(Barría de Cao *et al.,* 2013)
Sundarban mangroves, Ganges, N.E. India	22-23°N	557	C	S	(Rakshit *et al.,* 2015)
Kaštela Bay, Central Adriatic, Croatia	44°N	530	B	S	(Bojani *et al.,* 2001)
Kaštela Bay, Central Adriatic, Croatia	44°N	470	H	S	(Bojani *et al.,* 2001)
Vellar estuary and Pichavaram mangroves	11°N	420	B	S	(Godhantaraman, 2002a)
Ushuaia Bay, S. Argentina	54°S	345	C	S	(Barría de Cao *et al.,* 2013)
Jounieh Bay, Lebanon	34°N	314	C	S	(Abboud-Abi Saab, 1989)
Bay of Mail Ston, Adriatic, Croatia	43°N	288	B	S	(Kršini, 1987b)
Within 40 km of Isle of Man, Irish Sea	54°N	288	B	S	(Graziano, 1989)
Parangipettai coastal waters, S.E. India	11°N	227	I	S	(Godhantaraman, 2001)
Inland Sea of Japan and ocean waters	31-34°N	~200	B	S	(Godhantaraman and Uye, 2001)
Tyrrhenian Sea Coast, Sicily, S. Italy	38°N.	128	C	S	(Sitran *et al.,* 2009)
Ushuaia and Golandrina Bays, Argentina	54°S	143	C	S	(Barria de Cao *et al.,* 2013)
E and W Mediterranean offshore	33-44°N	115	C	S	(Dolan, 2000)
Parangipettai coastal waters, S.E. India	11°N	89	C	S	(Krishnamurthy and Santhanam, 1975)

Locations	Latitude	Maximum Abundance (ind.1⁻¹)	Remarks	Mesh size used (μm) or sedimentation (S)	References
Pichavaram mangroves, S.E. India	11°N	74	B	S	(Godhantaraman, 1994)
Pichavaram mangroves, S.E. India	11°N	67.5	I	S	Present study
Cuddalore mangroves, S.E. India	11°N	65	I	S	Present study
Ionian Sea Coast, Sicily, S. Italy	38°N.	58	C	S	(Sitran *et al.,* 2007)
Bahuda estuary, E. coast, India	19°N	17	C	S	(Mishra and Panigrahy, 1999)
Zuary estuary, Goa, S.W. India	15°N	75,760	B	20	(Jyothibabu *et al.,* 2006)
Cochin Back Waters, S.W. India	10°N	6560	K	20	(Jyothibabu *et al.,* 2006)
Larzarev Sea, Antarctic	68°S	1900	H	20	(Froneman *et al.,* 1996)
Larzarev Sea, Antarctic	68°S	100	B	20	(Froneman *et al.,* 1996)
Funka Bay, Hokkaido, Japan	43°N	219	B	40	(Dohi, 1982)
Admiralty Bay, S. Shetland Is.	62°S	5	B	50	(Wasik and Mikolajczyk, 1994)
Offshore, Southern Adriatic	40-43°N	1.0	B	53	(Kršini, 1982)
Coastal waters, Brazil	1-3°S	1.0	M	120	Garcia *et al.* (2021)
Coastal waters, Brazil	1-3°S	0.2	M	300	Garcia *et al.* (2021)

Notes: A – no. of non-tintinnid ciliates; B – no. of tintinnids; C – no. of total microzooplankton; D – no. of total microplankton, of which tintinnids comprised ~3% to ~35%, other ciliates - ~45% to ~95%; E – no. of total microzooplankton, of which ciliates comprised on average ~26%; F - tintinnids comprised 0.75% of mean ciliate abundance; G – no. of total microplankton; H – no. of aloricate ciliates; I – no. of total microplankton, dominated largely by tintinnids; J – tintinnids comprised 25% of mean ciliate abundance; K –tintinnids comprised about half; L – tintinnids comprised 42% of mean ciliate abundance; M - "maximum abundance is mean plus standard error.

(20-200 μm) in temporally extensive (several months or more) investigations in 53 estuarine and marine areas, taken also from 53 publications. Of these six studies used net-filtration to estimate abundance, while 47 used sedimentation. The different methods of sampling, identification, counting, fixation, preservation and no doubt the investigators' competence and taxonomic preferences preclude any rigorous statistical analysis of the differences in abundance between the investigations. Studies made using samples filtered through a net with the largest meshes, 54 μm (Kršini, 1982) and 50 μm (Wasik and Mikolajczyk, 1994), gave the lowest maximum counts of microzooplankton, supporting Abboud-Abi Saab's (1989) observation of lower estimated abundances of tintinnids obtained using 52-μm filtration compared with those obtained by sedimentation. The study using the third-largest mesh, 40 μm (Dohi, 1982), however, gave values within the range for sedimented samples, and so, unsurprisingly, did the studies using meshes of 20 μm (Froneman *et al*., 1996; Jyothibabu *et al*., 2006). Garcia *et al.* (2021), in equatorial coastal waters of Brazil, compared micro-mesozooplankton sampled by nets of two meshes, 120 and 300 μm. They also found marked differences in the taxon composition and abundances between the two kinds of the net. Table 5 showed that the total range of maximum abundance for microplankton concentrated by sedimentation is huge, spanning more than 4 orders of magnitude, from 17 (Mishra and Panigrahy, 1999) to 270,000 (Verity, 1987) tintinnids L^{-1}. No relationship between the abundance of total microplankton or tintinnids with the geographical region can be discerned. The hypothesis that microplankton (20-200 μm) abundance depends on the sampling method is tentatively confirmed, with mesh sizes greater than or equal to 40 μm giving abundances lower than those obtained using sedimentation methods or filtering through the 20 μm mesh. In the studies reported in Table 5, differences in sampling, counting and identification methods are reported, and other differences are likely to have been unreported, so we consider that rigorous statistical treatment would be inappropriate. However, an inspection of the data does not support the hypothesis that microplankton abundance is systematically related to geographical area (tropical vs. temperate vs. polar) (mangroves vs. estuarine vs. coastal vs. offshore-oceanic).

Conclusion

A comparison of investigations made around the world, including the present one, showed a marked negative relationship between maximum abundance and sampling method, sedimentation or plankton tows with different mesh sizes. This underlines the need for internationally agreed standardization of sampling protocols to compare microzooplankton abundance in space and time. The species composition and abundance of microzooplankton varied seasonally due to wide temperature fluctuations and salinity gradients. The change of salinity in the water column exerted either direct or indirect effect on the microzooplankton communities. This study gives new information on the dynamics of microzooplankton populations in the Cuddalore marine and estuarine regions and also the Pichavaram mangrove waters and the CCA analyses helps to associate these with physicochemical variables and the two annual cycles, although the correlation is not proof of causal effects. These areas warrant further investigation to gain a better understanding of the processes and the relationships in the microzooplankton communities.

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