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Distinct difference of littoral rotifer community structure in two mangrove wetlands of Qi'ao Island, Pearl River estuary, China

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Abstract

Background: Less study was focused on the ecological community of littoral rotifers than on pelagic area worldwide. Moreover, rotifers were overlooked mostly due to the improper sampling methods and lack of experienced taxonomists for ecological researches, and the diversity and role of estuarine rotifers in ecological systems were underestimated severely.

Results: A long-term investigation of the littoral rotifer in a shallow mangrove swamp (MS) and a tidal creek (TC) of Qi'ao Island, the Pearl River estuary of southern China, revealed significant differences of the community structure at different sites and in different seasons. Ninety-four monogonont rotifers were detected in total. The average abundance of rotifer at MS (97.0 individuals/L) was lower than that at TC (140.8 individuals/L), but all average diversity indexes at MS were higher than those at TC. The main species at MS were *Colurella* sp.1, *Encentrum marinum*, *Colurella adriatica*, *Synchaeta cf. kitina*, *Synchaeta* sp., and *Cephalodella cf. innersi*, whereas they were *Synchaeta cf. kitina* and *Brachionus angularis* at TC. The rotifer community was correlated with the salinity and total nitrogen group most at MS, while temperature contributed most at TC.

Conclusions: This study revealed higher diversity and abundance of littoral rotifers at the two close mangrove wetlands of Qi'ao Island compared to other studies. Different kinds of biotopes at the two sites displayed significant difference of the community structure, which was mainly due to the abundance of different main species present at the two sites. The peculiar environment of MS created an unusual rotifer community which had more marine species with higher abundance mostly in winter.

Keywords: Littoral rotifer; Abundance; Diversity; Community structure; Stenohaline; Mangrove wetlands

Background

Littoral zones of aquatic systems tend to have higher biodiversity and community structure which are dissimilar to that of the open water. Notably, about 75% of rotifer species occur in littoral zones (Duggan 2001; Smith 2001). However, knowledge of the diversity and biology of animals in littoral zones is still less than that of the pelagic area (Lemly and Dimmick 1982; Maia-Barbosa et al. 2008; Thorp and Covich 2010), especially in brackish-water estuaries (Rougier et al. 2005; Zhou et al. 2009).

Mesozooplankton, mostly copepods, usually are the most dominant components of zooplankton in estuarine environments (e.g., Tan et al. 2004; Li et al. 2006). Globally, the richness and distribution of microzooplankton (e.g., rotifers) and its ecological roles are rarely reported (Dolan and Gallegos 1991, 1992; Holst et al. 1998; Chick et al. 2010). It may result from the improper sampling methods. Samples collected with a 64-μm or larger mesh underestimate biodiversity because small animals are filtered through easily (Bottrell et al. 1976; Wang et al 2009; Chick et al. 2010; Tseng et al. 2011). Besides, different researchers with varying levels of taxonomic skill can severely affect the results of species diversity (Segers 2008; Fontaneto et al. 2012), abundance, community structure, etc. Most of ecological studies on estuarine rotifers were not implemented by experienced rotifer taxonomists (e.g., Table 1). In order to minimize loss of the microplankton and improve the accuracy of species

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Table 1 Species number and average abundance of rotifers on Qi'ao Island in comparison with other studies

Habitat	Sampling area	Methods	Species number	Average abundance[a] (individuals/L)	Sites	Sampling effort (times; dates)	References
Littoral	Pearl River estuary, China	Utermöhl (1931)	94	118.9 (0 ~ 2,050)	2	48; Jan 2007 to Dec 2010	This study
	Pearl River estuary, China	64 μm	21	-	39	1; Mar to Apr 2009	Zhang et al. (2012)
Open waters	Pearl River estuary, China	169 μm	2	-	31/21	2; Jul 1999; Jan 2000	Tan et al. (2004)
	Pearl River estuary, China	64 and 112 μm	8	<10	8	3; Aug 2006	Gao et al. (2008a)
	Pearl River estuary, China	64 and 112 μm	28	<10	8	3; Aug 2006; Nov 2006; Feb 2007	Gao et al. (2008b)
	Pearl River estuary, China	112 μm	12	-	2	3; Nov 2006; Feb; May; Aug 2007	Gao et al. (2010)
	Pearl River estuary, China	20 μm	69	18.3 (0 ~ 199)	3	Semimonthly; Jul 2009 to Jan 2010	Hou (2011)
	Yangtze River Estuary, China	64 μm	103	15.6 (0 ~ 2,500)	39	4; May 1988 to Jul 1990	Han and Hu (1995)
	Yangtze River estuary, China	64 μm	24	<0.2 (0 ~ 9.3)	24	1; Sept 1966	Wang et al. 1999
	Yangtze River estuary, China	Utermöhl (1931)	65	185.7 (0 ~ 600)	14	2; Sept 2005; Apr 2006	Hu et al. (2008)
	Lagos Harbour and Badagry Creek, Nigeria	55 μm	51	-	10	Monthly; Oct 1986 to Sept 1987	Egborge (1994)
	Elbe estuary, Germany	30 μm	77	about 800 (0 ~ 2,048)	8	Weekly; Mar 1995 to Jul 1995	Holst et al. (1998)
	Kaw River estuary, French Guiana	40 μm	108	about 135 (0 ~ 750)	3	2; Jun 1999; Nov 2001	Rougier et al. (2005)
	Schelde estuary, Belgium	50 μm	52	(0 ~ 2,500)	16	Monthly; Feb 2002 to Dec 2002	Azémar et al. (2010)
	Mossoró River estuary, Brazil	60 μm	16	about 9.8	3	Monthly; Oct 2006 to Sept 2007	Medeiros et al. (2010)

[a]Average abundance was calculated in all investigated samples; some of the data are approximate values.

identification in this study, Utermöhl's method (Utermöhl 1931) and the widely accepted taxonomy system of Wallace et al. (2006) and Segers (2007, 2011) were used.

Few papers investigated rotifer communities in estuarine areas worldwide (e.g., Egborge 1994; Holst et al. 1998; Rougier et al. 2005; Azémar et al. 2010). Additionally, so far, only one paper reported on rotifer community in mangrove forest habitats (e.g., Rougier et al. 2005). The same situation holds in China as well. There was no exclusive paper on littoral rotifer of estuaries. Only one recent ecological paper of zooplankton included littoral rotifer (e.g., Zhang et al. 2012). Researches on zooplankton covering rotifers mainly focused on open water areas (e.g., Tan et al. 2004; Gao et al. 2008a, 2008b, 2010; Hou 2011).

This study aimed to better understand the spatial and temporal characteristics of the littoral rotifer communities in two kinds of wetlands: shallow mangrove swamp and tidal creek. They are dominant aquatic ecological systems in the mangrove forest of Qi'ao Island, Pearl River estuary.

Methods

Study sites

The sampling sites (Figure 1) are situated in Qi'ao-Dan'gan Provincial Mangrove Nature Reserve (113° 36′ ~ 113° 39′ E, 22° 23′ ~ 22° 27′ N) on Qi'ao Island, west side of the Pearl River estuary, Guangdong province. Two close sites (about 300 m) were selected in the littoral zone of shallow mangrove swamp (MS) wetlands and tidal creek (TC) wetlands, respectively. The two different wetlands are the main kinds of aquatic ecological system in the mangrove forest of Qi'ao Island. The mangrove swamp (Figure 1) was semi-closed with a variation in water depth of 0 to 60 cm, mostly about 20 cm, but dried three times on the sampling days of May 2007, June 2007, and April 2009. Mostly, it was stagnant, but it could be inundated by high tides. It was covered with dominant mangrove trees *Kandelia candel* and some understory plant of *Acanthus ilicifolius*. The tidal creek, an open water body connecting to the Pearl River estuary in the mangrove forest (Figure 1), was influenced by tides with a variation in water depth of 50 to 250 cm. It was dominated by emergent *Phragmites communis* and mangrove trees *Kandelia candel* in the intertidal zone.

Field sampling

Littoral rotifer samples of the two sites were taken monthly, from January 2007 to December 2010. One semi-automatic plexiglass water sampler, with a volume of 2.5 L (Beijing Purity Instrument Co., Beijing, China), was used for the quantitative sampling. The distance from the

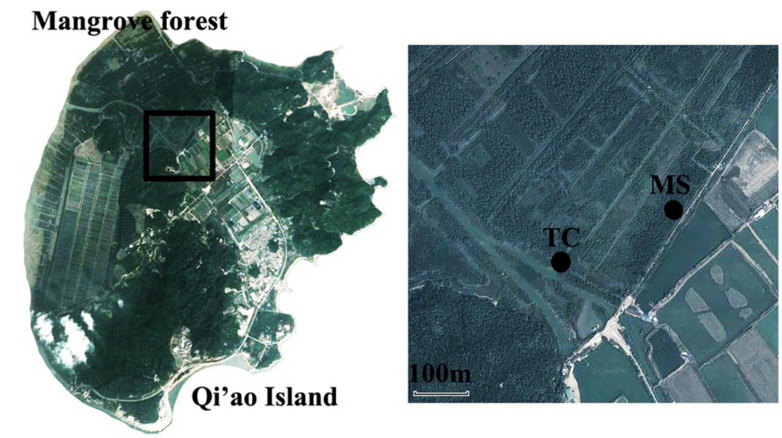

Figure 1 Location of the sampling sites in mangrove wetlands of Qi'ao Island. MS, mangrove swamp site; TC, tidal creek site.

shore was about 2 m. Each sample was metered 5 L water, so the samples from MS or TC needed to be collected randomly at least twice or more depending on the depth of water. Then, the samples were transferred to unified plastic kettles and fixed immediately by adding 40% formaldehyde up to a final concentration of 4%. Fixed samples were concentrated to 50 mL for quantitative counting by using a siphon tube to remove the supernatant fluid after more than 48 h of sedimentation (Utermöhl 1931). Qualitative samples were collected with 30- and 64-μm nets.

Duplicated samples were taken bimonthly for abiotic parameter analyses following the methods specified for oceanographic survey of China (State Oceanic Administration People's Republic of China 2007). Salinity (S), temperature (T), total phosphorus (TP), and total nitrogen (TN) were analyzed.

Species identification and statistics analysis

Monogonont rotifers were identified into species mainly according to Wallace et al. (2006), Segers (2007, 2011), and Koste (1978). Bdelloid rotifers were hard to identify with fixed specimens which were only enumerated. Animals were selected and examined with a Nikon Eclipse E800 microscope (Nikon Co., Tokyo, Japan). A 1-mL plankton counting chamber was used for enumerating. At least five subsamples were examined until a minimum of 200 individuals per sample was reached, in order to minimize subsampling errors and reduce the coefficient of variation to a maximum of 10% (Omori and Ikeda 1984).

Statistical analyses for the rotifer community, including ANOSIM (analysis of similarity), BEST/BIOENV (best match between biota and environment), CLUSTER (hierarchical clustering), MDS (non-metric multi-dimensional scaling), SIMPER (similarity percentages), and REALTE for serial shift and cyclic variation check within a year or within the investigation period, were conducted by PRIMER 5.0 following Clarke and Gorley (2006). Community abundance data for similarity matrices were square-root transformed and then constructed by the Bray-Curtis similarity method. Abiotic data (salinity, temperature, total phosphorus, and total nitrogen) were normalized, and similarity matrices were constructed by using the Euclidean distance similarity measure. Diversity indexes of rotifer at the two wetlands were expressed with Margalef's species richness index (D), Shannon diversity index (H', base-e logarithm), and Pielou's evenness (J'). CCA (canonical correspondence analysis) analyses between the main species (square-root transformed) at MS and TC and abiotic parameters (normalized) were performed by CANOCO 4.5 (Monte Carlo permutation tests, number of permutations = 999, $P < 0.1\%$). Abundance figures were constructed by SigmaPlot 11.0.

Results

Abiotic parameters

The abiotic parameters of salinity (Figure 2A) and temperature (Figure 2B) analyzed in this study had minor discrepancies between the two sampling sites at the same months and fluctuated regularly with months. The average salinity was a little higher at MS (9.08) than at TC (8.04), while the temperature was a little higher at TC (24.2°C) than at MS (23.6°C). In contrast, total nitrogen (Figure 2C) and total phosphorus (Figure 2D) had slightly larger discrepancies and fluctuated irregularly. The average total phosphorus was a little higher at MS (0.187 mg/L) than at TC (0.164 mg/L), whereas for total nitrogen, it was a little higher at TC (1.592 mg/L) than at MS (1.449 mg/L).

Species composition, abundance, and diversity indexes

Ninety-four species belonging to 25 genera of monogonont rotifers (Table 2, Figure 3) were recorded at the two sampling sites in total. Additionally, 3 published new species and 16 new records of China were found in this survey

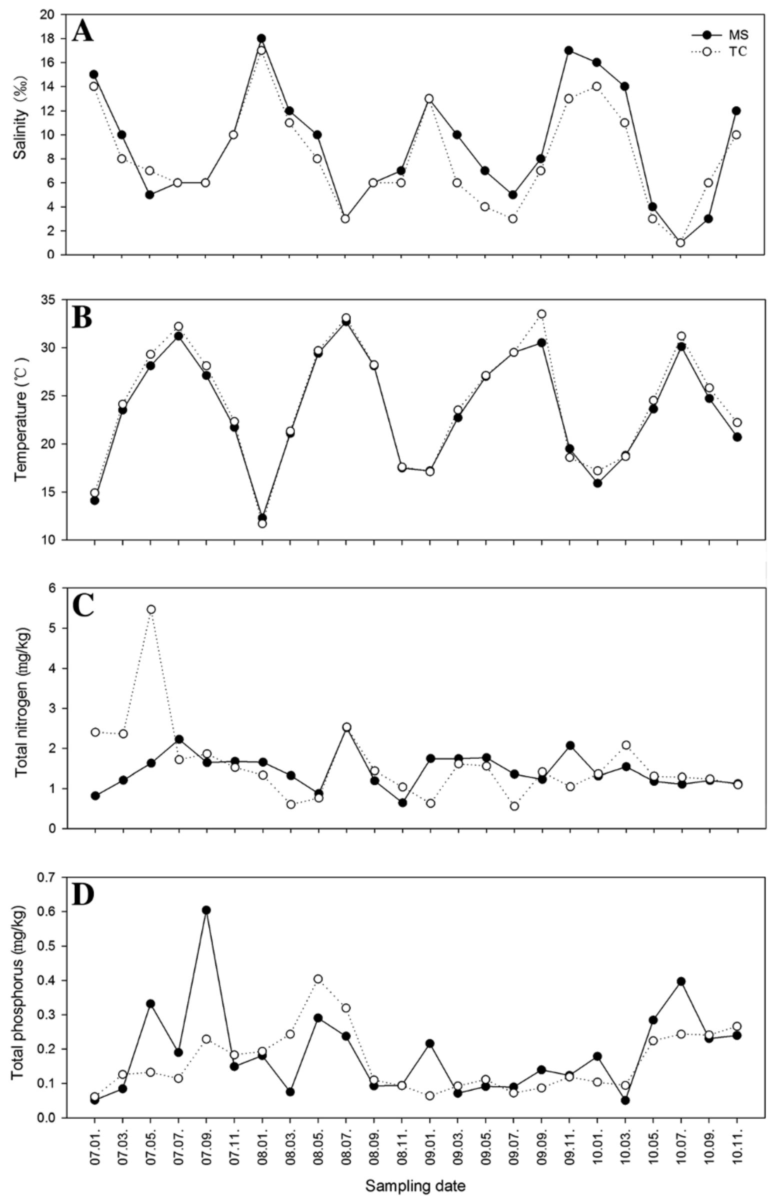

Figure 2 Variations of environment factors at the two sampling sites in mangrove wetlands of Qi'ao Island. (A) Salinity, **(B)** temperature, **(C)** total phosphorus, and **(D)** total nitrogen. MS, mangrove swamp site; TC, tidal creek site.

(Table 2), and some other new materials need to be further determined. Almost the same species number was found at the two sites; there were 68 species at MS and 67 species at TC, and 27 unique species appeared in MS and 26 in TC. At MS, the dominant rotifer genera in species diversity were *Brachionus*, *Colurella*, *Encentrum*, *Synchaeta* and *Lecane* with 10, 7, 7, 6, and 6 species, respectively, whereas at TC, they were *Brachionus*, *Lecane*, *Synchaeta*, and *Polyarthra* with 14, 9, 7, and 5 species (Figure 3).

Variations in rotifer abundance, including monogononta and bdelloida at the two sampling sites, are shown in Figure 4. The average abundance was much higher at TC than at MS (Table 3), and the average abundance of separate years followed the order of 2007 > 2008 > 2009 > 2010 (129.9, 128.8, 95.2, and 39.7 individuals/L) at MS and 2009 > 2007 > 2010 > 2008 (202.0, 181.2, 120.5, and 59.6 individuals/L) at TC. The highest abundance at MS was recorded in November 2008, while it appeared in June 2007 at TC (Figure 4).

The main species of the two sites - *Colurella* sp.1, *Encentrum marinum*, *Colurella adriatica*, *Synchaeta cf. kitina*, *Synchaeta* sp., and *Cephalodella cf. innersi* at MS, and *Synchaeta cf. kitina* and *Brachionus angularis* at TC - are presented in Figure 5 with their variations in

Table 2 Rotifer species and their ecological characteristics recorded in the two sampling sites of Qi'ao Island

Species	Sampling sites		Ecological characteristics
	MS	TC	
Bdelloid spp.			
Anuraeopsis coelata de Beauchamp, 1932		+	Haloxenous
Asplanchna brightwellii Gosse, 1850	+	+	Haloxenous
Beauchampiella eudactylota (Gosse, 1886)	+		Haloxenous
Brachionus angularis Gosse, 1851	+	+	Euryhaline
Brachionus budapestinensis Daday, 1885		+	Haloxenous
Brachionus calyciflorus Pallas, 1766	+	+	Euryhaline
Brachionus caudatus Barrois & Daday, 1894	+	+	Haloxenous
Brachionus dimidiatus Bryce, 1931[a]		+	Euryhaline
Brachionus diversicornis (Daday, 1883)	+		Haloxenous
Brachionus falcatus Zacharias, 1898	+	+	Haloxenous
Brachionus ibericus Ciros-Peréz, Gómez & Serra, 2001	+	+	Stenohaline
Brachionus murphyi Sudzuki, 1989		+	Haloxenous
Brachionus nilsoni Ahlstrom, 1940	+	+	Haloxenous
Brachionus plicatilis Müller, 1786	+	+	Stenohaline
Brachionus quadridentatus Hermann, 1783		+	Euryhaline
Brachionus rotundiformis Tschugunoff, 1921	+	+	Stenohaline
Brachionus rubens Ehrenberg, 1838		+	Euryhaline
Brachionus urceolaris Müller, 1773	+	+	Euryhaline
Cephalodella catellina (Müller, 1786)		+	Euryhaline
Cephalodella cf. gibba (Ehrenberg, 1830)	+	+	Euryhaline
Cephalodella cf. innesi Myers, 1924	+	+	Euryhaline?
Cephalodella cf. misgurnus Wulfert, 1937	+		Haloxenous?
Cephalodella sp.1		+	
Cephalodella sp.2	+		
Colurella adriatica Ehrenberg, 1831	+	+	Euryhaline
Colurella anodonta Carlin, 1939[a]		+	Euryhaline
Colurella colurus (Ehrenberg, 1830)	+		Euryhaline
Colurella psammophila Segers & Chittapun, 2001[a]	+		Haloxenous
Colurella sanoamuangae Chittapun, Pholpunthin & Segers, 1999[a]	+	+	Haloxenous
Colurella uncinata bicuspidata (Ehrenberg, 1832)	+		Euryhaline
Colurella sp. 1	+	+	Euryhaline?
Colurella sp. 2	+		
Encentrum marinum (Dujardin, 1841)	+	+	Euryhaline
Encentrum longidens Donner, 1943[a]	+	+	Haloxenous
Encentrum wiszniewskii Wulfert, 1939[a]	+		Haloxenous
Encentrum cf. limicola Otto, 1936	+		Stenohaline
Encentrum (*Isoencentrum*) sp. 1	+		Stenohaline
Encentrum (*Pseudencentrum*) sp. 2		+	Stenohaline
Encentrum sp. 3	+		
Encentrum sp. 4	+		
Epiphanes macroura (Barrois & Daday, 1894)		+	Euryhaline
Euchlanis dilatata Ehrenberg, 1832	+		Euryhaline
Filinia branchiata (Rousselet, 1901)	+	+	Haloxenous
Filinia longiseta (Ehrenberg, 1834)	+	+	Euryhaline
Filinia novaezealandiae Shiel & Sanoamuang, 1993	+	+	Haloxenous
Hexarthra fennica (Levander, 1892)	+	+	Stenohaline
Hexarthra intermedia (Wiszniewski, 1929)	+	+	Euryhaline
Hexarthra mira (Hudson, 1871)		+	Euryhaline
Hexarthra oxyuris (Sernov, 1903)[a]		+	Stenohaline
Itura cf. deridderae Segers, 1993		+	
Keratella cochlearis (Gosse, 1851)		+	Euryhaline
Keratella procurva (Thorpe, 1891)		+	Haloxenous
Keratella tropica (Apstein, 1907)	+	+	Euryhaline
Lecane baimaii Sanoamuang & Savatenalinton, 1999[a]	+		Euryhaline
Lecane bulla (Gosse, 1851)	+	+	Euryhaline
Lecane closterocerca (Schmarda, 1859)		+	Euryhaline
Lecane donneri Chengalath & Mulamoottil, 1974[a]		+	Euryhaline
Lecane grandis (Murray, 1913)		+	Stenohaline
Lecane hamata (Stokes, 1896)	+		Haloxenous
Lecane hastata (Murray, 1913)	+		Euryhaline
Lecane luna (Müller, 1776)		+	Euryhaline
Lecane punctata (Murray, 1913)		+	Euryhaline
Lecane pyriformis (Daday, 1905)		+	Haloxenous
Lecane quadridentata (Ehrenberg, 1830)	+	+	Euryhaline
Lecane stenroosi (Meissner, 1908)	+	+	Euryhaline
Lepadella acuminata (Ehrenberg, 1834)	+		Euryhaline
Lepadella patella (Müller, 1773)	+	+	Euryhaline
Lepadella sp.	+		
Lindia sp.	+		
Notholca sp.	+	+	Stenohaline
Paradicranophorus sinus De Smet, 2003[a]	+		Stenohaline
Platyias quadricornis (Ehrenberg, 1832)	+	+	
Polyarthra dolichoptera Idelson, 1925		+	Euryhaline
Polyarthra indica Segers & Babu, 1999[a]	+	+	Haloxenous
Polyarthra vulgaris Carlin, 1943	+	+	Euryhaline
Polyarthra sp. 1	+	+	Haloxenous
Polyarthra sp. 2	+	+	Haloxenous

Table 2 Rotifer species and their ecological characteristics recorded in the two sampling sites of Qi'ao Island *(Continued)*

Proales similis de Beauchamp, 1907[a]	+	+	Stenohaline
Resticula melandocus (Gosse, 1887)	+		Euryhaline
Synchaeta arcifera Xu, 1998	+	+	Stenohaline
Synchaeta bicornis Smith, 1904[a]	+	+	Stenohaline
Synchaeta elsteri Hauer, 1963[a]	+	+	Stenohaline
Synchaeta cf. kitina Rousselet, 1902	+	+	Euryhaline
Synchaeta oblonga Ehrenberg, 1832	+	+	Euryhaline
Synchaeta stylata Wierzejski, 1893		+	Euryhaline
Synchaeta vorax Rousselet, 1902[a]		+	Stenohaline
Synchaeta sp.	+		Stenohaline
Testudinella patina (Hermann, 1783)	+		Euryhaline
Testudinella pseudobscura Wei, De Smet & Xu, 2011[b]		+	Stenohaline
Testudinella quadilobata Wei, De Smet & Xu, 2011[b]	+		Stenohaline
Testudinella zhujiangensis Wei, De Smet & Xu, 2010[b]	+	+	Stenohaline
Trichocerca marina (Daday, 1890)	+		Stenohaline
Trichocerca pusilla (Jennings, 1903)	+	+	Euryhaline
Trichocerca sp.	+		

MS, mangrove swamp site; TC, tidal creek site. [a]New rotifer records of China; [b]Published new rotifer species found in this survey; +, species occurred in the sampling site.

abundance. The species were defined by the average abundance of the species with a cumulative contribution of more than 80% to the average Bray-Curtis similarity between all pairs of samples in the specific community (Clarke and Gorley 2006).

Species number (*S*), Margalef's species richness index (*D*), Shannon diversity index (H'), and Pielou's evenness (J') at MS were all higher than those at TC on average (Table 3).

Site difference and temporal variation of community structure

The results of ANOSIM routine for testing dissimilarity between the sampling sites revealed that the rotifer communities were significant different ($R = 0.346$, $P < 0.1\%$), and the analysis of CLUSTER (Figure 6) and MDS (Figure 7) also had similar results. Table 4 shows the average abundance of the main species (SIMPER) which added together contributed more than 50% to the dissimilarity of the rotifer communities between the two sites, and the two most dominant species at MS and TC, *Colurella* sp. 1 and *Synchaeta cf. kitina*, contributed up to 24.84% together.

There were four distinct groupings (A, B, C, D) on the dendogram (Figure 6) divided by a similarity of 35%, which were made up with most of lower temperature and higher salinity months of MS in group A, most of higher temperature and lower salinity months of MS in group B, most of lower temperature and higher salinity months of TC in group C, and most of higher temperature and lower salinity months of TC and few months of MS in group D. Additionally, group D had a tendency for two clusters (Figure 6D), *viz.*, most months of 2007 and 2008 in group D tended to cluster together, while all months of 2009 and 2010 of group D were in another branch. Four rotifer communities were found for the relevant groupings, including *Encentrum marinum-Colurella adriatica-Synchaeta* sp.-*Colurella* sp.1-*Encentrum* sp.1 (community A), *Colurella* sp.1-*Synchaeta cf. kitina* (community B), *S. cf. kitina* (community C), and *Brachionus angularis-C. adriatica-Brachionus rotundiformis-S. cf. kitina-Keratella tropica-Synchaeta oblonga-Filinia novaezealandiae-Polyarthra*

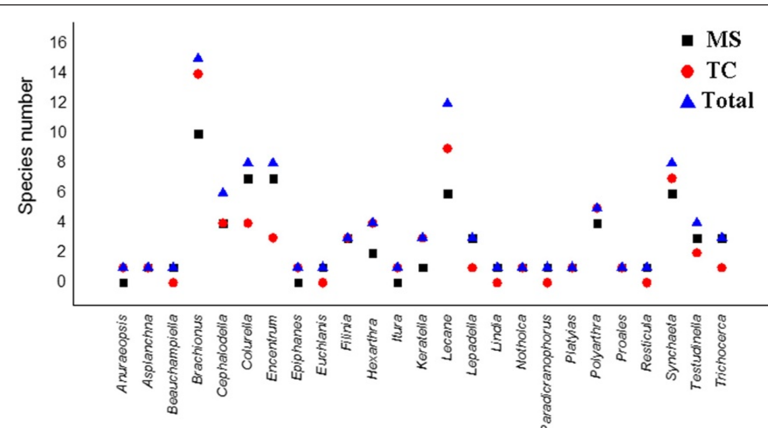

Figure 3 Numbers of species in rotifer genera recorded in mangrove wetlands of Qi'ao Island. MS, mangrove swamp site; TC, tidal creek site; Total, total number of species in rotifer genera at the two sites.

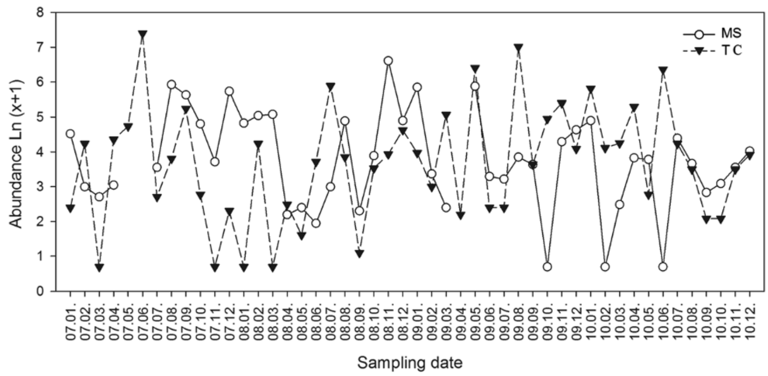

Figure 4 Variations of rotifer abundance at the two sampling sites in mangrove wetlands of Qi'ao Island. Raw data (individuals/L) was Ln ($x + 1$) transformed. MS, mangrove swamp site; TC, tidal creek site.

indica-Filinia longiseta (community D). The communities were represented by the main species of each community, in order of decreasing importance, and their average abundance added together contributed more than 80% to the community.

Since the communities were significantly different between the two sites, the temporal changes were analyzed separately. Seasonal community structure varied significantly at the two sampling sites (MS: $R = 0.311$, $P < 0.1\%$; TC: $R = 0.202$, $0.1\% < P < 5\%$), while no significant annual change was found ($P > 5\%$) (two-way ANOSIM). Annual cyclic change (RELATE) of the communities could be observed in 3 years at MS (2008: $\rho = 0.359$, $0.1\% < P < 5\%$; 2009: $\rho = 0.325$, $0.1\% < P < 5\%$; 2010: $\rho = 0.421$, $P < 0.1\%$), whereas it was only detected in 2007 and 2008 at TC (2007: $\rho = 0.581$, $P < 0.1\%$; 2008: $\rho = 0.503$; $P < 0.1\%$). For serial shift of rotifer communities (RELATE), only 2007 had a serial shift of the faunal communities at MS ($\rho = 0.403$, $0.1\% < P < 5\%$) and 2008 at TC ($\rho = 0.396$, $0.1\% < P < 5\%$), respectively.

BEST/BIOENV analysis of the correlation between rotifer communities and abiotic parameters of the two sampling sites revealed that the higher significant correlation recorded at TC was found only with temperature ($R = 0.417$). While at MS, the group salinity and total nitrogen together correlated with the communities most ($R = 0.246$), of which salinity contributed most ($R = 0.237$).

The correlation between main species (species weight range > 10%) and environmental factors at the two sites is shown in Figure 8. For MS, about half of the main species situated at the bottom left area of the plot, mostly stenohaline and few euryhaline species (Table 2), were associated with high salinity. The other half of the main species, located at the right side, were correlated with high temperature. Besides, one peculiar rare benthic species, *Ecentrum longidens*, was correlated with total nitrogen greatly. For TC, overwhelming majority of the main species arranged at the left side of the plot, mostly planktonic euryhaline or haloxenous species (Table 2), were correlated with high temperature.

Variations in abundance of the most dominant species, which were *Colurella* sp.1 at MS and *Synchaeta cf. kitina* at TC, significantly correlated with total nitrogen ($R = 0.722$, $P < 0.1\%$) and salinity ($R = 0.476$, $P < 0.1\%$), temperature ($R = -0.509$, $P < 0.1\%$), respectively. The next dominant species at MS, *Encentrum marinum*, also correlated with salinity ($R = 0.476$, $P < 0.1\%$) and temperature ($R = -0.509$, $P < 0.1\%$) significantly, which were in accordance with the equations shown in Figure 9.

Discussion

Species composition, diversity, and abundance

Since the sampling methods of the estuarine studies were not consistent, almost all the consulted studies of China were prone to overlook small-sized rotifers because of the improper methods and few papers considering littoral rotifers (Table 1); the discussion based on comparisons in this

Table 3 Average abundance and diversity indexes of rotifer communities at two sampling sites in mangrove wetlands of Qi'ao Island

	Average abundance (individuals/L)	*S*	*D*	*J'*	*H'*
MS	97.0 (1 ~ 742)	6.3 (1 ~ 20)	1.30 (0.00 ~ 3.80)	0.63 (1.19 ~ 0.99)	1.18 (0.00 ~ 2.61)
TC	140.8 (1 ~ 1,636)	5.9 (1 ~ 21)	1.18 (0.00 ~ 3.40)	0.55 (0.02 ~ 1.00)	0.95 (0.00 ~ 2.32)

MS, mangrove swamp site; TC, tidal creek site; *S*, species number; *D*, Margalef's species richness index; *J'*, Pielou's evenness index; *H'*,: Shannon diversity index (base-e logarithm).

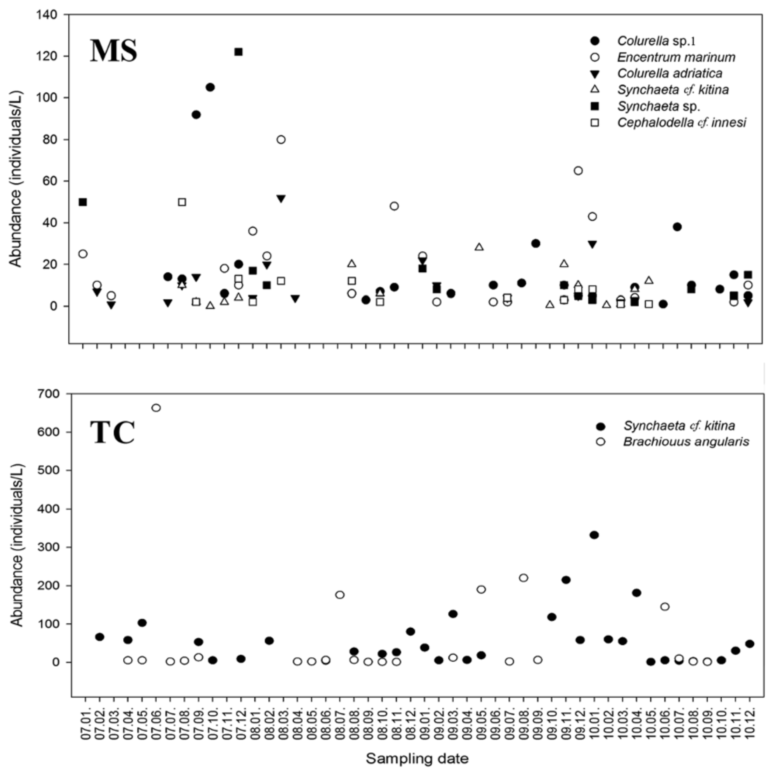

Figure 5 Variations in abundance of main rotifer species at the two sampling sites in mangrove wetlands of Qi'ao Island. MS, mangrove swamp site; TC, tidal creek site.

article was limited but may allow for a general grading of the present results.

The number of rotifer species was much higher than that of the few previous studies which covered rotifers in the Pearl River estuary (maximum 69 species: Tan et al. 2004; Gao et al. 2008a, 2008b, 2010; Hou 2011; Zhang et al. 2012) (Table 1). None of the papers reported any strictly marine species. However, in this study, more than 20 species were recorded (Table 2) according to Fontaneto et al. (2006, 2008) and the measured salinity of their habitats. The average rotifer abundance was more than 20 times higher than the zooplankton reports from Gao et al.

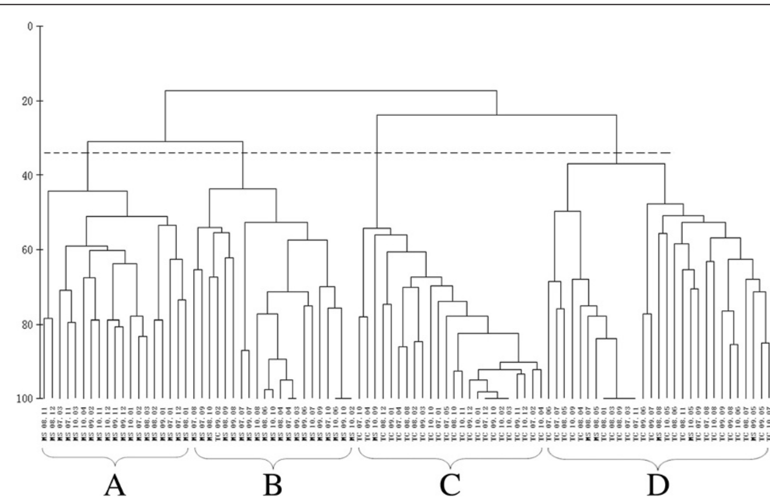

Figure 6 CLUSTER analysis of the rotifer community at the two sampling sites in mangrove wetlands of Qi'ao Island. MS, mangrove swamp site; TC, tidal creek site.

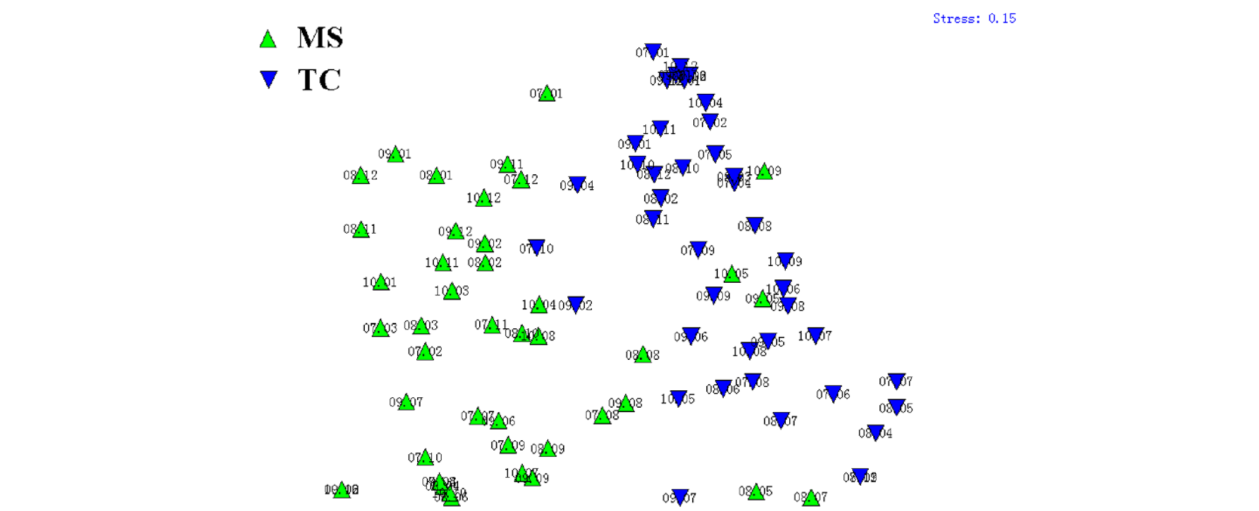

Figure 7 MDS analysis of the rotifer community at the two sampling sites in mangrove wetlands of Qi'ao Island. MS, mangrove swamp site; TC, tidal creek site.

(2008a, 2008b) on the eight outlets of the river (Table 1). When compared with the rotifer data well-documented in the Yangtze River estuary, China, the number of rotifer species (only monogonont rotifers) and abundance in this study were mostly higher too (maximum 103 species: Han and Hu 1995; Wang et al. 1999; Hu et al. 2008). For comparison to some estuaries out of China, the results were similar, especially on strictly haline species (e.g., Egborge 1994; Holst et al. 1998; Lam-Hoai et al. 2006; Rougier et al. 2005; Azémar et al. 2010).

Rotifers in the littoral zone of the two wetlands on Qi'ao Island in the Pearl River estuary had significantly high species diversity and abundance. It may mainly result from (1) suitable sampling methods applied for 4-year-long repeated sampling, (2) widely accepted taxonomy system and up-to-date authoritative references used, and (3) greater environmental heterogeneity and wider spectrum of ecological niches in the littoral zone which may bring higher species richness compared to pelagic area (Lemly and Dimmick 1982; Maia-Barbosa et al. 2008).

Table 4 Differences of the main species in average abundance between the two sampling sites

Species	Average abundance (individuals/L)		Contribution (%)
	MS	TC	
Synchaeta cf. kitina	2.7	37.9	15.31
Colurella sp.1	9.5	0.3	9.53
Colurella adriatica	4.3	0.2	7.87
Encentrum marinum	9.5	0.3	5.75
Brachionus angularis	3.1	30.7	5.55
Synchaeta sp.	6.1	0.0	3.19
Brachionus rotundiformis	0.4	8.1	2.73
Keratella tropica	0.2	7.4	2.33

MS, mangrove swamp site; TC, tidal creek site.

Site difference and temporal variation of community structure

It was indicated that the differences of the communities between the two sites are mainly caused by the abundance of different main species present at the two sites (Table 4). All of the main species of MS - *Colurella* sp.1, *Encentrum marinum*, *Colurella adriatica*, and *Synchaeta* sp. (Figure 5) - had at least more than 20 times higher average abundance than those at TC, while the main species of TC - *Synchaeta cf. kitina*, *Brachionus angularis* (Figure 5), *Keratella tropica*, and *Brachionus rotundiformis* - all presented more than 10 times higher average abundance than those at MS.

Great dissimilarity of the rotifer community detected between MS and TC indicated different biotopes for rotifers (Figures 6 and 7). The MS wetlands, where the depth of the water was no more than 60 cm, mostly about 20 cm with a small water area, were more likely to be occupied by a benthic community in most cases. It can be verified by the ecological characters of the main species present at MS. The most dominant species - *Colurella* sp.1, *Encentrum marinum*, and *Colurella adriatica* (together contributed to the community >70%) - belong to benthic genera (Koste 1978), and the rest of the main species (Figures 5 and 8) mostly are benthic or periphytic living animals, and only few pelagic. Whereas, in the case of TC with much deeper water, definitely a planktonic community, most of the main species (Figure 8) are planktonic, especially the overwhelming

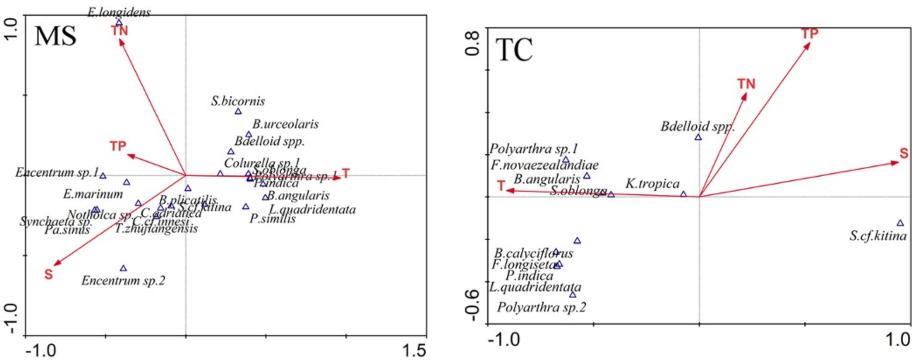

Figure 8 CCA analysis of the correlation between main species and environment factors. Species weight range > 10%. MS, mangrove swamp site; TC, tidal creek site; S, salinity; T, temperature; TP, total phosphorus; TN, total nitrogen.

dominant species *Synchaeta cf. kitina* (contribution = 70.94%). It was probably the main reason contributing to the difference of community structure between the two sites.

Both the BEST/BIOENV and CCA analysis had similar results that salinity and/or temperature were/was the primary decisive factors affecting the community structure in this study. It was similar to many other estuary aquatic systems. For instance, the abundance of planktonic rotifers was positively correlated with temperature and negatively correlated with salinity at Medaomen, one outfall of the Pearl River estuary (Hou 2011), and Huangpu site in upstream of the Pearl River estuary (Wang et al. 2009). Azémar et al. (2010) also found that salinity was the main spatial structuring factor for the Schelde River estuarine rotifer community.

Physiological tolerances of organisms prescribe the environment where survival and reproduction are possible

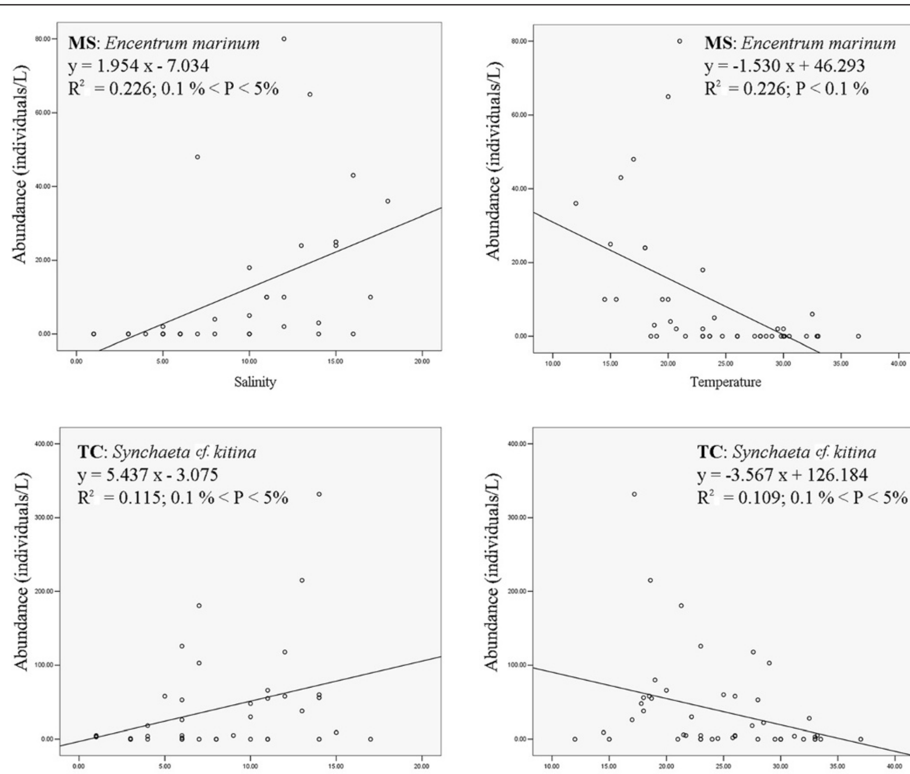

Figure 9 Correlation between *Encentrum marinum* at MS/*Synchaeta cf. kitina* at TC and salinity/temperature. MS, mangrove swamp site; TC, tidal creek site.

(Thorp and Covich 2010). For rotifers, although they have a very wide tolerance range, certainly the differences of dependence on temperature and salinity exist among separate species (Berzins and Pejler 1989; Fontaneto et al. 2006). For example, the species of *Encentrum marinum*, *Notholca* sp., *Synchaeta* sp., and *Paradicranophorus sinus* at MS mostly are present in winter with preference for high salinity and low temperature (Figures 8 and 9), while the *Filinia* and *Polyarthra* species were only found in summer, with preference for low salinity and high temperature (Figures 8 and 9). The alternation of the main species in abundance (Figure 5) influenced by the factors partly results in the temporal succession among the communities of each site (Figure 6). So the variations of abiotic factors might be one of the most important factors to shape the rotifer community structure of Qi'ao Island in the Pearl River estuary temporally; especially, salinity and temperature with strong temporal regularity (Figure 2) significantly correlated with rotifer abundances, particularly with the abundances of the main species (Figures 8 and 9).

The peculiar environment of MS created an unusual situation that the most important abiotic factors detected, temperature and salinity, had an opposite effect on the littoral rotifer communities between MS and TC (Figure 8). It mainly resulted from the fact that the most abundant species *Synchaeta cf. kitina* at TC (Figures 5, 8, and 9) was negatively correlated with salinity and positively correlated with temperature, whereas the majority of the most abundant species at MS - *Encentrum marinum*, *Colurella adriatica*, *Synchaeta cf. kitina*, *Synchaeta* sp., and *Cephalodella cf. innersi* (Figures 5, 8, and 9) - were positively correlated with salinity and negatively correlated with temperature.

The rational explanation for this unusual situation at MS may be as follows: with a low amount of evaporation in winter and being uneasily influenced by tides in dry season which resulted in a relatively stable environment with high salinity at MS, it tended to hold high diversity and abundance of marine species, such as *Encentrum marinum*, *Paradicranophorus sinus*, and *Synchaeta* sp. (Figures 4 and 5), while in summer it became unstable because of the frequent tide actions in rainy seasons and greater evaporation with high temperature, and it inclined to have a low species diversity and abundance (Figure 4). This was verified by the distinct temporal differentiation between community A with higher abundance of more marine species and community B with more euryhaline species (Figures 5 and 6).

Conclusions

This study revealed high diversity and abundance of littoral rotifers at the two close mangrove wetlands of Qi'ao Island in the Pearl River estuary, China. The great community structure differences detected between the two sites mainly resulted from the abundance of different main species present at the two sites, which indicated different kinds of biotopes between the two sites. Community structure varied greatly at all sites seasonally, but there was no significant yearly change. The rotifer communities were correlated with the salinity and total nitrogen group mostly at MS, while temperature contributed mostly at TC.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RLX designed the study. NW carried out the sampling, analyzed the data, and finalized the manuscript. Both authors read and approved the final manuscript.

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