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Geographical Variation in Oligochaete Density and Biomass in Subtropical Mangrove Wetlands of China

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Abstract Oligochaetes play an important role in nutrient cycling and energy flow in benthic food webs as well as in mangrove wetlands. However, they have not been as extensively studied as other macrofaunal groups such as polychaetes, gastropods, bivalves, and crustaceans. Under the assumption that oligochaete density and biomass obey specific geographical distribution patterns in subtropical mangrove wetlands of China, we investigated these two parameters in the Luoyang Estuary of Quanzhou Bay, Zhangjiang Estuary and Gaoqiao mangrove wetlands. A geographical gradient in oligochaete density was present in *Aegiceras corniculatum* and *Kandelia obovata* habitats, whereby it decreased from lower latitudes to higher latitudes. Further, ANOVA tests on oligochaete distribution revealed that both oligochaete density and biomass were significantly influenced by region, season and region × season at the *A. corniculatum* and *K. obovata* habitats. The annual average oligochaete density and biomass at the *A. corniculatum* habitat were higher than that at the *K. obovata* habitat, in both the Luoyang and Zhangjiang estuaries. There were significant correlations between oligochaete density and biomass and sediment particle size parameters, confirming that sand, silt, and clay contents were the key environmental factors affecting oligochaete distribution.

Key words oligochaete; distribution; mangrove wetlands; China

1 Introduction

Mangroves are typically considered as one of the most productive ecosystems in the world, but the contribution of resident mangrove macrofauna has rarely been discussed in terms of ecosystem function (Lee, 2008). Benthic macrofauna represent a key structural element of estuarine trophic webs, and plays an important role in the dynamics of these systems (Ysebaert *et al*., 1998; Kanaya and Kikuchi, 2008). Mangroves located along estuaries are important habitats and commonly support an abundant and diverse community of benthic invertebrates, which may serve as a food source for resident and transient fauna (Kristensen *et al*., 2008).

Many species of marine oligochaetes along the Chinese coast have been described in the last thirty years. Twenty-one estuarine and marine species of Tubificidae (Oligochaeta) were reported in Hong Kong and the New Territories of Hong Kong (Erséus, 1984). Fifty-two species of marine and brackish-water oligochaetes were reported to be unique to Hong Kong and the New Territories (Erséus, 1990). Thirteen species of marine and brackish-water Oligochaeta were also described there (Erséus, 1993). Two species of oligochaetes, *Ainudrilus geminus* and *Doliodrilus longidentatus*, were reported only in Hong Kong as well (Erséus, 1997). Six species of Phallodrilinae were reported at Hainan Island in southern China (Wang and Erséus, 2001). Two species of oligochaetes, *Limnodrilus hoffmeisteri* and *Limnodrilus claparedianus*, were reported in Shenzhen Bay (Wu *et al*., 2002). Six species of Rhyacodrilinae (Oligochaeta: Tubificidae) were reported in intertidal and shallow water subtidal habitats around Hainan Island in southern China (Wang and Erséus, 2003， 2004). Further, a new species was reported in Hong Kong mangroves and adjacent foreshore sandflats (Zhou and Erséus, 2003). Finally, a total of 18 species of oligochaetes were reported in Shenzhen Bay (Cai, 2015).

Oligochaetes are relatively poorly understood in comparison to other macrofaunal groups such as polychaetes, gastropods, bivalves and crustaceans. Along the Brazilian coast, no tropical or subtropical geographic sectors have ever been systematically investigated (Prantoni and Domênico, 2014). Along the Fujian and Guangdong coasts of southern China, only a few studies focusing on the distribution of oligochaete density and biomass in

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mangrove wetlands or intertidal zones have been conducted (Cai *et al*., 2001; Zhou *et al*., 2010). Accordingly, we analyzed oligochaete density and biomass from three subtropical mangrove wetlands, in order to understand their distribution patterns. The relationships between oligochaete density and biomass and sediment particle size parameters were also analyzed.

2 Materials and Methods

2.1 Study Area

In this study, oligochaete density and biomass inthe Luoyang Estuary of Quanzhou Bay, Zhangjiang Estuary, and Gaoqiao mangrove wetlands were analyzed (see Fig.1).

The Luoyang Estuary mangrove wetland is in Quanzhou Bay of Fujian and is located in the Quanzhou Bay Estuarine Wetland Provincial Nature Reserve (118˚37΄−118˚42΄E, 24˚47΄−24˚59΄N). Two mangrove habitats, dominated by *Aegiceras corniculatum* and *Kandelia obovata*, were selected for sampling.

The Zhangjiang Estuary mangrove wetland is located in southern Fujian, within the Zhangjiang Estuary Mangrove National Nature Reserve (117˚24΄−117˚30΄E, 23˚53΄−23˚56΄N). Here, three mangrove habitats, dominated by *Aegiceras corniculatum* or *Kandelia obovata*, were selected.

The Guangdong Gaoqiao mangrove wetland is located in the Shamao Estuary, Yingluo Harbor, in the Zhanjiang Mangrove National Nature Reserve (109˚40΄−110˚35΄E, 20˚14΄−21˚35΄N). A single *Aegiceras corniculatum* habitat was selected for sampling.

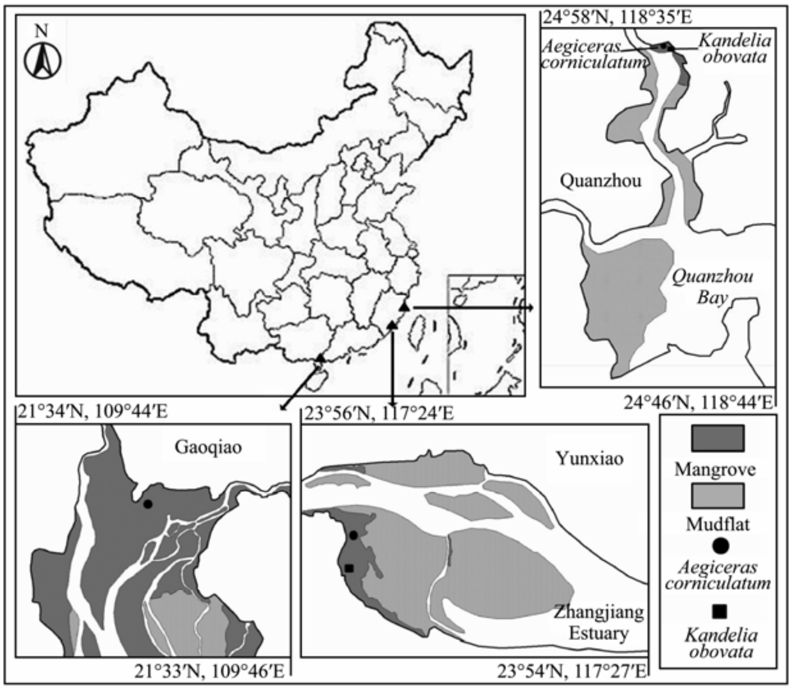

Fig.1 Geographic locations of the three estuarine mangrove wetlands selected for study along the Chinese coast.

2.2 Sampling of Oligochaete Annelids

The two mangrove habitats in Luoyang Estuary were investigated in 2011 (Guo *et al*., 2014), while the remainder in Zhangjiang Estuary and Guangdong Gaoqiao were investigated in 2010 (Cai *et al*., 2012; Chen *et al*., 2012). Benthic macrofauna (including oligochaetes) in all habitats were collected in four seasons, namely, in winter (January), spring (April), summer (July), and autumn (October).

Five quadrat samples (25×25 cm^2) were used for sample collection in each selected habitat (under mangrove trees) at low tide at each sampling time in each of the mangrove wetlands. Sediment samples for benthic macrofauna (including oligochaetes) analyses were washed through a 0.5 mm mesh size sieve, fixed in 5% formalin and seawater solution in the field, and then taken to the laboratory for sorting (Cai *et al*., 2012; Chen *et al*., 2012; Guo *et al*., 2014). After sorting, the benthic macrofauna were identified under a dissecting or compound microscope, classified to the lowest possible taxonomic level, counted, and weighed with an electronic balance (0.1 mg precision).

2.3 Data Analysis

All statistical analyses were conducted with SPSS 13.0 statistical software. Oligochaete density and biomass (fresh weight) were expressed as ind m^{-2} and g m^{-2}, respectively, at each sampling quadrat. Univariate two-way ANOVA was used to investigate differences among the regions (Luoyang Estuary, Zhangjiang Estuary and Gaoqiao Guangdong) or among habitats and seasons (winter, spring, summer and autumn) for oligochaete density and biomass. A Tukey HSD multiple comparisons test was used in pair-wise comparisons of samples, in order to explore statistically significant differences in oligochaete density and biomass. The sediment variables were temperature (℃), salinity, sand, silt and clay. Pearson coefficients of correlation were calculated to investigate the relationships between oligochaete density and biomass and sediment variables.

3 Results

3.1 Density and Biomass of Oligochaete Animals in the *A. corniculatum* Habitat

The annual average densities of oligochaete animals at the *A. corniculatum* habitat were 284.9 ind m^{-2}, 389.6 ind m^{-2} and 3596.8 ind m^{-2}, respectively, in Luoyang Estuary, Zhangjiang Estuary and Gaoqiao Guangdong (Fig.2). Thus, a geographical gradient in oligochaete density was observed in the three regions, whereby oligochaete density decreased from lower latitudes to higher latitudes. Futher, ANOVA tests revealed that oligochaete density was significantly influenced by region, season and region × season at the *A. corniculatum* habitat (Table 1).

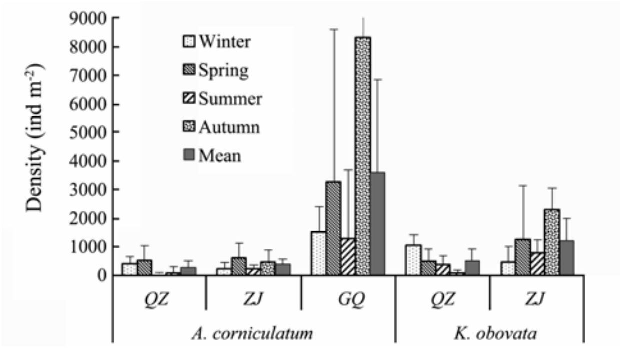

Fig.2 The density of oligochaetes at three locations and in four seasons (QZ, Quanzhou Bay Luoyang Estuary; ZJ, Zhangjiang Estuary; GQ, Gaoqiao).

Table 1 ANOVA tests of density and biomass of oligochaetes at the studied locations in subtropical mangrove wetlands of China

Habitat or region, season		*df*	Density		Biomass	
			F	*P*	*F*	*P*
Aegiceras corniculatum habitat	Region	2	17.001	<0.001[c]	39.173	<0.001[c]
	Season	3	4.763	0.005[b]	3.714	0.018[a]
	Region × Season	6	4.702	0.001[b]	4.203	0.002[b]
Kandelia obovata habitat	Region	1	25.476	<0.001[c]	13.459	<0.001[c]
	Season	3	3.511	0.026[a]	4.580	0.009[b]
	Region × Season	3	17.864	<0.001[c]	7.762	<0.001[c]
Two mangroves in Luoyang Estuary	Habitat	1	7.397	0.010[b]	14.916	0.001[b]
	Season	3	10.774	<0.001[c]	14.216	<0.001[c]
	Habitat × Season	3	3.419	0.029[a]	2.272	0.099
Two mangroves in Zhangjiang Estuary	Habitat	1	32.790	<0.001[c]	18.854	<0.001[c]
	Season	3	10.574	<0.001[c]	7.441	0.001[b]
	Habitat × Season	3	5.855	0.003[b]	2.837	0.054

Notes: [a] significant at the 0.05 level; [b] significant at the 0.01 level; [c] significant at the 0.001 level.

The annual average biomass of oligochaetes was 0.0475 g m^{-2}, 0.0879 g m^{-2} and 1.2515 g m^{-2}, respectively, at Luoyang Estuary, Zhangjiang Estuary and Gaoqiao Guangdong (Fig.3). The geographical gradient in oligochaete biomass was similar to that in oligochaete density: the higher the latitude, the lower the biomass of oligochaetes.

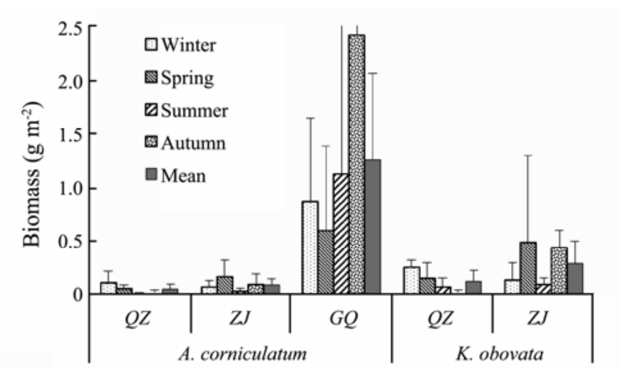

Fig.3 The biomass of oligochaetes in three regions and in four seasons (QZ, Quanzhou Bay Luoyang Estuary; ZJ, Zhangjiang Estuary; GQ, Gaoqiao).

3.2 Density and Biomass of Oligochaete Animals in the *K. obovata* Habitat

The annual average densities of oligochaetes at the *K. obovata* habitat were 516.8 ind m^{-2} and 1208.8 ind m^{-2} in Luoyang Estuary and Zhangjiang Estuary, respectively (Fig.2). Thus, the oligochaete density in the *K. obovata* habitat in Zhangjiang Estuary was higher than that in the *K. obovata* habitat in Luoyang Estuary. In other words, the oligochaete density was inversely correlated to latitude in the *K. obovata* habitats. Tests using ANOVA revealed that oligochaete density was significantly influenced by region, season and region × season in the *K. obovata* habitats (Table 1).

The annual average biomass of oligochaetes was 0.1222 g m^{-2} and 0.2890 g m^{-2}, respectively, in Luoyang Estuary and Zhangjiang Estuary (Fig.3). The geographical gradient in oligochaete biomass mirrored that described previously for density. Similarly, ANOVA tests revealed that oligochaete biomass was significantly influenced by region, season and region × season in the *K. obovata* habitats (Table 1).

3.3 Comparison of the Density and Biomass of Oligochaetes Between Mangrove Habitats

In Luoyang Estuary, the annual average densities of oligochaets in the *A. corniculatum* and *K. obovata* habitats were 284.8 ind m^{-2} and 516.8 ind m^{-2}, respectively (Fig.2). Tests using ANOVA revealed that oligochaete density was significantly influenced by habitat, season and habitat × season (Table 1). The annual average biomass of oligochaetes in the *A. corniculatum* and *K. obovata* habitats was 0.0475 g m^{-2} and 0.1222 g m^{-2}, respectively (Fig.3). In this case, ANOVA tests revealed that, oligochaete biomass was significantly influenced by habitat and season (Table 1).

In the Zhangjiang Estuary, the annual average densities of oligochaetes in the *A. corniculatum* and *K. obovata* habitats were 389.6 ind m^{-2} and 1208.8 ind m^{-2}, respectively (Fig.2). Tests of ANOVA indicated that oligochaete density was significantly influenced by habitat, season and habitat × season (Table 1). The annual average biomass of oligochaetes in the *A. corniculatum* and *K. obovata* habitats was 0.0879 g m^{-2} and 0.2890 g m^{-2}, respectively (Fig.3). Based on ANOVA, oligochaete biomass was significantly influenced by habitat and season (Table 1).

To summarize, the annual average oligochaete density and biomass in the *A. corniculatum* habitat were higher than at the *K. obovata* habitat in both the Luoyang and Zhangjiang Estuaries.

3.4 Relationships Between Oligochaetes and Sediment Environment

Sediment temperature was highest in summer and lowest in winter. Overall sediment temperature at the *A. corniculatum* habitat was highest in Luoyang Estuary and lowest at Gaoqiao (Fig.4). Tests based on ANOVA revealed that sediment temperature was significantly influenced by region, season and region × season in both *A. corniculatum* and *K. obovata* habitats (Table 2).

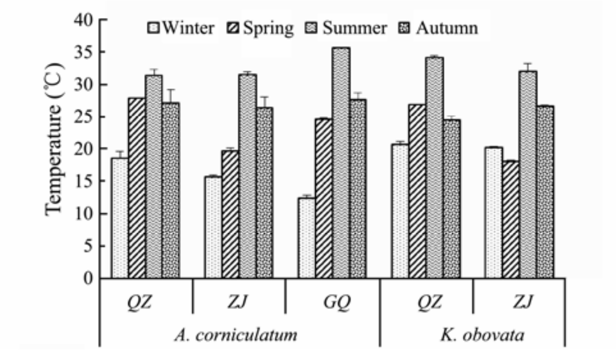

Fig.4 Sediment temperatures in the *A. corniculatum* and *K. obovata* habitats across seasons (QZ, Quanzhou Bay Luoyang Estuary; ZJ, Zhangjiang Estuary; GQ, Gaoqiao).

Sediment salinity was typically highest in winter and lowest in summer. In all seasons but winter, sediment salinity in the *A. corniculatum* habitat was lowest in the Zhangjiang Estuary (Fig.5); ANOVA tests revealed that salinity was significantly influenced by region, season and region × season in both the *A. corniculatum* and *K. obovata* habitats (Table 2).

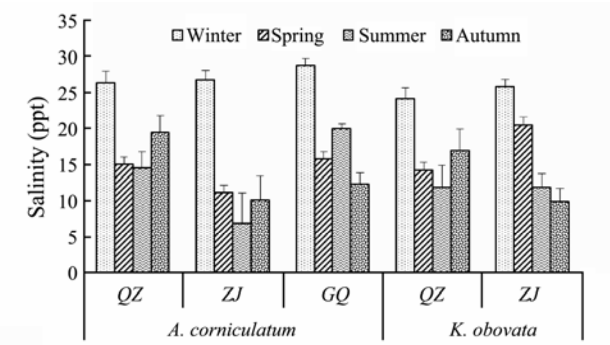

Fig.5 Sediment salinity in the *A. corniculatum* and *K. obovata* habitats across seasons (QZ, Quanzhou Bay Luoyang Estuary; ZJ, Zhangjiang Estuary; GQ, Gaoqiao).

Table 2 ANOVA tests on sediment temperature and salinity in the subtropical mangrove wetlands selected for study

Habitat or Region, Season		*df*	Temperature		Salinity	
			F	*P*	*F*	*P*
Aegiceras corniculatum habitat	Region	2	48.432	<0.001[c]	46.667	<0.001[c]
	Season	3	853.552	<0.001[c]	167.997	<0.001[c]
	Region × Season	6	44.205	<0.001[c]	15.432	<0.001[c]
Kandelia obovata habitat	Region	1	395.893	<0.001[c]	0.178	0.676
	Season	3	1395.275	<0.001[c]	101.846	<0.001[c]
	Region × Season	3	190.575	<0.001[c]	22.610	<0.001[c]
Both mangroves in Luoyang Estuary	Habitat	1	0.815	0.373	10.227	0.003[b]
	Season	3	349.152	<0.001[c]	72.344	<0.001[c]
	Habitat × Season	3	20.218	<0.001[c]	0.430	0.733
Both mangroves in Zhangjiang Estuary	Habitat	1	0.100	0.754	22.927	<0.001[c]
	Season	3	804.109	<0.001[c]	126.995	<0.001[c]
	Habitat × Season	3	3.925	0.017[a]	12.014	<0.001[c]

Notes: [a] significant at the 0.05 level; [b] significant at the 0.01 level; [c] significant at the 0.001 level.

The contents of sand, silt and clay were highest in the *A. corniculatum* habitats across all regions. In all sampling locations, silt contents exceeded 70% (Fig.6).

In the *A. corniculatum* habitat, there were significant positive correlations between oligochaete density/biomass and sand content. However, biomass was significantly negatively correlated to silt content. There were no significant correlations of oligochaete density and biomass with sediment temperature or salinity (Table 3).

In the *K. obovata* habitat, there were significant positive correlations of oligochaete density and biomass with silt content, while a significant negative correlation was detected between oligochaete density/biomass and clay content. Additionally, there was a significant negative correlation between oligochaete biomass and sediment temperature (Table 3).

Table 3 Correlation coefficients between oligochaetes and sediment environmental factors in the *Aegiceras corniculatum* and *Kandelia obovata* habitats in subtropical mangrove wetlands of China

Habitat		T	S	Sand	Silt	Clay
A. corniculatum habitat ($n=60$)	Density	0.069	−0.096	0.418**	0.385**	−0.168
	Biomass	0.095	0.008	0.662**	0.391**	−0.184
K. obovata habitat ($n=40$)	Density	−0.078	−0.168	−0.048	0.455**	−0.432**
	Biomass	−0.130	0.084	−0.048	0.421**	−0.398*

Notes: **significant at the 0.01 level; *significant at the 0.05 level.

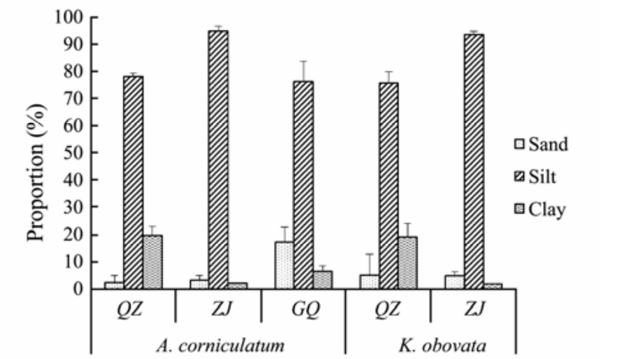

Fig.6 The proportions of sand, silt and clay in the *A. corniculatum* and *K. obovata* habitats (QZ, Quanzhou Bay Luoyang Estuary; ZJ, Zhangjiang Estuary; GQ, Gaoqiao).

4 Discussion

4.1 Influence of Temperature and Salinity on Oligochaete Density and Biomass

Carrol and Dorris (1972) reported that the reproductive season of *Branchiura sowerbyi* was during the period March to September, with temperature, DO, and organic matter content all influencing reproduction. Increasing temperature causes an increase in the egg laying rate, which peaks at 25℃ (Aston, 1973). At a sediment temperature between 20℃ and 25℃, the number of eggs of the freshwater oligochaete *Tubifex tubifex* displayed a logistic increase (Li, 2001; 2003). Within a temperature range of 15 to 30℃, the growth rate of *Aeolosoma hemprichi* increased with elevated temperature but decreased when the temperature was 35℃ (Liang *et al*., 2004). There were very significant differences in density and biomass of oligochaetes between seasons (Zhu *et al*., 2008). It can be concluded that temperature is a key environmental factor affecting oligochaete reproduction and their geographical distribution. However, this does not explain the lack of significant correlations between oligochaete density/biomass and temperature in both the *K. obovata* and *A. corniculatum* habitats in our study. This may be attributed to the fact that sediment temperature was measured at different times of the day (and on different days) across the sampled regions and habitats. For example, the sediment temperature in the *A. corniculatum* habitat in winter decreased from lower latitudes to higher latitudes, which should imply that the highest and lowest temperatures would have been recorded at Gaoqiao and Luoyang Estuary, respectively. However, our observations indicated the reverse (Fig.4). Winter in southeastern China is characterized by significant diurnal temperature variation. A geographical gradient in oligochaete density and biomass was observed in the *A. corniculatum* habitat in the present study. Oligochaete density and biomass decreased from lower latitudes to higher latitudes, namely from Gaoqiao to Quanzhou Bay Luoyang Estuary. This mirrored the distribution of oligochaete species richness. Marine oligochaetes exhibit greater species richness in southern than in northern China (Wang and Erséus, 2001). Increasing latitude was also correlated to higher temperatures within the season. Therefore, our results confirm that temperature affected oligochaete density and biomass. An inverse geographical gradient in temperature was observed in the *A. corniculatum* habitat in the present study, which indicates that temperature data were not comparable across habitats or regions due to discrepancy in observation times.

The absence of significant correlations of oligochaete density and biomass with salinity, in both the *K. obovata* and *A. corniculatum* habitats, remains puzzling. This may be attributed to differences in salinity across the three regions, particularly in summer. Therefore, oligochaete density and biomass in the *A. corniculatum* habitat in Gaoqiao were higher than in the Zhangjiang Estuary and Luoyang Estuary, in both summer and winter.

4.2 Sediment Particle Size as a Key Determinant of Oligochaete Density and Biomass

There were significant correlations of oligochaete density and biomass with silt content in both the *A. corniculatum* and *K. obovata* habitats. Most of the oligochaetes observed were brackish and soft mud species. *Ainudrilus lutulentus* has been reported in the intertidal and subtidal zones of Hong Kong from soft mud to coarse sand, generally in brackish waters (Wang and Erséus, 2003). Lee (1993) recorded five species of oligochaetes from the marshes of Mai Po, Hong Kong, including *Limnodriloides biforis*, *Limnodriloides fraternus*, *Tectidrilus achaetus* and *Rhizodrilus russus*. All of these were distributed in brackish water and freshwater soft sediments. *Doliodrilus tener* is commonly distributed in estuarine intertidal soft mud and muddy sand (Erséus, 1990). There was no significant correlation between oligochaete density/biomass and clay content in the *A. corniculatum* habitat. This was consistent with that observed in high-organic-matter mudflats in Shenzhen and Hong Kong

(Cai *et al.*, 2001, 2013).

4.3 Differences in Macrofauna Between the *A. corniculatum* and *K. obovata* Habitats

Our results indicated that the annual average oligochaete density and biomass in the *A. corniculatum* habitat were lower than in the *K. obovata* habitat; this was evident in both the Luoyang Estuary and in the Zhangjiang Estuary. Few studies have explored the influence of mangrove habitat on oligochaete density and biomass, as most have focused on macrofauna. In the Zhangjiang Estuary, the annual average polychaete density and biomass in the *A. corniculatum* habitat were higher than in the *K. obovata* habitat (Chen *et al.*, 2012); these were inversely proportional to the distribution of oligochaetes. The crab burrows in the *A. corniculatum* habitat were deeper than those in the *K. obovata* habitat, and the opening diameter of the crab burrows in the *A. corniculatum* habitat were larger than those in the *K. obovata* habitat (Wang *et al.*, 2014). In Luoyang Estuary, although the mean macrofaunal biomass in the *K. obovata* habitat was higher than that in the *A. corniculatum* habitat, the species number, density, diversity index (H'), evenness index (J) and richness index (d) in the *A. corniculatum* habitat were all higher than those in the *K. obovata* habitat (Guo *et al.*, 2014). Mangroves are beneficial to oligochaetes such as *Limnodriloides* sp. that thrive in sediments with high total organic matter (TOM) (Zhou and Cai, 2010). A significant correlation was observed between oligochaete density in the sediments and aqueous NO_3-N and NH_4-N concentrations (Armendáriz *et al.*, 2012). The animal assemblages in the *A. corniculatum* habitat were different from those in the *K. obovata* habitat across different taxonomic groups and regions.

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