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# Seasonal and Spatial Variations of Macro Benthos in the Intertidal Mudflat of Southern Yellow River Delta, China in 2007/2008

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**Abstract** In order to examine the seasonal and spatial distributions of benthic animals in the intertidal mudflat of the southern Yellow River Delta, field investigations were carried out in 2007 and 2008 and multiple methods were applied. Results showed that, the biomass of macro benthos ranged at 0.75−1151.00 g wet m$^{-2}$ and averaged at 156.31 g wet m$^{-2}$, in which *Mactra veneriformis* accounted for 75.6%–93.4% of the total macro benthic biomass. More than 90% of macro benthos inhabited in the middle and low tide lines, and higher biomass occurred in early summer and lower in winter. Statistical analysis showed that: 1) *M. veneriformis* growth was primarily favored at higher temperature and lower salinity; 2) after long time interaction, benthic bivalve grazers led to patching distributions of Chlorophyll *a* (Chl *a*); 3) macro benthic biomass positively related with Chl *a* when the concentration of Chl *a* was low, but they were negatively related when Chl *a* concentration was high; and 4) furthermore, the biomass of benthic bivalves peaked in the sediment with median grain size about 0.55 mm, but decreased gradually in coarse or fine sediments. The secondary productivity ranged at 0.37−283.68 g m$^{-2}$yr$^{-1}$ and averaged at 47.88 g m$^{-2}$ yr$^{-1}$, in which 69.7% was contributed by *M. veneriformis* It was estimated that primary production was transformed to secondary production at a rate of 6.87% approximately, which implies that there is a local sustainability of high bivalve production.

**Key words** macro benthos; *Mactra veneriformis*; distribution; intertidal mudflat; southern Yellow River Delta

## 1 Introduction

The temperate intertidal mudflats were characterized by high productivity and dominated by invertebrate (Pinckney and Zingmark, 1993; McLusky and Elliott, 2004). Bivalves play a key role as the primary consumer in these areas and control vital balance between organic matters and predators, as well as benthic and aquatic food webs (Heip *et al.*, 1995). Therefore, many researches have examined the compositions and distributions (Fortin *et al.*, 2002; Legendre and Legendre, 2012), dynamics (Blanchard 1990; Guarini *et al.*, 1998; Kostylev and Erlandsson, 2001; Seuront and Spilmont, 2002; Weerman *et al.*, 2011; Benoit-Bird and McManus, 2012; Benoit-Bird *et al.*, 2013 a, b; Rameshkumar and Rajaram, 2017), and feeding-predating relationship (Sims *et al.*, 2008; Reynolds and Rhodes, 2009; Benoit-Bird and McManus, 2012; Beninger and Boldina, 2014) of intertidal benthos. Meanwhile, abiotic factors were also investigated as associated with abundance, composition, and structure of benthic animals (Miller *et al.*, 1996).

The Yellow River, originating from the Loess Plateau and discharging into the Bohai Sea, ranks at the top 6th of the world's largest river in length, the 20th in water discharge (McKee *et al.*, 2004), and the 1st in particle discharge (1.05×10$^7$tons yr$^{-1}$) (Cui *et al.*, 2009). Thus, a Yellow River Delta (YRD) as well as a broad intertidal mudflat, has been developed at the rates of 0.08−0.30 km yr$^{-1}$ (Qiao and Shi, 2010). The mud in the intertidal flat is comparatively course with a median grain size of 0.025–0.081 mm and low content of organic carbon (0.1%–0.5%), while the nutrients are abundant and higher primary productivity have been discovered spontaneously (Yao *et al.*, 2010; Zhang *et al.*, 2011). As a key species of

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macro benthos in middle and low intertidal mudflats in North China (Han *et al*., 2014; Zhang *et al*., 2016), the southern intertidal mudflat of YRD is abundant in *Mactra veneriformis*, but it has been unclear how the temporal and spatial distributions of *M. veneriformis* vary in the intertidal YRD.

In 2007 and 2008, field investigation was carried out in order to examine: 1) temporal and spatial variations of benthic biomasses in the intertidal mudflat of southern YRD, 2) factors affecting the benthic biomasses, and 3) the secondary production and appropriate transformation efficiency from primary production to macro benthos.

## 2 Materials and Methods

### 2.1 Study Area and Sampling Sites

The intertidal mudflat of the southern YRD, which locates at the South-East Bohai, North China, is greatly impacted by the Yellow River. In this study, three sections were selected in the middle of the southern YRD, which covers an area about 6 km long and 3–5 km wide off the coastline (Fig.1). Samples were collected from 11, 10 and 7 sites along Sections A, B and C, depending on the distance between high and low water lines. One time series station (L) was close to the middle water line at Section B.

Three cruises were carried out in spring tide period, in order to cover the intertidal region as wide as possible in September, 2007, and April and July, 2008. The time series station was monitored every month from July 2007 to July 2008 except January and February 2008 due to ice coverage. Samples were collected from near shore to off shore areas by following the tide cycle and surface sediment exposure time. The furthest sample was collected on the low water line in low tidal region.

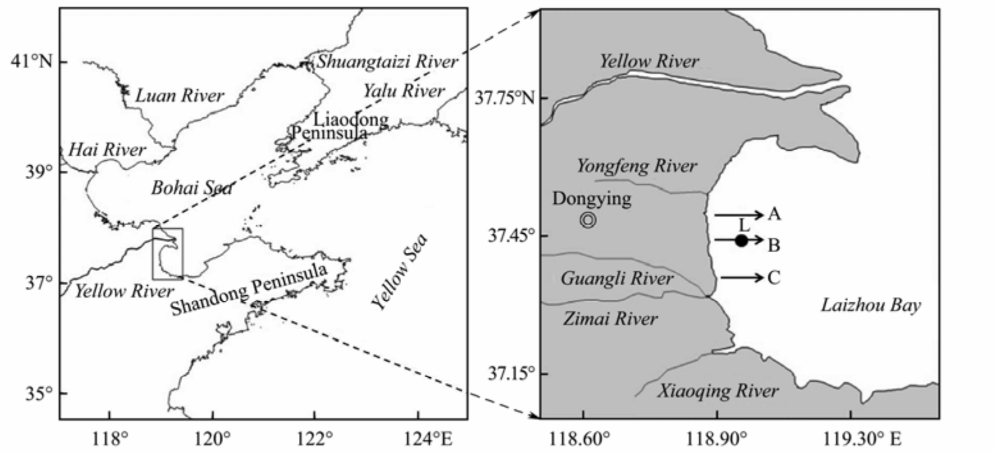


Fig.1 Study area and sampling sites in the intertidal area of the southern Yellow River Delta.

### 2.2 Sampling Methods

Muds were first collected with an Eckmane Birge grab sampler (24 by 24 cm area to a depth of 30 cm), and then flushed through a 1 mm mesh sieve. Benthic macro fauna, including *M. veneriformis*, on the sieve were fixed with 10% formalin. The sampling was duplicated at every station. Bivalve *M. veneriformis* for isotope analysis was kept frozen until laboratory analysis. Surface sediments (0–1 cm) were collected and kept frozen for Chl *a* and grain size analyses.

### 2.3 Biomass Analysis of Macro Benthos and *Mactra veneriformis*

Macrobenthic animals were sorted, counted, and weighted (excess waters were removed with blotting paper) into three groups, which were bivalve – *M. veneriformis*, shellfish (shells except *M. veneriformis*) and the others (non shells), using a magnifying glass.

### 2.4 Chl *a* Analysis

Chl *a* samples were thawed in room temperature, extracted with 90% acetone at 4℃ in dark overnight, and measured by fluoresce spectrometry. Pure Chl *a* (Sigma) were quantified by spectrometry (Jeffery and Humphrey, 1975) and then diluted as standard for fluorescence spectrometry (Hitachi F-4500, Germany).

### 2.5 Statistical Analysis

Pearson's correlation analysis (PCA) was used to evaluate the relationships between benthic biomass and environmental factors with SPSS software (version 18.0, SPSS Inc.).

## 3 Results and Discussion

### 3.1 Distribution of Macro Benthic and *M. veneriformis* Biomasses

Macro benthos were sorted as three groups: *M. veneriformis* (*M.v.*), shells except *M. veneriformis* (shells except *M.v.*) and non-shells. 15 species of macro benthos were identified: polychaetes (5 species), mollusca (6 species) and Crustacea (3 species). The total biomass (Fig.2) of macro benthos in September, 2007, April and July, 2008 were 0.72–574.44, 1.28–814.08 and 15.14–1151.00 g wet $m^{-2}$ and averaged at 87.88, 164.56 and 261.80 g wet $m^{-2}$. The biomass of *M. veneriformis* accounted for 75.6%–

91.3%, 79.5%–93.4% and 81.2%–91.1% of the total biomass of macro benthos, correspondingly.

Monthly biomass of macro benthos at time series station from August 2007 to July 2008 varied among 36.96–655.57 g wet m$^{-2}$, with an average of 301.37 g wet m$^{-2}$ (Fig.3). The biomass in June, July and August reached high levels as 500 gww m$^{-2}$, followed by those in April at about 450 g wet m$^{-2}$, and decreased below 50 g wet m$^{-2}$ in March and December at last. A difference of 16 times was observed between the higher biomass in August and lower in December. Same as the seasonal biomass pattern, monthly benthic biomass was primarily contributed by *M. veneriformis* which was more than 50%, and even close to 100% in March and November.

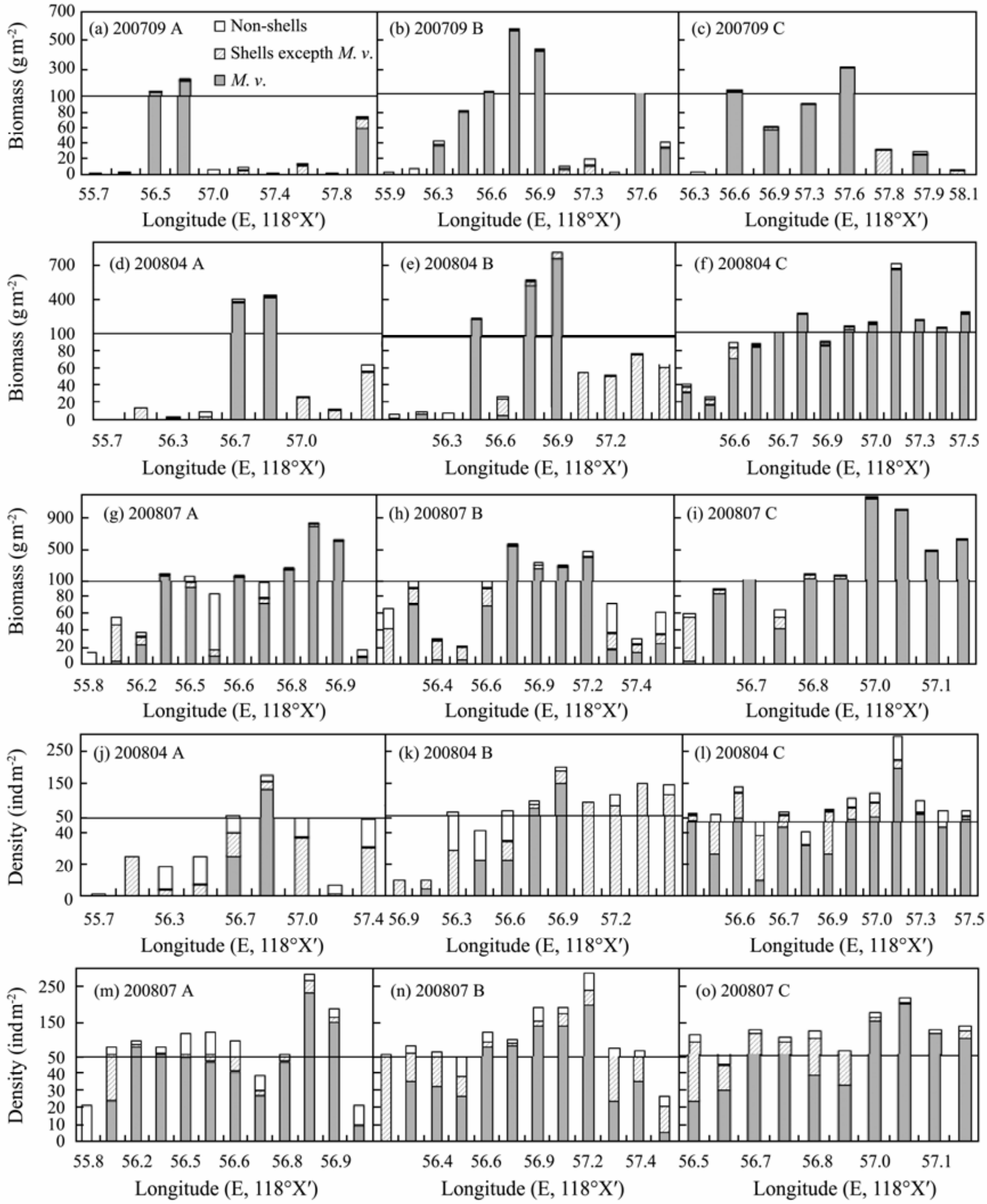


Fig.2 Biomass and density of macro benthos in the intertidal mudflat of the southern Yellow River Delta.

Macro benthic density ranged at 12–868 ind m$^{-2}$ (Fig.3). The highest density was observed in August, followed by that in July (50.0% of the density in August), and then lower in the other months. *M. veneriformis* accounted for 17.6%–100.0% of the total density, in which higher percentages in March and November, followed by April and June, and then as low as 17.6%–34.0% from July to September. Although the relative density of *M. veneriformis* decreased, *M. veneriformis* biomass increased and kept as the dominant in July and August.

Macro benthic biomass varied largely with locations and sedimentary conditions. It was reported that, the macro benthic biomass averaged at 35.28 g m$^{-2}$ in the estuarine sediment of YRD (Zhang *et al.*, 1990), which located in the north of study area, and 7.96 g m$^{-2}$ in the Bohai Sea (Yu *et al.*, 2001), which was at eastward location from study area. The macro benthic biomass varied among 22.10 and 257.30 g m$^{-2}$ in the intertidal flats southward from YRD along the coastal line of North-West Pacific Ocean (Gao *et al.*, 2009; Cai *et al.*, 1980; Shao *et al.*, 1980), in which the largest estuarine intertidal flat of Yangtze River was included (44.54 g m$^{-2}$, Gao *et al.*, 2009). However, the maximum macro benthic biomass might reach 782.5 g m$^{-2}$ in Shuangtaizi River estuary (Zhang *et al*., 2016). Meanwhile, in Sato Sea, Japan, located in similar latitude, the macro benthic biomass ranged at 0.4–78.8 g m$^{-2}$ in coastal area (Yamaguchi *et al.*, 2007). Mostly dominated in the sand flat of Midori River Estuary, Kyushu, Japan, *M. veneriformis* accounted for 15.2%–28.4% of total numerical composition (Yamaguchi *et al.*, 2004). It appears that macro benthic biomass stood at a higher level in the intertidal mudflat of YRD, compared with other locations. This higher benthic biomass was likely related to and attributed by the aquaculture of *M. veneriformis* in the southern mudflat of YRD, sowing every spring and growing naturally. Then, two questions are arisen: who supported the higher benthic biomass, and would this higher benthic biomass be sustained?

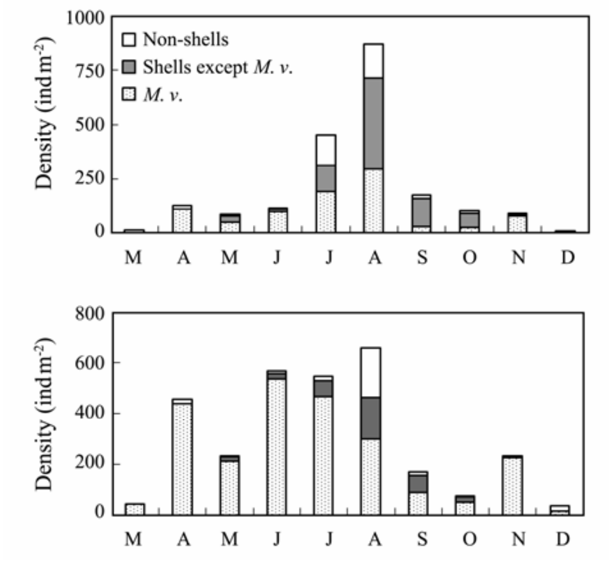

Fig.3 Monthly density and biomass of macro benthos in the intertidal mudflat of southern Yellow River Delta.

Similar patterns on the biomass distribution of macro benthos in September, 2007, April and July, 2008 were observed: the biomass increased from high tide line to middle tide line and then decreased to the low tide line gradually. About 100 times difference was seen between the high and low total biomass, especially to *M. veneriformis*. *M. veneriformis* was hard to be found in high tide area, but it was abundant in middle and low tide areas, accounting for over 90% of the total biomass. This distribution pattern of *M. veneriformis* was consistent with its habitat of coastal mudflat in middle and low tide areas (Yuan *et al.*, 2006). But it was a little seaward shift compared with those fitted in middle to high tide areas in the sand flat of Midori River Estuary, Japan (Yamaguchi *et al.*, 2004). The total density of macro benthos kept at a similar level from high to middle and then to low tide areas, except several episodic sites in low and high tide areas.

### 3.2 Factors Affecting the Macro Benthic Biomass

Multiple factors influence the growth and distribution of macro benthos and bivalves. Based on the spontaneously monitoring parameters, the relationship between the macro benthic biomass and temperature, salinity, sediment grain size, pH and Chl *a* were analyzed by PCA method (Fig.4). It was revealed that, temperature was the most positively related with macro benthic biomass ($r$= 0.8159). Salinity followed and negatively influenced the macro benthic biomass ($r$ = −0.6152), suggesting that macro benthic animals preferred higher temperature but lower salinity in a certain range.

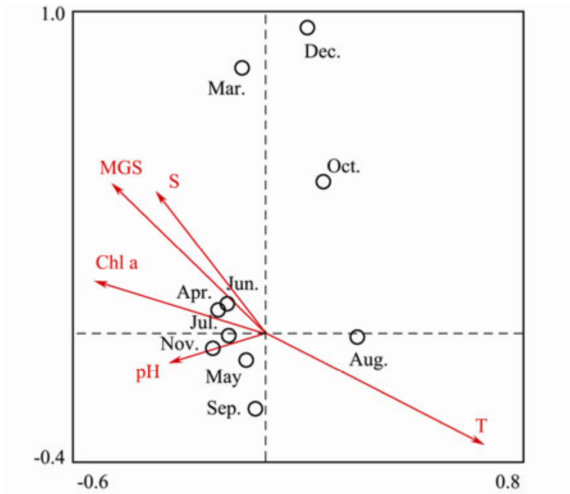

Fig.4 Relationship between macro benthic biomass and environmental factors in study area by PCA analysis.

Grain size stands for the benthic background and its distribution may be influenced by current and tide dynamics, accumulation of organic carbon and nutrients, and even redox conditions. Chl *a* represents for the standing stock and productivity of primary producer, which may serve as an indicator of the potential food source to *in situ* bivalves. Relationships between Chl *a*, median grain size, macro benthic biomass, and *M. veneriformis* biomass were different (Fig.5). The relationships between Chl *a* and macro benthic and bivalve biomasses were generally segmented into two parts, except several episodic points. A positive relationship between Chl *a* and macro benthic and bivalve biomasses existed when Chl *a* concentration was lower than 25 mg m$^{-2}$, while a negative relationship occurred when Chl *a* concentration was higher than 25 mg m$^{-2}$. The feeding interaction may be responsible for these different relationships because microphytobenthos proliferated with Chl *a* increase corresponding to a positive relationship, while the food supplication by microphytobenthic biomass controlled the benthic bivalves when Chl *a* was limited, showing a negative relationship. The long time interaction led to the patching distribution of benthic animals and algae (van de Koppel *et al*., 2008).

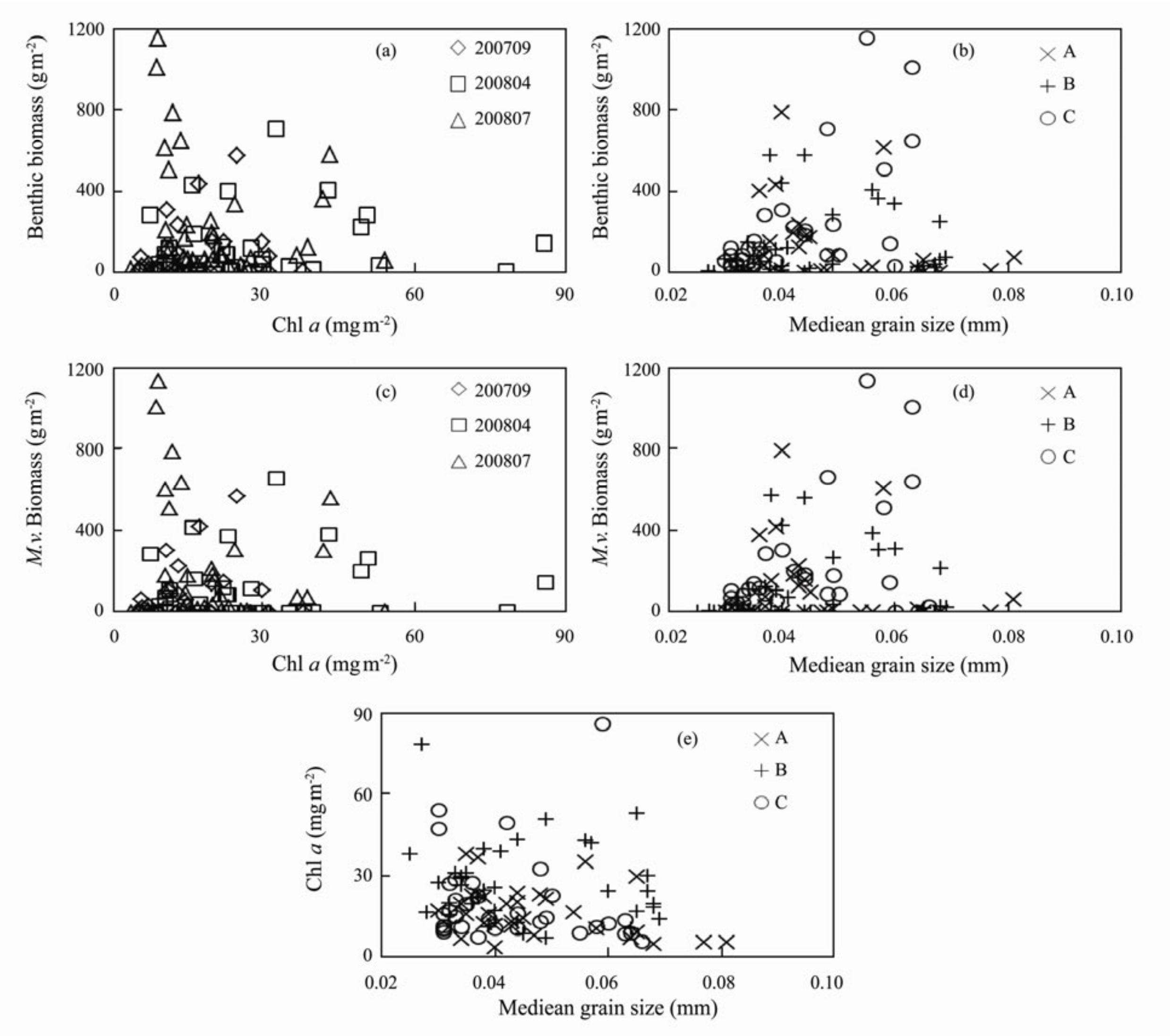


Fig.5 Distributions of macro benthic and *M. veneriformis* biomasses, Chl *a* content and median grain size in sediment of the southern Yellow River Delta.

As shown in Figs.5b and 5d, the median grain size primarily was at 0.027–0.081 mm, and the most was in the size smaller than 0.050 mm. It was also observed that, higher macro benthic biomass presented in the sediments with median grain size closing to 0.055 mm, and macro benthic biomass decreased gradually in the sediments with median grain size apart from 0.055 mm. The sediments in smaller grain size generally enriched in organic carbon, which might provide more organic carbon to bivalves. However, oxygen is usually depleted in sediment with smaller grain size and higher organic carbon, which might limit the growth and reproduce of bivalves. It was also observed that the sediments quickly changed from oxic to anoxic conditions from surface to subsurface (0.5–1 cm) in most sampling stations. Meanwhile, low Chl *a* and organic carbon may be responsible for the low macro benthic biomass in sediment with larger grain size. That is to say, the sediment grain size controlled the Redox conditions and accumulation of organic carbon, and then influenced the macro benthic and bivalve biomasses. For the case in YRD, macro benthos and bivalves tended to reside in the sediment with median grain size of 0.055 mm, due to the food availability and dwelling conditions.

## 3.3 Estimation on the Local Secondary Production

According to the density and biomass of macro benthos, secondary production was estimated by the following equation in the intertidal mudflat of YRD (Yu *et al.*, 2001).

$$\mathrm{Lg}P = 0.27\mathrm{Lg}A + 0.737\mathrm{Lg}B - 0.4, \quad (1)$$

in which, $P$ ($g\,m^{-2}yr^{-1}$) represents the secondary production, $A$ ($ind\,m^{-2}yr^{-1}$) and $B$ ($g\,m^{-2}yr^{-1}$) represent the density and biomass of macro benthos, separately. The estimations on spatial and monthly secondary production (Figs.6 and 7) showed that in the intertidal mudflat of southern YRD, the spatial distributions of secondary production followed a quite similar pattern with those of macro benthic biomass and density, but the higher values concentrated in the middle and low tide lines. The variations of secondary production showed that, macro benthos reproduced more in early summer and the highest in August, while *M. v.* reproduced the highest in July.

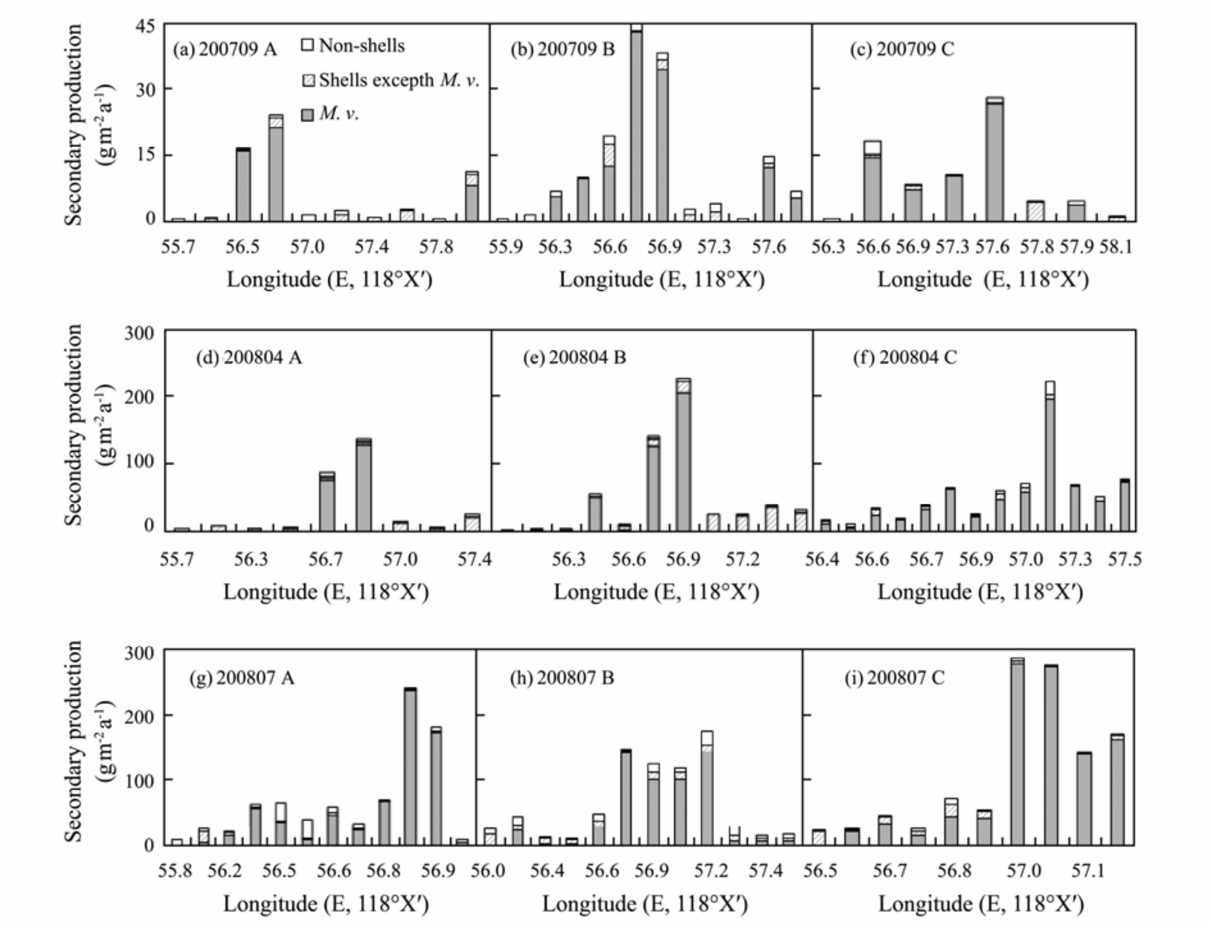


Fig.6 Spatial secondary production of macro benthos in the intertidal mudflat of southern Yellow River Delta.

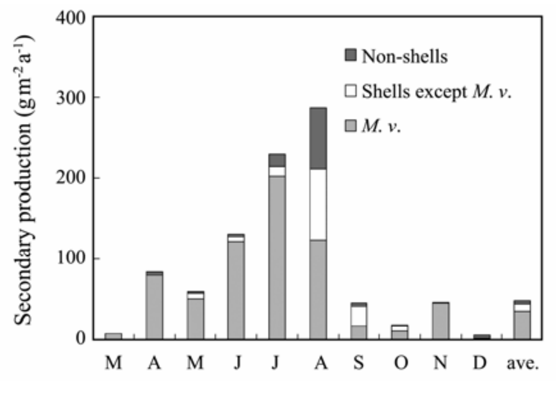


Fig.7 Monthly secondary production of macro benthos in the intertidal mudflat of southern Yellow River Delta.

Secondary productions ranged at 0.37–44.75 $g m^{-2} yr^{-1}$ (average 9.69 $g m^{-2} yr^{-1}$), 0.64–230.62 $g m^{-2} a^{-1}$ (average 50.08 $g m^{-2} yr^{-1}$) and 6.64–283.68 $g m^{-2} yr^{-1}$ (average 79.43 $g m^{-2} yr^{-1}$) in September 2007, April and July 2008. The monthly secondary production averaged at 47.88 $g m^{-2} yr^{-1}$, in which 69.7% of the production was contributed by *M. veneriformis*. This higher secondary production, corresponding to higher macro benthic biomass, might be caused by the aquaculture activity in the intertidal mudflat, which was comparable with other similar aquaculture areas, such as the higher benthic secondary production of 47.34 $g m^{-2} yr^{-1}$ in Jiaozhou Bay, north China (Yuan *et al.*, 2007). Simultaneously, the primary production ranged at 116.07–2779.8 $g m^{-2} yr^{-1}$ (average 696.48 $g m^{-2} yr^{-1}$) in the benthic environment (Yao *et al.*, 2010). Thus, a transformation rate of about 6.87% was calculated from primary to secondary productions. Considering the general 10% transformation efficiency from primary to secondary productions, it was implied that the *in situ* primary production sufficiently supported the sustainability of macro benthos in the intertidal mudflat of southern YRD.

In addition, a 3.13% of primary production was remained in the intertidal sediment and/or transported to offshore area. Water dynamics, both tiding and current in the intertidal zone was quite active, by which the surface sediment was disturbed heavily. The heavy disturbance not only re-suspended and removed the microphytobenthos into the overlying water, but also transported microphytobenthos from shallow to deep waters (Colijn and de Jonge, 1984; Varela and Penas, 1985; Sullivan and Moncreiff, 1988; Cahoon and Cooke, 1992). Due to the presence of the coarse sediment and low OC content of 0.1%–0.5% (Yao *et al.*, 2010), it was suggested that majority of the 3.13% primary production was likely transported to offshore area in study area.

## 4 Conclusions

Shellfish ranching was highly developed in the mudflat of southern Yellow River Delta, in which *M. veneriformis* was one of the key species. One year investigations showed that, the biomass of macro benthos varied widely at 0.75–1151.00 g wet $m^{-2}$, in which higher biomass and productivity occurred in early summer, and more than 90% macro benthos was located in the middle and low tide lines. Multiple factors affected on the growth and biomass of *M. veneriformis*, including both sediment background (temperature, salinity and grain size) and potential food source of microphytobenthos. 75.6%–93.4% of the total macro benthic biomass was contributed by *M. veneriformis*. However, it was suggested that the high production of *M. veneriformis* would be sustainable in the mudflat of southern Yellow River Delta, based on the ratio of secondary production to primary production (6.87%).

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## References

Beninger, P. G., and Boldina, I., 2014. Fine-scale spatial distribution of the temperate infaunal bivalve *Tapes* (=*Ruditapes*) *philippinarum* (Adams and Reeve) on fished and unfished intertidal mudflats. *Journal of Experimental Marine Biology and Ecology*, **457**: 128-134.

Benoit-Bird, K., and McManus, M. A., 2012. Bottom-up regulation of a pelagic community through spatial aggregations. *Biological Letters*, **8**: 813-816.

Benoit-Bird, K., Battaile, B., Nordstrom, C., Andrew, W., and Trites, A., 2013a. Foraging behavior of northern fur seals closely matches the hierarchical patch scales of prey. *Marine Ecology–Progress Series*, **479**: 283-302.

Benoit-Bird, K., Battaile, B., Heppell, S., Hoover, B., Irons, D. and Jones, N., 2013b. Prey patch patterns predict habitat use by top marine predators with diverse foraging strategies. *PLoS One*, **8** (1): e53348.

Blanchard, G. F., 1990. Overlapping microscale dispersion patterns of meiofauna and microphytobenthos. *Marine Ecology - Progress Series*, **68**: 101-111.

Cahoon, L. B., and Cooke, J. E., 1992. Benthic microalgal production in Onslow Bay, North Carlina, USA. *Marine Ecology –Progress Series*, **84**: 185-196.

Cai, E. W., Lin, S. D., Zhang, S. J., Jiang, J. X., Wu, Q. Q., Xu, H. Z., and Liu, Q. S., 1980. A study on ecology of intertidal zones along northern coast in Hangzhou Bay. I. A survey on the benthic fauna community in the soft bottom. *Acta Oceanology Sinica*, **2** (4): 122-131 (in Chinese with English abstract).

Colijn, F., and de Jonge, V. N., 1984. Primary production of microphytobenthos in the Ems-Dollard estuary. *Marine Ecology–Progress Series*, **14**: 185-196.

Cui, B., Yang, Q., Yang, Z., and Zhang, K., 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecological Engineering*, **35**: 1090-1103.

Fortin, M. J., Dale, M. R. T., and ver Hoef, J., 2002. Spatial analysis in ecology. In: *Encyclopedia of Environmetrics*. El-Shaarawi A. H., and Piegorsch, W. W., eds., Wiley, Chichester, 2051-2058.

Gao, A. G., Yang, J. Y., Zeng, J. N., Shou, L., Liao, Y. B., Xu, X. Q., Chen, Q. C., and Hu, X. G., 2009. Distribution of the intertidal macrobenthos in the Haizhouwan Bay. *Journal of Marine Science*, **27** (1): 22-29.

Guarini, J., Blanchard, G., and Bacher, C., 1998. Dynamics of spatial patterns of microphytobenthic biomass: Inferences from a geostatistical analysis of two comprehensive surveys in Marennes-Olèron Bay (France): Results from a geostatistical approach. *Marine Ecology–Progress Series*, **166**: 131-141.

Han, Q. X., Yuan, Z. Y., Chen, B. J., Wang, Y. J., Shi, Y. J., Liu, D. Y., 2014. The community structure and distribution pattern of intertidal macrobenthos in the intertidal zone of Yantai. *Marine Sciences*, **9**: 59-68.

Heip, C. H. R., Goosen, N. K., Herman, P. M. J., Kromkamp, J., Middelburg, J. J., and Soetaert, K., 1995. Production and consumption of biological particles in temperate tidal estuaries. *Oceanography and Marine Biology: An Annual Review*, **33**: 1-149.

Jeffrey, S., and Humphrey, G. F., 1975. New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. *Biochemical Physiological Pflanzen*, **167** (2): 191-194.

Kostylev, V., and Erlandsson, J., 2001. A fractal approach for detecting spatial hierarchy and structure on mussel beds. *Marine Biology*, **139**: 497-506.

Legendre, P., and Legendre, L., 2012. *Numerical Ecology*. Elsevier, Oxford, 1-12.

McKee, B., Aller, R., Allison, M., Bianchi, T., and Kineke, G., 2004. Transport and transformation of dissolved and particulate materials on continental margins influenced by major rivers: Benthic boundary layer and seabed processes. *Continental Shelf Research*, **24**: 899-926.

McLusky, D., and Elliott, M., 2004. *The Estuarine Ecosystem: Ecology, Threats and Management*. Oxford University, Oxford, 1-34.

Miller, D. C., Geider, R. J., and MacIntyre, H. L., 1996. Microphytobenthos: The ecological role of the 'Secret Garden' of unvegetated, shallow-water marine habitats. II. Role in sediment stability and shallow-water food webs. *Estuaries*, **19**: 202-212.

Pinckney, J. L., and Zingmark, R. G., 1993. Modeling the annual production of intertidal benthic microalgae in estuarine ecosystems. *Journal of Phycology*, **29**: 396-407.

Qiao, S. Q., and Shi, X. F., 2010. Status and prospect of studies on sedimentary characteristics and evolution of the Yellow River Delta. *Journal of Advanced Marine Science and Technology Society*, **28** (3): 408-416 (in Chinese with English abstract).

Rameshkumar, S., and Rajaram, R., 2017. Experimental cultivation of invasive seaweed *Kappaphycus alvarezii* (Doty) Doty with assessment of marco and meiobenthos diversity from Tuticorin coast, Southeast coast of India. *Regional Studies in Marine Science*, **9**: 117-125.

Reynolds, A. M., and Rhodes, C. J., 2009. The Lévy flight paradigm: Random search patterns and mechanics. *Ecology*, **90**:

877-887.

Sullivan, M. J., and Moncreiff, C. A., 1990. Edaphic algae are an important component of salt marsh food-webs: Evidence from multiple stable isotopes analysis. *Marine Ecology–Progress Series*, **62**: 149-159.

Seuront, L., and Spilmont, N., 2002. Self-organized criticality in intertidal microphytobenthos patch patterns. *Physica A*, **313** (3-4): 513-539.

Shao, X. M., Cai, R. X., Wang, H. M., and Fan, M. S., 1996. Studies on intertidal zone ecology of the benthic fauna in Xiangshan Harbor and Sanmen Bay. II. Quantities and distributions. *Donghai Marine Science*, **14** (4): 35-41.

Sims, D. W., Southall, E. J., and Humphries, N. E., 2008. Scaling laws of marine predator search behavior. *Nature*, **451**: 1098-1102.

van de Koppel, J., Gascoigne, J. C., Theraulaz, G., Rietkerk, M., Mooij, W. M., and Herman, P. M. J., 2008. Experimental evidence for spatial self-organization and its emergent effects in mussel beds. *Science*, **322**: 739-742.

Verela, M., and Penas, E., 1985. Primary production of benthic microalgae in an intertidal sand flat of the Ria de Arosa. *Marine Ecology–Progress Series*, **25**: 111-119.

Weerman, E. J., Van Belzen, J., Rietkerk, M., Temmerman, S., K éfi, S., Herman, P. M. J., and de Koppel, J. V., 2011. Changes in diatom patch-size distribution and degradation in a spatially self-organized intertidal mudflat ecosystem. *Ecology*, **93** (3): 608-618.

Yao, X., Yamaguchi, H., Zou, L., Gao, H. W., and Guo, X. Y., 2010. Effects of sediment environment on distribution pattern of benthic cholophyll-*a* in southern intertidal area of Yellow River Delta. *Journal of Ecology*, **29** (9): 1762-1769 (in Chinese with English abstract).

Yamaguchi, H., Montani, S., Tsutsumi, H., Hamada, K., Ueda, N., and Tada, K., 2007. Dynamics of microphytobenthic biomass in a coastal area of western Seto Inland Sea, Japan. *Estuarine Coastal and Shelf Science*, **75**: 423-432.

Yamaguchi, H., Tsutsumi, H., Tsukuda, M., Nagata, S., Kimura, C., Yoshioka, M., Shibanuma, S., and Montani, S., 2004. Utilization of photosynthetically produced organic particles by dense patches of suspension feeding bivalves on the sand flat of Midori River Estuary, Kyushu, Japan. *Benthos Research*, **59** (2): 67-77.

Yu, Z. S., Zhang, Z. N., and Han, J., 2001. Primary study on secondary production of macrobenthos in Bohai Sea. *Journal of Ocean University of Qingdao*, **31** (6): 867-871 (in Chinese with English abstract).

Yuan, C. T., Liu, J. M., Bo, X. F., Liu, Z. G., and He, R. G., 2006. Investigation report on the *Bullacta exarata* (Philippi) culture in the intertidal mudflat in Dongying. *Qilu Fishery*, **23** (3): 25-26 (in Chinese with English abstract).

Yuan, W., Zhang, Z. N., and Yu, Z. S., 2007. Secondary productivity of macrobenthos in Jiaozhou Bay. *Journal of Applied Ecology*, **18** (1): 145-150 (in Chinese with English abstract).

Zhang, A. G., Yuan, X. T., Yang, X. L., Shao, S. L., Li, J., and Ding, D. W., 2016. Temporal and spatial distributions of intertidal macrobenthos in the sand flats of the Shuangtaizi Estuary, Bohai Sea in China. *Acta Ecologica Sinica*, **36**: 172-179.

Zhang, P., Zou, L., Yao, X., Guo, X. Y., Gao, H. W., and Yamaguchi, H., 2011. Transportation fluxes of nutrients in the intertidal area of the Yellow River Delta. *Marine Environmental Science*, **30** (1): 76-80 (in Chinese with English abstract).

Zhang, Z. N., Tu, L. H., and Yu, Z. S., 1990. Preliminary study on the marcofauna in the Huanghe River Estuary and its adjacent waters. *Journal of Ocean University of Qingdao*, **20** (1): 37-45 (in Chinese with English abstract).

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