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Potential role of scallops *Argopecten irradians* in deposition of particulate nutrient and trace elements in a eutrophic estuary, northern China

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ABSTRACT: Anthropogenic inputs of nutrients and trace elements have globally significant impacts on coastal waters. In order to evaluate the effect of the filter-feeding bay scallop *Argopecten irradians* on benthic–pelagic coupling in a eutrophic estuary (Laizhou Bay), biodeposition of total suspended materials, particulate nutrient (C, N, P) and trace elements (Cu, Zn, Pb, Cr, Cd, Hg, As) were determined using modified sediment traps during autumn 2013. Results showed that biodeposition rates of the bay scallops were rather high compared with those reported for other bivalves. The allometric relationship between the biodeposition rate (BDR; g ind.$^{-1}$ d^{-1}) and soft tissue dry weight (W; g ind.$^{-1}$) was modeled (BDR = aW^b) with the value of a being 1.24 in September and dropping to 0.96 in October. The biodeposition contributed to the enrichment of organic matter, C and N in the local sediment. Trace element concentrations in the scallop biodeposits were significantly higher than those of the natural surrounding sediments, especially during the months of October and November. *A. irradians* significantly increases the mass fluxes from the water column to the bottom, with estimated 1140 tonnes of total suspended material being deposited to the seabed each day in the culture zone. Results also suggest that biotransformation and biodeposition by such efficient filter-feeders may play a pivotal role in the fate and transportation of particulate nutrient and trace elements in aquatic ecosystems. In coastal waters and estuaries subject to anthropogenic inputs, suspended bivalve aquaculture could be environmentally advantageous via intense filtering and biodeposition, potentially mitigating eutrophication and trace element pressures.

KEY WORDS: Biodeposition · Biogenic elements · Trace elements · Benthic–pelagic coupling · Bioremediation · *Argopecten irradians* · Filter-feeding bivalve · Laizhou Bay

INTRODUCTION

Oceans, especially their coastal waters and estuaries, have been strongly affected by numerous human activities (Halpern et al. 2008), and these impacts are projected to increase over the next few decades (Doney 2010). Anthropogenic nutrient inputs and resulting eutrophication is considered as one of the major human perturbations to marine ecosystems worldwide (Smith et al. 1999). Eutrophication of coastal waters and estuaries has been a global problem for many years, and is considered one of the largest threats to coastal ecosystems (Micheli 1999, Wang et al. 2016, Andersen et al. 2017). Significant changes in nutrient regimes, including rising nutrient levels and alterations in nutrient supply, have led

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to increased incidences of toxic algal blooms in marine waters worldwide (e.g. Anderson et al. 2008), posing great threats to many ecologically important ecosystems including salt marshes, seagrass meadows and coral reefs (Waycott et al. 2009, Deegan et al. 2012). In addition, elevated oceanic levels of trace elements have also raised a concern for the overall health of marine ecosystems, and indisputably, human health also (Doney 2010, Pan & Wang 2012, Gao et al. 2014).

In shallow coastal waters, benthic filter-feeders (e.g. bivalves) often dominate the benthos, both in abundance and biomass. Previous studies have revealed that dense assemblages of filter-feeding bivalves in shallow waters can play a significant role in the pelagic–benthic coupling of organic matter, as well as controlling nutrient recycling (Haven & Morales-Alamo 1972, Kautsky & Evans 1987, Newell 2004, Zhou et al. 2006a, Beseres Pollack et al. 2013, Hoellein et al. 2015, Testa et al. 2015, Li et al. 2016). Densely cultured bivalves can filter large amounts of phytoplankton and other suspended particulate matter from the water column and enhance natural sedimentation (Newell 2004, Zhou et al. 2006a, Yuan et al. 2010, Zúñiga et al. 2014). Through filtration and deposition of suspended particulate matter, intensive bivalve populations can exert a top-down control on phytoplankton biomass, resulting in alterations to the benthic environment and benthos composition (Grant et al. 1995, Crawford et al. 2003, Callier et al. 2007). The type and extent of changes in the benthic environment is linked to the scale and density of cultivation and hydrographic conditions of the mariculture waters. Generally, a combination of good water exchange and a diverse benthic community contribute to efficient dispersal and breakdown of the sedimented material, thus mitigating any negative impacts caused by shading, erosion and/or organic enrichment (Hayakawa et al. 2001). With a worldwide concern for the increase in waters impacted by eutrophication and trace element contamination, some researchers have suggested that the dramatic growth in bivalve mariculture could mitigate, or even biologically control the pollution of coastal waters (e.g. Zhou et al. 2006a, Stadmark & Conley 2011, Petersen et al. 2014, Nielsen et al. 2016, Grizzle et al. 2017, Filgueira et al. 2017).

The bay scallop *Argopecten irradians* (Lamarck, 1819) naturally occurs on the eastern coast of the United States (Maine to New Jersey) and historically supported a vibrant, successful fishery until populations began to collapse over the past 30 yr. The bay scallop grows best when temperatures are between 18 and 28°C and ceases to grow below 5°C (Wang & Wang 2008). In the 1980s, bay scallops were introduced to both Canada and China (Zhang 1986), achieving great success in China with an annual production of 300 000 tonnes in 1994.

With such profitable vast development of intensive mariculture, there is an obvious need to examine potential effects within localized coastal zones. To date, studies on biodeposition of particulate nutrients and trace elements by filter-feeding bivalves in coastal waters are still lacking, especially for trace elements. It is well known that physiological rates (clearance rate, oxygen consumption rate and ammonia excretion rate) respond allometrically with the tissue dry weight (DW) of suspension-feeding bivalves (Bayne & Newell 1983). However, it is not known whether biodeposition rates also respond in a similar way. The aims of this study were to determine (1) whether the biodeposition rates respond exponentially with the tissue DW of filter-feeding bivalves and (2) whether the suspension-cultured rapid growing bay scallop *Argopecten irradians* could markedly influence the sedimentation of total particulate matter, particulate biogenic elements (C, N, P) and trace elements (Cu, Zn, Pb, Cr, Cd, Hg, As).

MATERIALS AND METHODS

Study area

Laizhou Bay (Fig. 1) is located in the northwest of the Shandong Peninsula, northern China, and covers a total area of approx. 7000 km^2, with a mean depth of 9 m. In the west zone of the bay, the Yellow River (Huanghe River in Fig. 1), the 6th longest river in the world, empties into the bay. Laizhou Bay is listed as a frequently occurring 'red tide' area for coastal Chinese waters (Huang et al. 2003). The nutrient regime of Laizhou Bay has experienced a dramatic change in the past 30 yr, with a 10-fold increase in dissolved inorganic nitrogen concentrations, alongside an equivalent 10-fold decrease in dissolved inorganic phosphorus levels (Zhang et al. 2014). The major component of dissolved inorganic nitrogen also changed from NH_4–N to NO_3–N due to excessive anthropogenic nitrogen input (Shan et al. 2000). In addition, the heavy metal pollution in Laizhou Bay raised great concerns which prompted numerous investigations (Hu et al. 2011, Gao et al. 2013, Wu et al. 2014). It has been reported that a total of 1000 tonnes of Cu, Pb, Zn, Cr, As and Hg have drained into this region from riverine sources (NCSB 2011). Sediments and organisms with

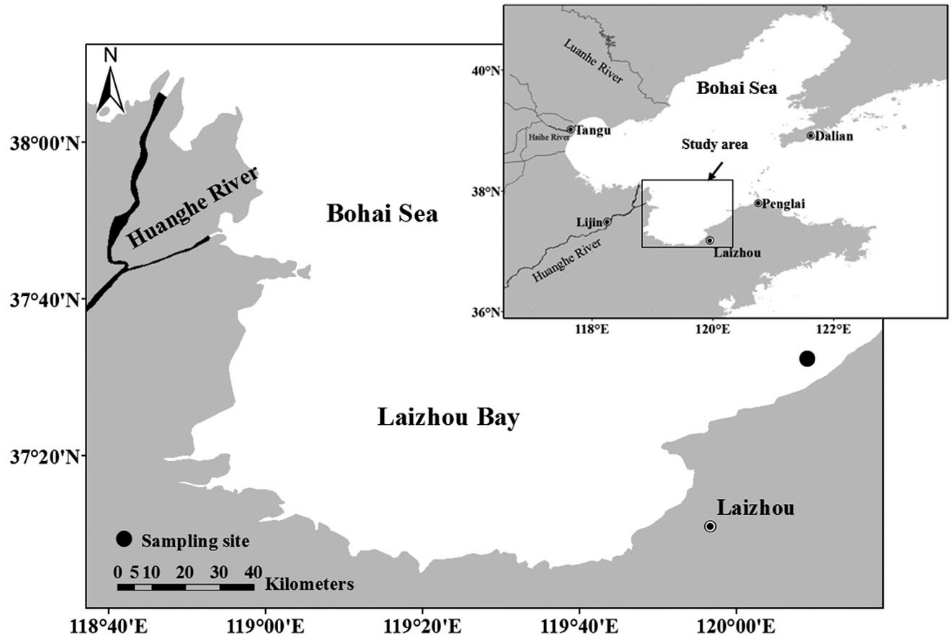


Fig. 1. Location of experimental site in Laizhou Bay (●), northern China

excessive trace metal concentrations have been found in this region (NMEB 2009, Zhuang & Gao 2013).

Scallop mariculture in Laizhou Bay started in the late 1980s and has lasted for almost 30 yr. The suspension longline culture area is concentrated along a thin strip in the south bay, extending from Sanshandao Town to Zhaoyuan Town in Yantai City, covering a total area of 534 ha and supporting a culture density of approx. 200 ind. m^{-2} (Liu et al. 2004). The growing period for scallops in the bay is about 5 mo. Numerous investigations were conducted in the late 1990s to study the hydrology (Zhao & Chen 2001), nutrient distributions and seasonal variations (Qu et al. 2002, Liu et al. 2004), phytoplankton ecology (Chen et al. 2001, Liu et al. 2004) and seston dynamics (Liang et al. 2001) of the bay.

The current study was specifically focused on the bay scallop mariculture area of Laizhou Bay (37° 30′ 12″ N, 120° 10′ 36″ E) and was carried out over a 3 mo period from September to December 2013. The mean seawater semi-exchange period of this study area was 74 d (in autumn) (Zhao & Chen 2001). Seston in these mariculture waters was of high quality (Liang et al. 2001), with diatoms dominating the phytoplankton community during the scallops' rapid growth period (Liu et al. 2004). The surface sediments of Laizhou Bay were found to be of high quality and unlikely to cause negative effects on the ecosystem (Gao et al. 2013), but related research by Zhang et al. (2013) found that the macrobenthic communities in Laizhou Bay were probably negatively affected by the trace elements in the surrounding sediments.

Biodeposition

Biodeposition was determined using sediment traps (Fig. 2) that were modified based on our previous study (Zhou et al. 2006a). The research involved

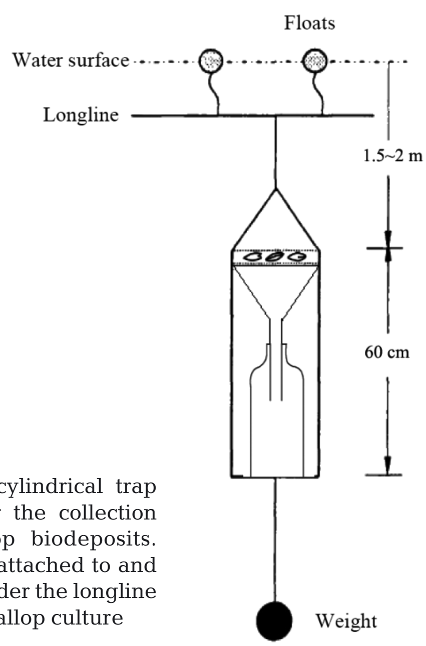


Fig. 2. PVC cylindrical trap developed for the collection of bay scallop biodeposits. The trap was attached to and suspended under the longline used for scallop culture

4 separate treatments (based on size) with 4 replicates each. One treatment was designed for small scallops (5 ind. trap^{-1}), the second for medium scallops (4 ind. trap^{-1}), the third for big scallops (3 ind. trap^{-1}) and the fourth contained only scallop shells, acting as a control. The shell height of small scallops was 47.87 ± 3.43 mm (tissue DW 0.91 ± 0.39 g ind.$^{-1}$), medium scallops, 56.38 ± 2.08 mm (1.54 ± 0.48 g ind.$^{-1}$) and big scallops 64.73 ± 6.14 mm (2.64 ± 1.07 g ind.$^{-1}$). The top of each sediment trap was covered by 2 nets (20 mm mesh), and set apart by 70 mm. Natural sedimented material and any biodeposits produced by scallops were collected in all traps. Biodeposition rate (BDR; g ind.$^{-1}$ d^{-1}) was measured based on the amount of material collected from each trap containing animals, as well as that from the control. In the beginning, scallops were randomly selected from a culture site in Laizhou Bay, and their shell surfaces were cleaned to remove any fouling epibiota and other materials. During the experiment, the scallops were placed evenly between the nets of the sediment traps. Since the scallops in September were relatively small, they were divided into 2 size categories (small [S] and medium [M]), while in October and November, scallops were divided into 3 size categories: small, medium and big (B).

All sediment traps were suspended from an empty longline (Fig. 2) with no scallops cultured within a radius of 10 m, so that the experimental animals were at a depth of ca. 2 m, corresponding to a routine depth for scallops cultivated in lantern nets. After the traps had been deployed for approximately 5 d, they were retrieved from a boat. The polypropylene bottles inside the traps were transported to the laboratory, where excess water in the sediment was siphoned out and the collected material was rinsed 3 times with distilled water to remove salts. The weight of sediment collected in each bottle was determined following oven drying of the material at 60°C for 4 d, and then the sedimented material was ground to a fine powder (80 mesh). Shell height (±0.01 mm) of scallops in each trap was determined and dry weight of soft tissue was measured by drying at 60°C to constant weight (±0.01 g).

In addition, clearance rate (CR) was indirectly estimated from biodeposition rates (Iglesias et al. 1998,Cranford & Hill 1999, Yu et al. 2017), by using the inorganic matter (ash) in biodeposits as a quantitative tracer of the filtered material. The relationships between physiological rates (BDR and CR) and tissue DW were modeled using the allometric equation: BDR / CR = aW^b, where W is the tissue DW of bay scallop, constant b is the weight exponent and a is the rate for a scallop of 1 g tissue DW. In order to preclude variability in physiological rates owing to size difference, the physiological rates (BDR and CR) were standardized to an equivalent individual based on the following formula: $Y_s = Y_e \times (W_s / W_e)^b$; where Y_s represents the physiological rate for a standardized individual, Y_e is the uncorrected (measured) physiological rate, W_s is the standard tissue DW (0.91 g for small scallops, 1.54 g for medium scallops and 2.64 g for big scallops), and W_e is the observed tissue DW weight of an experimental individual.

Water column

Environmental parameters, including temperature, salinity, pH and chlorophyll *a* (chl *a*) were examined by Yellow Spring Instruments (YSI 6600). Surface water samples were collected twice every day (08:00 and 16:00 h) for 2 to 4 d (depending on weather conditions during each sampling month) at a depth of 2 m, and immediately filtered to measure total suspended particulate matter (TPM), particulate organic material (POM), particulate inorganic material (PIM), particulate carbon (POC), particulate nitrogen (PON) and particulate phosphorus (PP) concentrations. For determination of POM and PIM, 1 l of each sample was filtered through a pre-weighed and pre-ignited (450°C for 6 h) GF/F glass fiber filter. The filter was then rinsed with 50 ml of distilled water to remove salts, dried at 60°C for 24 h and then weighed. The filter was later ignited at 450°C for 6 h. For determination of POC and PON, 0.2 l of each sample was filtered through a GF/F glass fiber filter. The filter was dried at 60°C for 24 h and then analyzed with a CHN analyzer (Model 240c; Perkin Elmer) standardized with acetanilide. PP was measured by means of a modified method that followed Solórzano & Sharp (1980) for determination of PP (Zhou et al. 2003, 2006a). In addition, the collected water samples were analyzed for nutrients, including dissolved inorganic nitrogen (DIN; NO_3–N, NO_2–N, NH_4–N) and dissolved inorganic phosphorus (DIP; PO_4–P). The nutrients were determined with an automatic nutrient analyzer (Skalar San Plus System).

Analysis of organic matter and nutrient elements in sediments

Subsamples of the dried sedimented material were used to determine the concentration of organic matter (OM) by igniting (500°C for 4 h) dried and preweighed samples. Subsamples of soft tissue and sediments from the traps were pre-treated with 0.2 mol l^{-1} HCl to remove carbonates and then analyzed for organic carbon (OC) and total nitrogen (TN) with a CHN analyzer (Model 240c; Perkin Elmer) standardized with acetanilide. Total phosphorus (TP) and organic phosphorus (OP) concentrations of subsamples were also analyzed by means of a modified method that followed Solórzano & Sharp (1980) for particulate P determination (Zhou et al. 2003, 2006a).

Analysis of trace elements in sediments and scallops

Trace elements of Cu, Zn, Pb, Cr, Cd, Hg and As in the sedimented material and scallop soft tissue were determined with the analytical procedure described in Wang et al. (2017) for sediment and organism, respectively. Trace elements in scallop shells were measured using the same analytical procedure as sediment.

Statistical analysis

Data are presented as means ± SD. OM, biogenic and trace element concentrations are provided on dry weight basis. Differences in OM, biogenic and trace element concentrations within sediments between different treatments were analyzed using 1-way analysis of variance (ANOVA). Differences among different months were also analyzed using ANOVA. Prior to statistical analysis, data were examined for normality of distribution and homogeneity of variance with Kolmogorov-Smirnov test and Levene's test, respectively. A statistical significance level of 0.05 was used. Statistical analyses were carried out using the software R v.1.0 for Windows (R Development Core Team 2016).

RESULTS

Water column characteristics

The monthly variations of physical and chemical parameters and particulate trace element concentrations of surface waters at our experimental site in Laizhou Bay are shown in Table 1. During the study period, the sea surface temperature decreased from 23.38°C in September to 16.94°C in October and 9.50°C in November. Salinity was stable, ranging from 27.69 to 28.91. Chl *a* concentrations were low, ranging from 1.12 to 2.27 µg l^{-1}, lower than concentrations recorded in October 1997 (3.2 µg l^{-1}; Liang et al. 2001). TPM varied markedly during the study period, with values in October (17.75 ± 6.87 mg l^{-1}) 2 times greater than concentrations recorded in either September (5.97 ± 2.23 mg l^{-1}) or November (7.52 ± 1.66 mg l^{-1}). The OM proportion was high in September (56.37 ± 7.41 %), followed by a dramatic 3-fold decline in October and November. The concentrations of DIN ranged from 15.08 to 36.86 µmol l^{-1} (mean: 23.28 µmol l^{-1}); these values were higher than those recorded in 1997 (6.35 to 18.6 µmol l^{-1}; Qu et al. 2002). NO_3-N constituted the major part (62.20 to 89.97 %) of DIN. The concentrations of DIP ranged from 0.06 to 0.20 µmol l^{-1} (mean: 0.11 µmol l^{-1}), which were remarkably lower than values recorded in 1997 (0.41 to 0.85 µmol l^{-1}; Qu et al. 2002).

Nutrient composition and trace element concentrations in bay scallop tissue

There were no significant differences in the C, N and P concentrations of scallop tissue between differ-

Table 1. Mean (±SD) monthly variations of environmental factors and concentrations of particulate material and trace elements of surface waters at the experimental site in Laizhou Bay. *T*: temperature; S: salinity; TPM: total particulate matter; POM: particulate organic matter; OM: organic matter; POC: particulate organic carbon; PON: particulate organic nitrogen; PP: particulate phosphorus; Chl *a*: chlorophyll *a*

Time	*T* (°C)	S (ppt)	TPM (mg l^{-1})	POM (mg l^{-1})	OM (%)	POC (µg l^{-1})	PON (µg l^{-1})	PP (µg l^{-1})
Sep	23.38 ± 0.98	27.70 ± 0.25	5.97 ± 2.23	3.27 ± 0.80	56.37 ± 7.41	412.5 ± 103.2	63.4 ± 16.3	4.08 ± 0.77
Oct	16.94 ± 0.17	28.91 ± 0.13	17.75 ± 6.87	3.40 ± 1.24	19.58 ± 2.39	394.4 ± 127.6	49.3 ± 12.6	4.17 ± 1.39
Nov	9.50 ± 0.14	27.69 ± 0.25	7.52 ± 1.66	1.38 ± 0.31	18.79 ± 4.04	431.0 ± 92.7	93.3 ± 34.1	5.63 ± 0.71
	Chl *a* (µg l^{-1})	As (ng l^{-1})	Cd (ng l^{-1})	Cr (ng l^{-1})	Cu (ng l^{-1})	Zn (ng l^{-1})	Pb (ng l^{-1})	Hg (ng l^{-1})
Sep	2.26 ± 0.25	0.25 ± 0.00	1.41 ± 0.03	0.46 ± 0.00	0.24 ± 0.01	0.70 ± 0.02	0.58 ± 0.25	3.40 ± 0.28
Oct	1.12 ± 0.53	0.29 ± 0.01	1.94 ± 0.71	0.36 ± 0.02	0.20 ± 0.01	0.49 ± 0.01	0.20 ± 0.02	3.08 ± 0.06
Nov	2.27 ± 0.87	0.15 ± 0.05	1.03 ± 0.23	0.26 ± 0.01	0.10 ± 0.01	0.45 ± 0.01	0.06 ± 0.01	1.38 ± 0.16

Table 2. Mean (±SD) biogenic element composition in bay scallop *Argopecten irradians* tissue. S: small size scallop; M: medium size; B: big size. Different lowercase letters in the same month indicate significant differences ($p < 0.05$). Different uppercase letters among different months indicate significant differences ($p < 0.05$)

Time	Size	C (%)	N (%)	P (‰)
Sep	S	43.89 ± 1.03[a]	12.14 ± 0.20[a]	11.22 ± 1.33[a]
	M	43.24 ± 1.57[a]	11.99 ± 0.31[a]	11.61 ± 1.36[a]
	Mean	43.57 ± 1.24[A]	12.06 ± 0.25[B]	11.42 ± 1.22[B]
Oct	S	43.53 ± 0.34[a]	10.94 ± 0.30[a]	11.86 ± 0.35[a]
	M	43.96 ± 0.54[a]	10.96 ± 0.23[a]	11.57 ± 0.59[a]
	B	43.90 ± 0.91[a]	10.61 ± 0.24[a]	12.31 ± 0.11[a]
	Mean	43.80 ± 0.59[A]	10.84 ± 0.28[A]	11.91 ± 0.47[B]
Nov	S	45.44 ± 0.77[a]	11.12 ± 0.16[a]	9.37 ± 1.28[a]
	M	42.65 ± 3.69[a]	10.44 ± 0.95[a]	8.53 ± 1.12[a]
	B	41.01 ± 4.65[a]	9.99 ± 0.94[a]	10.13 ± 0.16[a]
	Mean	43.22 ± 3.48[A]	10.56 ± 0.83[A]	9.34 ± 1.10[A]

ent sizes, within each month (1-way ANOVA, $p > 0.05$; Table 2). However, the N tissue concentrations in September were significantly higher than in October and November (1-way ANOVA, $p < 0.05$) and the P concentrations in September and October were significantly higher than in November ($p < 0.05$; Table 2). No significant differences were found for C concentrations over the 3 mo period ($p > 0.05$). Results showed that the N concentration of scallop tissue varied more than that of C; similar findings were recorded in a study on the Pacific oyster *Crassostrea gigas* (Bayne 2009). Levels of trace elements in the scallop tissue (Table 3) differed markedly from those found in the shell ($p < 0.001$). The concentrations of As, Cd, Cu, Pb, Zn and Hg in the flesh were dozens of times higher than concentrations in the shell ($p < 0.001$) and on the contrary, the concentrations of Cr in the flesh were significantly lower than in the shell ($p < 0.001$). Thus, we can infer that trace element concentrations vary in scallop tissue anatomy. There were no significant differences in trace element concentrations either in tissue or shell among sizes ($p > 0.05$).

Biodeposition rate and its relationship with the tissue DW of the bay scallop

The biodeposition rates of scallops of different sizes during the study period ranged from 0.84 to 2.03 g ind.$^{-1}$ d^{-1}, with higher values generally recorded in the largest size category ($p < 0.001$; Table 4). The allometric relationship between biodeposition rates and dry weight is shown in Table 5. It was obvious that the allometric relationship ceased to exist when water temperatures dropped below 10°C, when the scallops were harvested; this phenomenon may be due to a change in their physiological status, energy demand and/or allocation among individuals of different sizes. The average daily biodeposition rates expressed as g (g tissue DW)$^{-1}$ d^{-1} were 1.24 g (g tissue DW)$^{-1}$ d^{-1} in September and 0.96 g (g tissue DW)$^{-1}$ d^{-1} in October.

Biogeochemical characteristics of the sediments from the traps

Generally, the concentrations of OM, TC, TN, TP and OP in sediments from the control traps were

Table 3. Trace element (As, Cd, Cr, Cu, Zn, Pb and Hg) concentrations in tissue and shells of small (S), medium (M) and big (B) sized bay scallops

	Time	Size	As (mg kg^{-1})	Cd (mg kg^{-1})	Cr (mg kg^{-1})	Cu (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	Hg (µg kg^{-1})
Tissue	Sep	S	9.760	14.93	0.803	115.6	8.862	548.1	487
		M	7.525	15.57	0.793	131.5	6.984	868.8	334
	Oct	S	12.631	15.19	0.712	100.4	8.236	737.1	319
		M	11.432	13.76	0.494	74.56	6.734	513.7	289
		B	10.304	14.60	0.345	90.1	8.351	656.8	274
	Nov	S	7.800	16.92	0.232	32.17	4.689	484.7	152
		M	7.773	16.11	0.341	28.13	4.131	367.7	151
		B	6.935	16.17	0.189	27.04	3.977	486.4	156
Shell	Sep	M	0.074	0.012	17.65	1.417	0.358	0.554	42.9
	Oct	S	0.218	0.045	18.13	2.552	1.756	2.952	60.7
		M	0.109	0.058	10.12	1.922	0.544	2.435	28.7
		B	0.129	0.080	10.36	2.053	1.019	1.450	53.2
	Nov	M	0.123	0.110	3.393	1.799	1.423	1.517	32.3

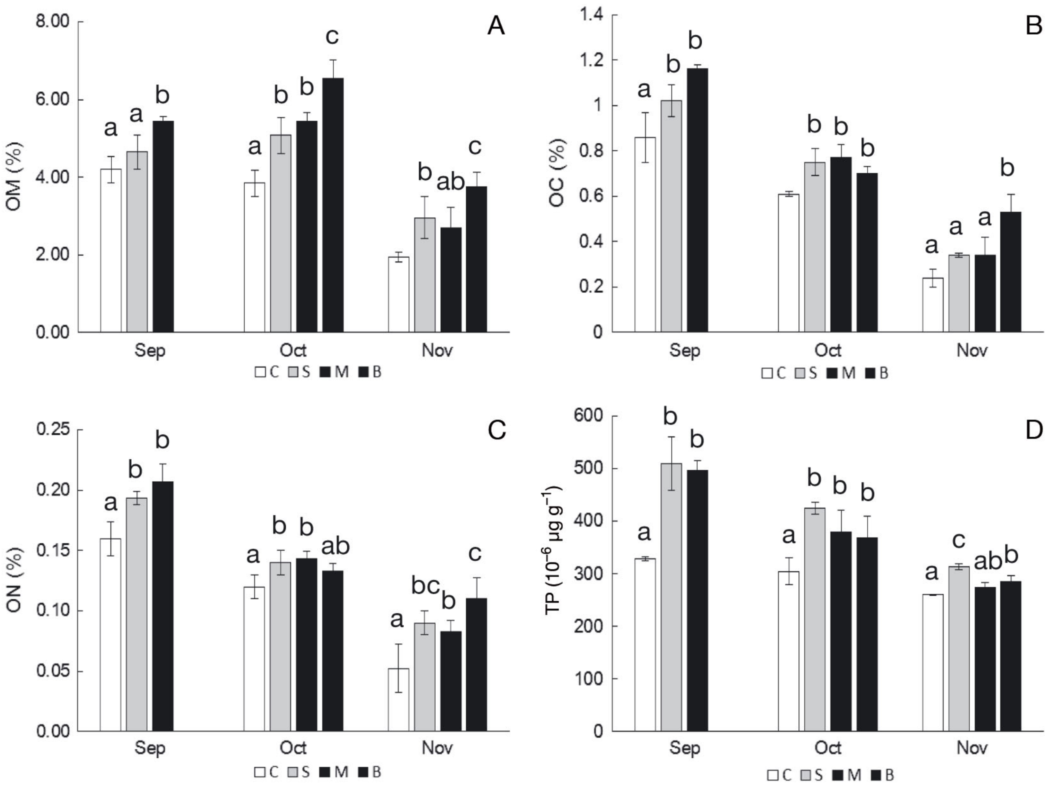
Table 4. Tissue dry weight (*W*) and biodeposition rate (BDR) of bay scallop *Argopecten irradians* in different months. S: small size scallops; M: medium size; B: big size. Different letters in the same month and column indicate significant differences ($p < 0.05$)

Time	Size	*W* (g ind.$^{-1}$)	BDR (g ind.$^{-1}$ d^{-1})
Sep	S	0.63 ± 0.04[a]	0.96 ± 0.15[a]
	M	1.19 ± 0.18[b]	1.37 ± 0.26[b]
Oct	S	0.74 ± 0.07[a]	0.84 ± 0.13[a]
	M	1.33 ± 0.06[b]	1.07 ± 0.16[b]
	B	1.88 ± 0.07[c]	1.60 ± 0.11[c]
Nov	S	1.35 ± 0.09[a]	1.17 ± 0.19[a]
	M	2.09 ± 0.11[b]	2.03 ± 0.20[b]
	B	3.39 ± 0.36[b]	1.23 ± 0.07[c]

Table 5. Allometric relationships for biodeposition rates for different months in bay scallop *Argopecten irradians*. *a*: the coefficient indicating the biodeposition rate for a scallop of 1 g soft tissue dry weight; *b*: the weight exponent. **$p < 0.01$

Time	*a*	*b*	R^2	*F*
Sep	1.24	0.55	1.00	26.52**
Oct	0.96	0.66	0.92	37.67**
Nov	1.40	0.03	0.00	0.15

significantly lower than concentrations found in the experimental traps (Fig. 3), which indicated that the biodeposition of bay scallop may in fact be contributing to the enrichment of these substances in the sediment.



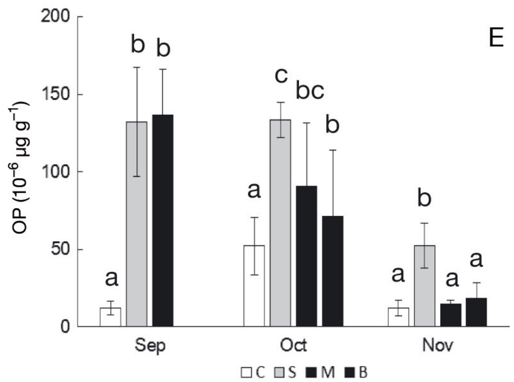


Fig. 3. Mean (±SD) concentrations of particulate (A) organic matter (OM, mass %), (B) organic carbon (OC, mass %), (C) organic nitrogen (ON, mass %), (D) total phosphorus (TP, µg g^{-1}) and (E) organic phosphorus (OP, µg g^{-1}) in bay scallop biodeposits and natural sediments from traps. C: control; S: small scallops; M: medium scallops; B: big scallops. Different lowercase letters above the bars within the same month indicate significant differences among treatments ($p < 0.05$)

Table 6. Mean (±SD) trace element concentrations of the sediment from traps in Laizhou Bay (µg g^{-1}). C: control; S: small size scallop; M: medium size; B: big size. Different letters in the same month and column indicate significant differences ($p < 0.05$)

Time	Size	As	Cd	Cr	Cu	Zn	Pb	Hg
Sep	C	32.34 ± 0.28^{a}	0.184 ± 0.003^{a}	60.69 ± 0.16^{b}	31.58 ± 0.95^{a}	91.49 ± 3.26^{a}	19.14 ± 1.14^{a}	0.445 ± 0.037^{a}
	S	29.72 ± 0.20^{a}	0.183 ± 0.004^{a}	85.93 ± 5.79^{c}	31.92 ± 0.72^{a}	96.34 ± 4.41^{a}	18.08 ± 1.93^{a}	0.391 ± 0.004^{a}
	M	28.33 ± 10.31^{a}	0.283 ± 0.035^{b}	47.31 ± 6.48^{a}	28.66 ± 4.53^{a}	102.26 ± 12.06^{a}	14.62 ± 3.68^{a}	0.409 ± 0.042^{a}
Oct	C	25.20 ± 1.93^{a}	0.254 ± 0.093^{a}	47.28 ± 2.41^{a}	25.81 ± 1.05^{a}	63.73 ± 0.76^{a}	18.08 ± 1.97^{a}	0.403 ± 0.007^{a}
	S	34.88 ± 4.46^{b}	0.197 ± 0.036^{a}	102.10 ± 4.65^{bc}	29.39 ± 0.58^{b}	99.11 ± 29.42^{b}	31.10 ± 9.88^{b}	0.436 ± 0.016^{a}
	M	29.36 ± 5.82^{a}	0.181 ± 0.033^{a}	91.83 ± 6.80^{b}	27.787 ± 0.68^{ab}	105.39 ± 15.18^{b}	17.90 ± 0.17^{a}	0.445 ± 0.029^{a}
	B	25.23 ± 1.15^{a}	0.284 ± 0.116^{a}	106.62 ± 10.39^{c}	27.44 ± 2.42^{ab}	93.04 ± 3.17^{ab}	18.25 ± 0.04^{a}	0.342 ± 0.113^{a}
Nov	C	20.22 ± 4.85^{a}	0.133 ± 0.025^{a}	31.07 ± 5.74^{a}	12.56 ± 1.54^{a}	51.36 ± 18.99^{a}	26.76 ± 3.64^{a}	0.183 ± 0.018^{a}
	S	22.10 ± 1.01^{ab}	0.216 ± 0.079^{b}	38.97 ± 1.64^{b}	17.96 ± 0.77^{b}	68.52 ± 5.32^{ab}	31.17 ± 9.69^{a}	0.375 ± 0.014^{b}
	M	24.95 ± 4.73^{ab}	0.123 ± 0.003^{a}	38.82 ± 1.37^{b}	17.29 ± 1.43^{b}	67.63 ± 11.48^{ab}	32.94 ± 9.90^{a}	0.374 ± 0.047^{b}
	B	28.20 ± 2.92^{b}	0.232 ± 0.046^{b}	40.20 ± 2.04^{b}	19.05 ± 2.73^{b}	89.35 ± 7.76^{b}	28.06 ± 1.69^{a}	0.453 ± 0.039^{c}

The trace element concentrations in trap sediments are outlined in Table 6. Trace element concentrations from traps containing scallops were significantly higher than those without scallops (controls), especially during the months of October and November ($p < 0.05$). In September, the concentrations of As, Cu, Zn, Pb and Hg in sediments from the experimental traps were similar to those from the control traps ($p > 0.05$). However, Cd concentrations in the experimental traps containing medium sized scallops were significantly higher than in the control traps or the traps containing the smaller sized scallops ($p < 0.05$). For Cr, significant differences also exist among sediments from different traps, with small scallops registering the highest concentrations and medium sized scallops the lowest ($p < 0.05$). In October and November, nearly all trace element concentrations in the sediments from the traps containing scallops were significantly higher than those from the control traps ($p < 0.05$), except for Hg and Cd in October and Pb in November.

Biodeposition rates of organic matter, biogenic elements and trace elements

Mean biodeposition rates of OM, OC, ON, TP and OP for small scallops were 50.2 ± 11.4, 8.38 ± 4.55, 1.72 ± 0.68, 0.51 ± 0.18 and 0.160 ± 0.065 mg $ind.^{-1}$ d^{-1}, respectively (Table 7). Biodeposition rates of OM, OC, ON and TP for big scallops were significantly higher than small and medium scallops ($p < 0.05$), and there were no significant differences among sampling months ($p > 0.05$).

The biodeposition rates of trace elements for bay scallops are shown in Table 8. Biodeposition rates of As, Cr, Cu, and Zn for big scallops were significantly higher than small scallops ($p < 0.05$). In addition, there were no significant differences in biodeposition rates of trace elements among sampling months ($p > 0.05$). Negative values for Cd in September and October should be mentioned, as this could indicate a more intense absorption rate by the scallops.

Table 7. Mean (±SD) standardized biodeposition rates for small (S), medium (M) and big (B) bay scallops during different months in Laizhou Bay. TPM: total particulate matter; OM: organic matter; OC: organic carbon; ON: organic nitrogen; TP: total phosphorus; OP: organic phosphorus. Different letters in the same month and column indicate significant differences ($p < 0.05$)

Time	Size	TPM (g $ind.^{-1}$ d^{-1})	OM (mg $ind.^{-1}$ d^{-1})	OC (mg $ind.^{-1}$ d^{-1})	ON (mg $ind.^{-1}$ d^{-1})	TP (mg $ind.^{-1}$ d^{-1})	OP (mg $ind.^{-1}$ d^{-1})
Sep	S	1.21 ± 0.15^{a}	58.0 ± 7.6^{a}	13.13 ± 2.58^{a}	2.49 ± 0.36^{a}	0.70 ± 0.09^{a}	0.214 ± 0.053^{a}
	M	1.60 ± 0.18^{b}	94.0 ± 9.2^{b}	20.24 ± 2.35^{b}	3.58 ± 0.62^{a}	0.88 ± 0.06^{a}	0.289 ± 0.086^{a}
Oct	S	0.95 ± 0.09^{a}	55.6 ± 4.5^{a}	7.95 ± 0.81^{a}	1.44 ± 0.21^{a}	0.48 ± 0.05^{a}	0.177 ± 0.031^{a}
	M	1.17 ± 0.15^{a}	73.6 ± 11.8^{a}	9.91 ± 1.06^{a}	1.82 ± 0.19^{a}	0.49 ± 0.13^{a}	0.133 ± 0.087^{a}
	B	1.98 ± 0.11^{b}	153.9 ± 19.8^{b}	14.58 ± 1.60^{b}	2.76 ± 0.25^{b}	0.79 ± 0.15^{b}	0.160 ± 0.126^{a}
Nov	S	1.12 ± 0.10^{a}	37.1 ± 11.5^{a}	4.06 ± 0.55^{a}	1.22 ± 0.16^{a}	0.34 ± 0.04^{a}	0.088 ± 0.028^{a}
	M	1.94 ± 0.14^{b}	54.8 ± 12.4^{ab}	6.85 ± 1.95^{a}	1.83 ± 0.26^{b}	0.48 ± 0.02^{b}	0.029 ± 0.008^{b}
	B	1.43 ± 0.12^{c}	71.8 ± 7.1^{b}	10.79 ± 2.33^{b}	2.24 ± 0.38^{b}	0.35 ± 0.03^{a}	0.030 ± 0.026^{b}
Mean	S	1.09 ± 0.13	50.2 ± 11.4	8.38 ± 4.55	1.72 ± 0.68	0.51 ± 0.18	0.160 ± 0.065
	M	1.57 ± 0.39	74.1 ± 19.6	12.33 ± 7.02	2.41 ± 1.01	0.62 ± 0.23	0.150 ± 0.131
	B	1.70 ± 0.19	112.8 ± 29.0	12.68 ± 1.34	2.50 ± 0.18	0.57 ± 0.16	0.095 ± 0.46

Table 8. Mean (±SD) trace element (As, Cd, Cr, Cu, Zn, Pb and Hg) biodeposition rates (µg ind.$^{-1}$ d^{-1}) of *Argopecten irradians* during September through November in Laizhou Bay. S: small size; M: medium size; B: big size. Different letters in the same month and column indicate significant differences ($p < 0.05$)

Time	Size	As	Cd	Cr	Cu	Pb	Zn	Hg
Sep	S	49.65 ± 4.34[a]	–0.09 ± 0.04[a]	143.90 ± 17.67[b]	53.42 ± 4.80[a]	30.26 ± 4.41[a]	161.15 ± 16.16[a]	0.25 ± 0.07[a]
	M	60.82 ± 21.82[a]	0.14 ± 0.12[b]	101.58 ± 14.58[a]	61.54 ± 9.91[a]	31.48 ± 8.37[a]	219.56 ± 28.17[b]	0.41 ± 0.08[a]
Oct	S	54.96 ± 14.10[a]	–0.06 ± 0.02[a]	160.17 ± 28.63[a]	45.94 ± 6.02[a]	47.73 ± 11.39[b]	157.64 ± 64.95[a]	0.31 ± 0.04[a]
	M	52.10 ± 9.93[a]	–0.05 ± 0.06[a]	163.31 ± 19.01[a]	49.40 ± 4.30[a]	31.79 ± 2.26[a]	187.21 ± 29.63[a]	0.42 ± 0.07[a]
	B	72.74 ± 5.95[b]	0.26 ± 0.31[a]	306.84 ± 19.73[b]	79.32 ± 9.76[b]	52.65 ± 2.04[b]	268.52 ± 18.95[b]	0.44 ± 0.16[a]
Nov	S	42.39 ± 3.49[a]	0.17 ± 0.15[a]	74.80 ± 5.57[a]	34.47 ± 2.59[a]	59.45 ± 16.72[a]	131.61 ± 14.24[a]	0.48 ± 0.05[a]
	M	73.04 ± 15.98[b]	0.05 ± 0.03[a]	115.80 ± 1.37[b]	50.78 ± 3.72[b]	95.36 ± 33.14[a]	201.58 ± 39.61[b]	0.77 ± 0.13[b]
	B	81.56 ± 12.43[b]	0.23 ± 0.14[a]	115.95 ± 8.97[b]	54.78 ± 6.24[b]	80.86 ± 4.54[a]	258.33 ± 33.77[b]	0.87 ± 0.13[b]
Mean	S	46.45 ± 4.71	0.00 ± 0.15	119.49 ± 38.75	42.73 ± 9.71	45.68 ± 14.66	144.02 ± 15.33	0.34 ± 0.13
	M	61.96 ± 10.56	0.05 ± 0.09	126.89 ± 32.33	53.91 ± 6.65	52.88 ± 36.79	202.79 ± 16.21	0.53 ± 0.21
	B	77.15 ± 6.23	0.24 ± 0.02	211.39 ± 134.98	67.05 ± 17.35	66.75 ± 19.95	263.42 ± 7.20	0.65 ± 0.15

Clearance rate of bay scallops

Due to unfavorable weather conditions in September and November, concentrations of TPM could only be determined in the study area during the month of October. The concentrations of TPM, POM and PIM were 17.8 ± 6.9, 3.4 ± 1.2 and 14.4 ± 5.7 mg l^{-1}, respectively. The clearance rate of scallops for the 3 size categories of small, medium and big were 2.28 ± 0.37, 3.08 ± 0.28 and 4.09 ± 0.56 l ind.$^{-1}$ h^{-1} (mean ± SD), respectively, with the largest size being significantly higher than the smallest ($p < 0.01$). The exponential relationship between clearance rate and tissue DW was $CR = 2.68 \times W^{0.63}$ ($R^2 = 0.87$).

DISCUSSION

In this study, we first reported the allometric relationship between biodeposition rates and soft tissue DW of bivalves. The result was in agreement with a previous report (e.g. Haven et al. 1998), that showed biodeposition per soft tissue weight of the mussel *Mytilus edulis* L. decreased with increasing size (shell length). Our results showed that the biodeposition rates of the bay scallop *Argopecten irradians* increased allometrically with flesh weight in temperate seasons when water temperatures ranged between 16 and 24°C. This relationship, however, ceased to exist when water temperatures fell below 10°C in the colder months.

This study also demonstrated that the bay scallop biodeposition rates in Laizhou Bay were rather high (1.24 g [g tissue DW]$^{-1}$ d^{-1}) and fall within the upper range reported previously for other filter-feeding bivalves (0.042 to 2.25 g [g tissue DW]$^{-1}$ d^{-1}; Table 9 and references therein). It has also been demonstrated that the bay scallop could enhance the sedimentation of seston, equal to their dry weight in magnitude. Li et al. (2009) estimated the BDR of *A. irradians* in laboratory raceway tanks to be 0.155 to 0.175 g (g DW)$^{-1}$ d^{-1}. However, the dry weight in their study was the total DW including shells; based on the flesh tissue DW, the BDR was calculated to be 0.62 to 0.70 g (g tissue DW)$^{-1}$ d^{-1}, which is lower than the values in our study. The high growth rate (0.35 mm d^{-1} in shell height) and thus high energy demand may contribute to the quick filtration–biodeposition process and sedimentation of TPM.

As is shown in Tables 7 & 9, the biodeposition rates of POM and particulate biogenic elements were very high. POM can absorb large quantities of trace elements due to their larger specific surface area and functional groups like carboxyl, ketone and hydroxyl, and cation exchange capacity (Hooda & Alloway 1998). Thus, the suspension-cultured bay scallops could significantly increase the fluxes of organic matter, biogenic elements and trace elements from the overlying water to the seabed. In Laizhou Bay, *A. irradians* is cultured at a density of 200 ind. m^{-2}. Based on the mean biodeposition rate of scallops of medium size in October (54.80 ± 1.13 mm shell height), the daily biodeposit production by *A. irradians* amounted to 214 g m^{-2}; the daily C, N and P were 1.98, 0.36 and 9.8×10^{-2} g m^{-2}, respectively; and the daily trace element (As, Cd, Cr, Cu, Pb, Zn and Hg) biodeposition rates were 10.42, –0.01, 32.66, 9.88, 6.36, 37.44 and 0.08 mg m^{-2}, respectively. For total cultured scallops (ca. 1.07×10^9 ind.) in the bay, the daily biodeposition rate was 1140 metric tonnes (t) dry material, or 10.60 t C, 1.95 t N, 0.52 t TP, 0.05 t As, -5.35×10^{-5} t Cd, 0.17 t Cr, 0.05 t Cu, 0.03 t Pb, 0.20 t Zn and 4.49×10^{-4} t Hg.

Table 9. Comparison of bivalve biodeposition rates. DW: dry weight; TPM: total particulate matter

Species		Biodeposition rate (mg [g tissue DW]$^{-1}$ d^{-1})	Reference
Mytilus edulis	TPM	42.4	Kautsky & Evans (1987)
	C	3.88	
	N	0.505	
	P	5.49×10^{-2}	
Choromytilus chorus	TPM	689	Jaramillo et al. (1992)
	C	44.1	
	N	2.07	
Mytilus chilensis	TPM	595	Jaramillo et al. (1992)
	C	35.7	
	N	2.38	
Modiolus demissus	N	1.2	Jordan & Valiela (1982)
Modiolus americanus	TPM	2250	Peterson & Heck (1999)
	C	24.8	
	N	2.47	
	P	8.16×10^{-2}	
Chlamys farreri	TPM	173.1	Zhou et al. (2006a)
	C	6.8	
	N	0.86	
	P	0.22	
Chlamys farreri	TPM	122.3	Zhou et al. (2006b)
	C	6.3	
	N	0.80	
	P	0.17	
Argopecten irradians	TPM	617–697	Li et al. (2009)
Patinopecten yessoensis	TPM	686	Yuan et al. (2010)
Mytilus edulis	C	2.69	Jansen et al. (2012)
	N	0.31	
	P	0.02	
Argopecten irradians	TPM	1244	Present study
	C	9.49	
	N	1.95	
	P	0.58	

Thus, biodeposition loadings from subtidal bay scallop culture can be significant. Furthermore, the harvest of scallops can potentially remove 966 t C, 236 t N, and 20.89 t P in their soft tissue and 2046 t C, 16.6 t N, 3.33 t OP and 5.33 t TP in their shells (Table 10). The organic concentration of surface sediments in Laizhou Bay is relatively low, with a TOC of approx. 0.30% and TN of 0.03% (Table 11). The large quantities of biodeposits produced by the densely cultured bay scallops may compensate for the deficiency of organic matter in seabed and increase the secondary production rate of the benthos.

Table 10. Annual nutrient removals (in tonnes) from the Laizhou Bay ecosystem through the harvest of bay scallops in November. C: carbon; N: nitrogen; TP: total phosphorus; OP: organic phosphorus; (–) not measured

Nutrient removal	C	N	OP	TP
Soft tissue harvest	966	236.2	–	20.89
Shell harvest	2046	16.6	3.33	5.33

Enrichment of OM, OC and TN in sediments produced by biodeposits of suspension feeders has been found in various coastal waters (Vinther & Holmer 2008, Yuan et al. 2010, Rampazzo et al. 2013). This study also found that the OM concentration in sediments from traps containing bay scallops was significantly higher than those in reference traps, which suggested that the bay scallops may have a preference for the organic-enriched matter in the water column. Evidence from a previous laboratory study conducted by Heinonen et al. (2007) showed that the feeding activities of suspension feeders (i.e. the blue mussel *M. edulis* and the bay scallop *A. irradians*) could significantly enhance transparent exopolymer particle (TEP) concentrations in ambient waters, which could lead to enhanced flocculation of OM and C deposition in near-shore waters. The TEP production by densely cultured scallops may be more intense and contribute to the sedimentation of OM and the enrichment of sediment. The OM concentration of faeces produced by bay scallops feeding on a diet of phytoplankton (Chrysophyceae) and kelp is 33.31 and 24.14% (Mao et al. 1997), well above that of the natural sediment (<5%; Fig. 3).

The allometric relationship between clearance rate and tissue DW (CR = $2.68 \times W^{0.63}$) was modeled. The value of b in the equation is 0.63, similar to the mean of from 21 bivalves (0.62), as reviewed by Cranford et al. (2011). In the present study, the clearance rate of standard tissue DW (1 g) was 2.68 l ind.$^{-1}$ h^{-1}. This value is higher than laboratory determined values (shell height 50–51 mm, 0.23–0.89 l g^{-1} h^{-1}, Li et al. 2009; shell height 22–24 mm, 0.48–1.97 l g^{-1} h^{-1}, Wang et al. 2000). It has been suggested that these differences may be attributed to a disparity in scallop size, temperature, seston quantity and quality and also possibly research methodologies.

Table 11. Organic concentrations of surface sediments (mean in parentheses if available) in Laizhou Bay. TOC: total organic carbon; TN: total nitrogen; OM: organic matter

	Range (mean)	Reference
TOC	0.10–0.58 (0.32)	Hu et al. (2011)
	0.07–0.54 (0.25)	Wu et al. (2014)
	0.12–1.5	Gao et al. (2013)
	0.05–0.60 (0.24)	Zhang et al. (2014)
TN	0.01–0.06 (0.03)	Zhang et al. (2014)
OM	0.2–1.3	Liu et al. (2004)
	0.11–0.98 (0.37)	Zhou et al. (2010)
	0.76	Zhou et al. (2012)
	0.59	Zhou et al. (2012)

CONCLUSIONS

This study indicated that suspended bay scallop mariculture in Laizhou Bay may have a significant impact on the ambient coastal ecosystems through the filtering–biodeposition process. Large amounts of nitrogen and phosphorus are removed from the aquatic system during harvesting. The intensely cultured scallops in the bay may function as biofilters or recyclers by mitigating the eutrophication and trace element pollution pressure on the coastal ecosystem by controlling seston and phytoplankton levels via filtering–biodeposition processing and removing excessive nutrients from the ecosystem, while simultaneously generating valuable products. In coastal waters and estuaries subject to anthropogenic nutrient and trace element inputs, suspended bivalve aquaculture could be environmentally advantageous via intense filtering and biodeposition, as well as by potentially mitigating eutrophication and trace element pressures.

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