Chinese Journal of Oceanology and Limnology
Vol. 34 No. 5, P. 985-991, 2016
http://dx.doi.org/10.1007/s00343-016-4242-y

Temporal variation in biodeposit organic content and sinking velocity in long-line shellfish culture*

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Received Oct. 20, 2014; accepted in principle Apr. 27, 2015; accepted for publication Jul. 14, 2015

Abstract We measured the organic content and sinking velocities of biodeposits from two scallop species (*Chlamys farreri*, *Patinopecten yessoensis*) and abalone (*Haliotis discus hannai*) that were cultured on suspended long-lines. Measurements were conducted every two months from April 2010 to February 2011. The shellfish were divided into three size groups (small, middle, and big sizes). At each sample point, we assessed biodeposit organic content, average sinking velocity, the frequency distribution of sinking velocities, and the correlation between organic content and sinking velocity. The organic content of biodeposits varied significantly among months ($P<0.05$) and the pattern of change varied among species. Sinking velocities varied significantly, ranging from <0.5 cm/s to >1.9 cm/s. The sinking velocities of biodeposits from *C. farreri* and *P. yessoensis* were 0.5–1.5 cm/s and from *H. discus hannai* were <0.7 cm/s. The organic content was significantly negatively correlated to the sinking velocity of biodeposits in *C. farreri* ($P<0.001$) and *P. yessoensis* ($P<0.05$).

Keyword: biodeposit; organic content; shellfish; sinking velocity

1 INTRODUCTION

The harvest of food products from aquatic ecosystems contributes significantly to human welfare. Aquaculture is the world's fastest growing food production system, with an increasing volume and variety of species being produced. Over 500 million people in developing countries depend on fisheries and aquaculture for their food and livelihood (PaCFA, 2009). Developments in aquaculture techniques, such as suspended long-line shellfish culture, have increased the feasibility of cultivating a large biomass in a small area.

In China, suspended long-line culture is widely used in shellfish farming (Mao et al., 2009; Qi et al., 2010; Zhang et al., 2011). Marine farmers have for decades cultured commercial shellfish such as oyster, abalone, and other bivalves. Biodeposits produced by shellfish, including feces and pseudofeces, sink to the sea bottom in and around farms. The effect of biodeposition on sedimentation rates is obvious when shellfish are cultured intensively. Sedimentation rates at mussel culture sites may be twice those observed in non-aquaculture areas (Hatcher et al., 1994), and this addition of biodeposits has been shown to have a significant impact on the benthic environment. For example, mussel culture has been associated with increased releases of ammonium, increased oxygen uptake, and changes in benthic community structure in many areas (Hatcher et al., 1994; Mirto et al., 2000; Hargrave, 2005). Recently, increasing attention is being paid to the role biodeposits play in these changes.

Knowledge of the sinking dynamics of biodeposits

* Supported by the National Key Technology Research and Development Program of China (No. 2011BAD13B06), the National Natural Science Foundation of China (No. 41276172), and the Special Scientific Research Funds For Central Non-Profit Institute, CAFS (No. 2014A01YY01)
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is needed to understand the link between biodeposition and various ecosystem processes. Feces sinking rate calculations have been widely used in studies on fish (Robison and Bailey, 1981; Chen et al., 1999a, b), salps (Bruland and Silver, 1981; Phillips et al., 2009), and shellfish (Miller et al., 2002; Giles and Pilditch, 2004; Callier et al., 2006; Zhang et al., 2014). These studies were primarily focused on biodeposit production rates, their potential for dispersion (Miller et al., 2002; Giles and Pilditch, 2004), or the relationship between biodeposit size and sinking velocity (Robison and Bailey, 1981; Chen et al., 1999a; Callier et al., 2006). Conversely, little attention has been paid to seasonal variation in shellfish biodeposit composition and sinking rates.

We measured the sinking rate of shellfish biodeposits every two months during 2010–2011, using three cultured species from Sanggou Bay, Northern China: two species of scallop (*Chlamys farreri*, *Patinopecten yessoensis*) and abalone (*Haliotis discus hannai*). This allowed us to evaluate the changes in natural diet, biodeposit composition, and sinking velocity at different temporal scales. Our results can be used to inform the development of related models.

2 MATERIAL AND METHOD

2.1 Study site

The study was carried out from April 2010 to February 2011 in Sanggou Bay, Northern China (37°01′–37°09′N, 122°24′–122°35′E). The total area of the bay is about 144 km^2 with an average depth of 7.5 m. The bay has been used for aquaculture since the 1980s, and is an important study area for scientists in China. The location and characteristics of Sanggou Bay have been well described in past studies (Zhang et al., 2009, 2012, 2014; Qi et al., 2010). Environmental conditions, including temperature, salinity, dissolved oxygen, pH, and chlorophyll *a* were measured using YSI-6600 multi-parameter probes. The probes were placed in the water at the time shellfish were sampled from each farm, and set to monitor at an interval of 30 s. The probes were deployed at a depth of 1.5–2 m, the same depth as the shellfish culture cages. The three shellfish farms we evaluated were in close proximity to each other, so data for temperature, salinity, dissolved oxygen, and pH were processed together. Suspended particulate matter concentration and particulate organic matter (POM) were quantified every two months by filtering a 1-L seawater sample with pre-combusted (450°C, 4 h) and pre-weighed glass fiber filters (Whatman GF/C, 0.45 μm), then dried at 60°C for 48 h and combusted at 450°C for 4 h. The weight loss due to combustion was representative of the organic content of the suspended sediments and other seston.

Table 1 Shell length, shell weight, and body weight of shellfish used in experiment

Species	Sizes	Shell length (mm)	Shell height (mm)	Body weight (g)
C. farreri	S	25.1±2.9	28.9±2.7	3.1±0.6
	M	52.5±3.9	54.2±3.2	23.2±3.8
	B	67.2±4.7	65.9±1.6	40.7±6.5
P. yessoensis	S	38.3±3.6	39.6±1.8	4.7±1.8
	M	54.8±2.8	55.4±3.3	18.2±3.5
	B	70.9±3.1	72.6±2.5	40.2±5.3
H. discus hannai	S	42.4±2.8	-	7.4±1.5
	M	56.1±2.3	-	20.7±3.4
	B	68.8±2.6	-	34.9±3.8

"-" indicates that the dimensions were not measured.

2.2 Shellfish

Three species of shellfish, *C. farreri*, *P. yessoensis*, and *H. discus hannai*, are commonly cultured in Sanggou Bay. We collected samples of each species from three shellfish farms that were in close proximity to each other. These three species are all cultured in a 2–3 year grow-out cycle, so it is easy to obtain different sizes of the same species at the same time. Similar sizes of shellfish were selected when sampling and they were divided between three size groups (S, M, and B for small, middle, and big sizes). The shell length, shell weight, and body weight of the shellfish used in the experiments are given in Table 1. Among these species, *C. farreri* and *P. yessoensis* are filter feeders and are cultured in 6–10 layer cages and *H. discus hannai* is fed with cultured seaweed (*Sacchariana japonica*) in 3 layer abalone cages.

2.3 Organic content and sinking velocity of biodeposits

The shellfish were collected from a commercial aquaculture farm every two months. At least 10 individuals in each group were used to measure biodeposition rates at each sample point. Each individual was carefully cleaned of its epibionts before being transported to the laboratory within 4 h in a plastic box containing ice to keep the temperature low. Chambers with filtered seawater were used for temporary culture, and biodeposits were collected 4–5 h later.

A fraction of the biodeposits were analyzed to determine biodeposit organic content.

Biodeposit sinking velocities were measured using the settling tank method described by Giles and Pilditch (2004) and Zhang et al. (2014). We transferred 1–2 biodeposit pellets to the top of the settling tank using a pipette; these were released 1 cm below the water surface to reduce the impact from being suddenly dropped. During the sinking process, the time taken to fall three consecutive 30 cm intervals was recorded. At least 40 replicates were conducted, and measurements from biodeposit pellets that sank irregularly were discarded.

Frequency distributions of sinking velocities were constructed using all velocities observed during the experimental period, summarizing velocities below 0.5 cm/s and above 1.9 cm/s. Intervals of 0.2 were defined between 0.5 and 1.9 cm/s. Sample sizes were greater than 275 for all distributions.

2.4 Data analysis

All statistical analyses were performed using software SPSS 17.0 for Windows. Variation in content among the species was evaluated using one-way ANOVA. Multiple comparisons were performed using LSD tests. Correlation analyses between organic content and sinking velocities were evaluated using Pearson correlation analysis. Given that re-collection of each pellet used during measurement of sinking velocity was impracticable, data for the correlation analyses consisted of the mean per species, month, and size class.

3 RESULT

3.1 Environmental conditions of shellfish cultured area

The observed environmental conditions are summarized in Fig.1. During the sampling period, the maximum water temperature was 22.5°C in August, and the minimum was 1.1°C in February. Salinity and pH varied slightly. The dissolved oxygen concentration decreased from April to October, the minimum being 4.64 mg/L, and then increased to 14.61 mg/L in February 2011. POM and chlorophyll a values in the abalone area were not collected in February because abalones are transported to southern China for winter culture. POM content ranged from 2.12 to 7.30 mg/L.

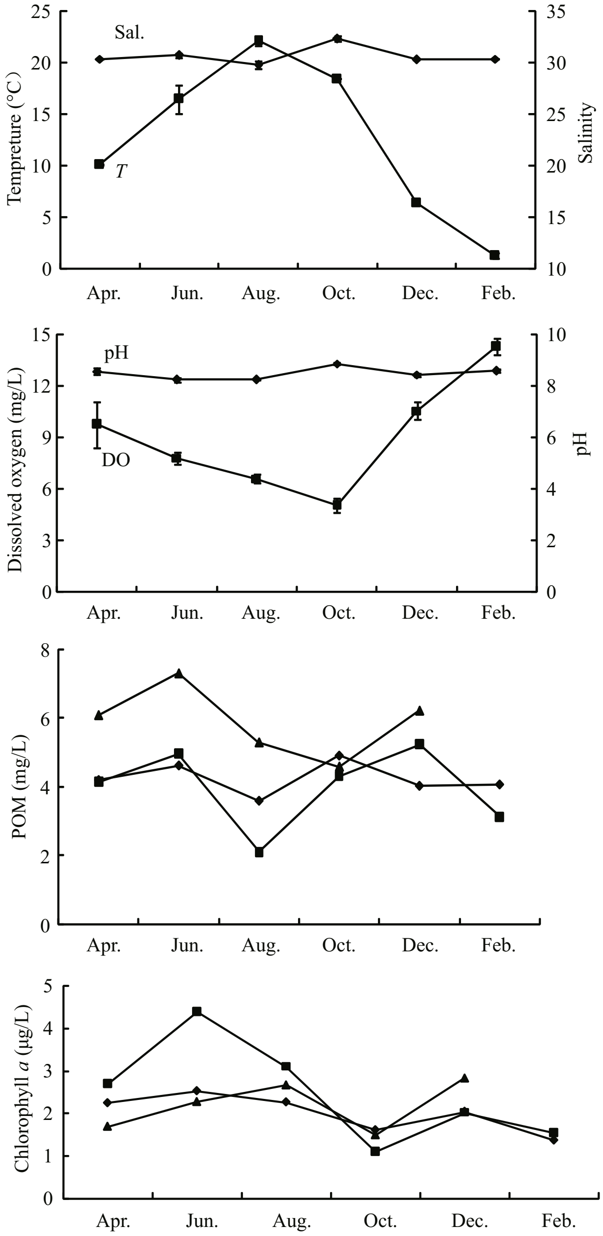

Fig.1 Time series of environmental data for temperature, salinity, dissolved oxygen, pH, POM and chlorophyll *a*

For POM and chlorophyll *a*, symbols are as follows: *C. farreri* (diamond), *P. yessoensis* (square) and *H. discus hannai* (triangle).

Chlorophyll *a* was consistently greater than 1 μg/L, with a maximum of 4.39 μg/L.

3.2 Sizes of shellfish

The mean sizes of all individuals in each group used over the whole experiment are listed in Table 1.

3.3 Organic content of biodeposits

The organic content of shellfish biodeposits used in this study varied over time, and the trend in variation

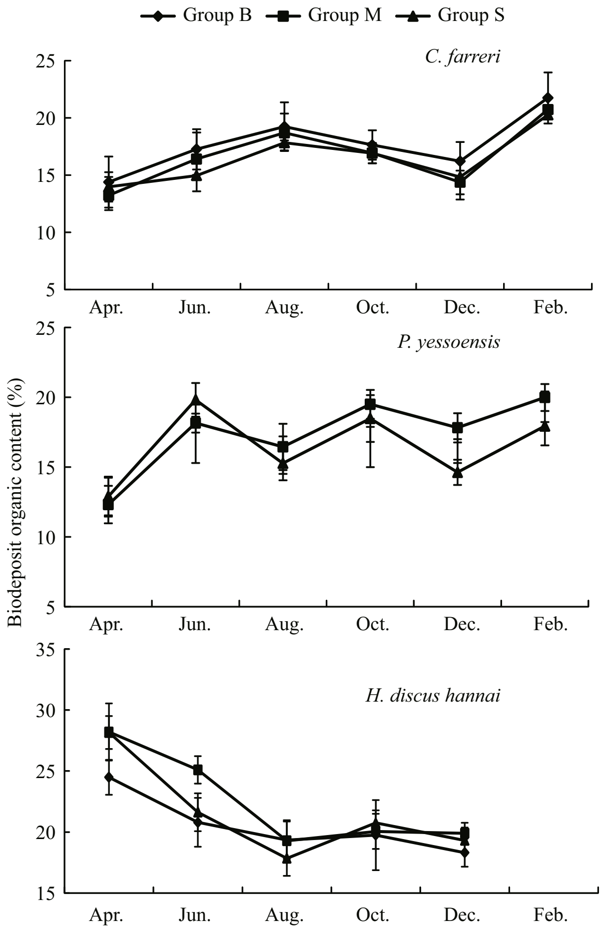

Fig.2 Species-specific organic content of biodeposits in different months

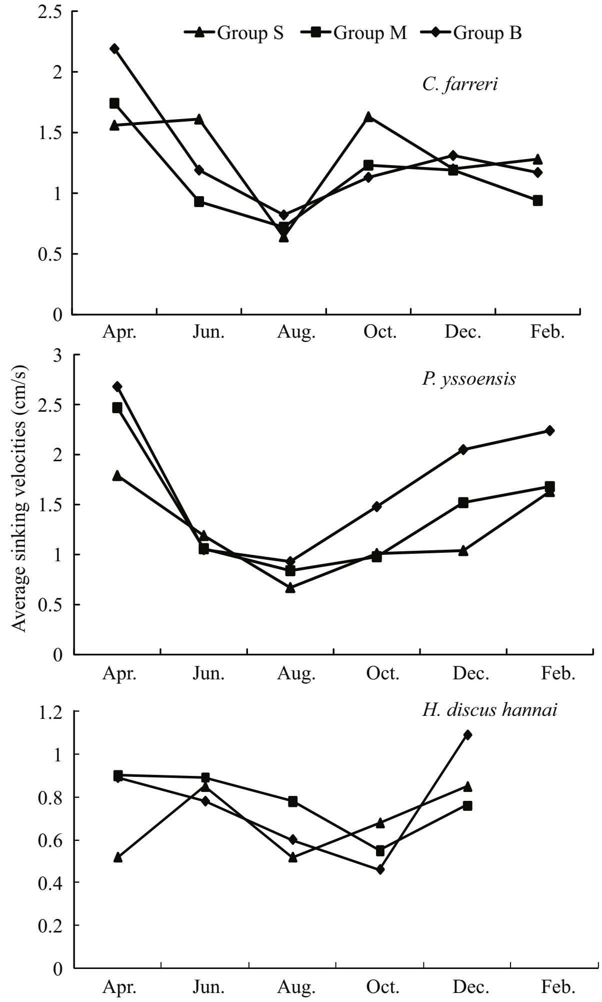

Fig.3 Species-specific biodeposit pellet sinking velocities over the study period

was similar among different size groups (Fig.2). One-way ANOVA revealed that the organic content of *C. farreri* biodeposits did not differ among size groups (P>0.05).

The organic content of biodeposits differed significantly (P<0.05) among bivalve size classes in 3 (*P. yessoensis*: June, October, and December) and 2 (*H. discus hannai*: April and June) months. The organic content of biodeposits also varied significantly between these months (P<0.05). The organic content of biodeposits from *C. farreri* was about 15% lower in April and December than in other months, but had a secondary peak (in August) between these two months. The primary peak (20.9%) occurred in February when values were significantly higher than in other months (P<0.05). The range of organic content of biodeposits was similar in *P. yessoensis and C. farreri*, but the pattern of change among the months differed. In April, the organic content of *P. yessoensis* biodeposits was lowest, at about 12.7%. Low and high values recurred every two months. The organic content of *H. discus hannai* biodeposits decreased from April to August. In April, the organic content of *H. discus hannai* biodeposits was 27%, but declined to 18.8% in August. Changes from August to December were minimal.

3.4 Sinking velocities of biodeposits

Biodeposit sinking velocities varied significantly between months, size groups, and within groups (Fig.3). The sinking velocities of *C. farreri* and *P. yessoensis* had a similar range, from 0.5 to 2.5 cm/s, and were lowest in August. The peak sinking velocity of *C. farreri* biodeposits was about 2.2 cm/s in group B in April. The trend in sinking velocity was similar among the three sizes groups of *P. yessoensis*, decreasing from April to August and then increasing until February. The sinking velocities of *H. discus hannai* fecal pellets were lower than those of the other two species, with mean values being less than 1 cm/s

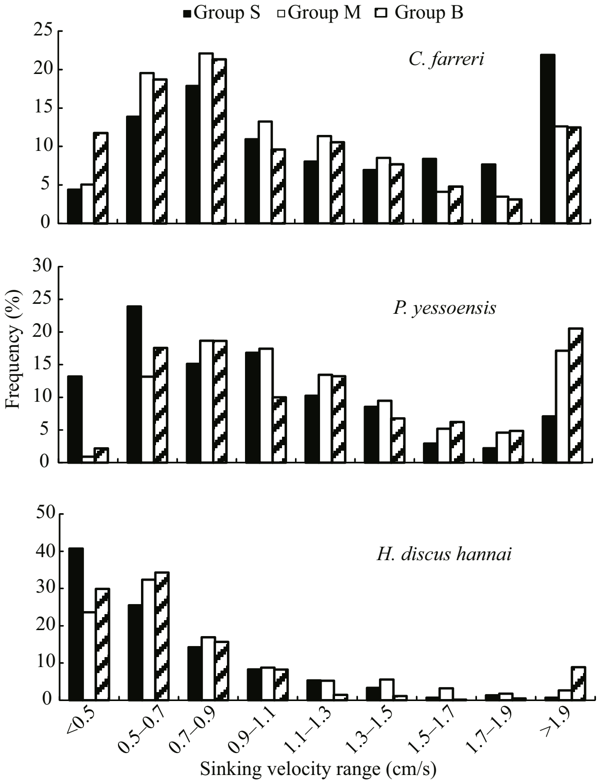

Fig.4 Species-specific frequency distributions of biodeposit pellet sinking velocities

Table 2 Correlated analysis between organic content and sinking velocities

	Organic content	
Sinking velocities	Pearson correlation	*P*
C. farreri	-0.516	0.000
P. yessoensis	-0.356	0.008
H. discus hannai	1.271	0.405

throughout most of the 10 months. The trend was similar in groups B and M, falling from April to October, and then increasing in December. In group S, the values in April and August were low, at about 0.52 cm/s.

3.5 Frequency distribution of sinking velocities

Species- and size-specific biodeposit pellet sinking velocity frequency distributions are shown in Fig.4. Biodeposit pellet sinking velocities varied over a wide range for all species and size groups examined. For *C. farreri* and *P. yessoensis*, most biodeposit pellets sank at a rate of 0.5–1.1 cm/s, though velocities >1.9 cm/s were also observed. Sinking velocities less than 0.7 cm/s accounted for greater than 50% of those measured for all size groups of *H. discus hannai*.

3.6 Correlation analysis between organic content and sinking velocities

Organic content was significantly correlated to the sinking velocities of biodeposits from *C. farreri* and *P. yessoensis*, but not from *H. discus hannai* groups (Table 2).

4 DISCUSSION

Filter feeders produce feces and pseudofeces, collectively called biodeposits. These biodeposits are compacted aggregates of particles (0.5–3 mm) that sink more rapidly than their constituent particles (Haven and Morales-Alamo, 1968; McCall, 1979). The natural diet of bivalves may include a variety of organic and inorganic components that vary widely in space and time (Fegley et al., 1992; Bayne, 1993). As the nature and concentration of POM and chlorophyll a change with the season, so too do the constituents of biodeposits. In a study of annual biodeposition by the Pacific oyster *Crassostrea gigas*, biodeposit organic content varied from 18.6% in February to 46.5% in June (Bernard, 1974). In the mussel *Mytilus edulis*, the organic content varied from 20% to greater than 35% (Callier et al., 2006). Wang et al. (2003) found that the POM and chlorophyll a concentrations in biodeposits from *C. farreri* changed with the concentration of POM and chlorophyll a in the seawater. Other research has documented similar findings for Pacific oyster (Wang et al., 2005). Zhou et al. (2003) reported that the organic matter of *C. farreri* biodeposits was 11.3%, lower than the minimum value observed in our study (Fig.2); this may have been due to differences in the methods employed in the two studies. The organic content of biodeposits from abalone ranged from 17.8% to 28.2%, higher than those from the other species examined in this research. The organic content of biodeposits from abalone was 18.3%–19.9% in December, according to a report by Zhang et al. (2014), and similar to our results. The variation in biodeposit organic content for abalone is likely influenced by their food, *S. japonica*. From April to June, fresh kelp was not available to fulfill the dietary needs of abalone in Sanggou Bay, so dry kelp stored from the previous year was used instead. This may explain, in part, why the biodeposit organic content was higher in those months.

Larger animals are likely to produce larger biodeposits (Paffenhöfer and Knowles, 1979; Uye and Kaname, 1994; Feinberg and Dam, 1998). Given the positive correlation between sinking velocity and biodeposit size (Chen et al., 1999a, b; Giles and Pilditch, 2004; Callier et al., 2006), group B should have produced biodeposits with the greatest sinking velocities. However, as the results in Fig.3 show, the sinking velocities of biodeposits from the three size groups varied among months and those from the largest size groups did not always have the highest sinking velocity. Results from the analysis of the frequency distribution of sinking velocities may provide a reasonable explanation for this (Fig.4). Larger animals produce larger biodeposits as well as having a higher biodeposit production rate (Wang et al., 2003, 2005; Zhou et al., 2003; Zhang et al., 2014), but the contribution of large size biodeposits to the total determines the average size of biodeposits and the average sinking velocities. Our research is the first to report the frequency distribution of sinking velocities from different species of shellfish. These frequency distributions should be useful in allowing the careful description of the sinking state of biodeposits from these three species.

Data on sedimentation velocities were used to estimate potential dispersal distances using the following model:

$$D=V\cdot d/v, \quad (1)$$

where D is the potential spread distance (m), V is the current speed (m/s), d is the depth of water below the mussel lines, and v is the sinking velocity of biodeposits (Silvert and Cromey, 2001). Based on observed farm waste sedimentation rates, Jiang et al. (2012) suggested that waste would be dispersed to only about 150 m from a farm cage, although field measurements of benthic sediment conditions suggested that dispersal occurred up to 400 m. Perturbation by wild fish and resuspension were suggested as mechanisms that may account for the greater observed dispersal (Sarà et al., 2004; Danielsson et al., 2007). Our study shows that there is significant variation in sinking velocities, ranging from about 0.4 cm/s to greater than 2.4 cm/s. This variation will affect estimates of potential dispersal.

The relationship between sinking velocity and biodeposit size, especially fecal pellet width, has been well documented in previous studies (Bruland and Silver, 1981; Chen et al., 1999a, b; Giles and Pilditch, 2004; Callier et al., 2006; Zhang et al., 2014). Fecal pellet composition, density, and size are thought to play a role in influencing sinking velocity (Ploug et al., 2008), but the influence of different constituent components in the biodeposits are poorly understood. The correlation between biodeposit organic content and sinking velocity was significant and negative for two of the bivalve species we evaluated. In contrast, the two variables were not correlated for *H. discus hannai*. The irregular shape of biodeposits from *H. discus hannai* may account for this lack of correlation (Zhang et al., 2014). We hypothesize that composition and density may affect sinking velocities, and further research will be conducted to clarify this.

5 CONCLUSION

The organic content of biodeposits varied significantly between months, and the temporal and size-specific trend in changes varied among species. Sinking velocities varied significantly, ranging from <0.5 cm/s to >1.9 cm/s. The frequency distribution of sinking velocities was a suitable method to describe the variation in sinking velocities. The sinking velocities of *C. farreri* and *P. yessoensis* biodeposits varied between 0.5–1.5 cm/s whereas those of *H. discus hannai* were less than 0.7 cm/s. Biodeposit organic content was significantly and negatively correlated to sinking velocity for *C. farreri* and *P. yessoensis*, but not for *H. discus hannai*.

6 ACKNOWLEDGEMENT

We are grateful to Mr. ZHANG Huayue of Xunshan Fishery Group for his help in this work, and to Mr. BIAN Dapeng with his team from the National Marine Shellfish Engineering Technology Center for their support.

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