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Filtration rates of the green-lipped mussel *Perna viridis* (Linnaeus, 1758) exposed to high concentration of suspended particles

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ABSTRACT: High suspended loading is one of the environmental stressors which could affect survival rates and feeding activities of marine bivalves especially the coastal species. Therefore, this study aimed to examine the effects of suspended particles (SP) on filtration rates of the green-lipped mussel *Perna viridis*, which is a commercial bivalve species in Thai coastal waters. The large and small mussels were subjected to 250 mg and 500 mg of SP/l, and a control treatment (0 mg of SP/l) in the experimental laboratory. Filtration rates of the mussels were measured at day 0, day 15, and day 20 after the exposure to SP. The results showed that filtration rates of two class-sizes of the mussels significantly decreased after the exposure to SP for 15 and 20 days. Before the exposure to SP (day 0), the large mussels had significantly greater filtration rates than the smaller individuals, indicating the size-dependent effects. Filtration rates of the mussels decreased with increasing concentrations of SP. Gill abnormalities, e.g., loss of cilia on the gill lamella, were detected in the selected mussels at 500 mg of SP/l. The small mussels exhibited less capability in maintaining filtration rates compared with the larger mussels under high SP concentration. Moreover, changes in filtration rates over the exposure time were also discussed based in our study. Overall, the results can reflect deleterious effects of high SP on the mussels, particularly in filter-feeding activities. These findings could raise environmental concerns over high SP that could damage cultured mussels and coastal ecosystems.

KEYWORDS: filtration rate, marine bivalves, green-lipped mussel, suspended solids, coastal pollution

INTRODUCTION

Coastal ecosystems provide various ecological services for humans and other organisms. However, the systems have been currently disturbed by several anthropogenic activities [1, 2]. Coastal construction, land reclamation, and land erosion can generate high suspended particles (SP) in water, which could be subsequently transported to coastal environments by riverine runoffs [3]. SP are considered as non-toxic pollutions, which however have some negative effects on coastal ecosystems [4]; for examples, they reduce primary productions [5], transport toxins and chemicals to coastal food webs [1, 6], and change the behaviours and ecological traits of marine biota [7].

Marine bivalves are primarily vulnerable to water turbidity due to their filter-feeding behaviour. Exposure to high suspended solids can lead to gill damages [8], changes in respiratory and filtration rates [9, 10], and reduced growth performance [11, 12]. Adaptive strategies to high suspended solids may be different between species and populations due to their adaptive capabilities and environmental histories. Intra- and inter-specific variations in responses to high suspended solids and sestons have been reported in previous studies [13, 14]. Those variations may be associated with several intrinsic and extrinsic factors, for examples, concentrations and characteristics of suspended solids, body sizes of animals, filtration rates, and pseudofaeces production [15]. For ecological concerns, marine bivalves play crucial roles in coastal ecosystems which include biofiltration and biodeposition [16], ecological links between pelagic and benthic processes [17], and the key species for controlling abundance of phytoplankton [18]. Also, many bivalve species are among the most important species in fisheries along coastlines in many countries of Southeast Asia [19]. Therefore, it is necessary to determine bivalve responses to high turbidity to understand the impacts of solid particles on filter-feeding bivalves and coastal ecosystems.

The green-lipped mussel *Perna viridis* is a native marine bivalve of the Indo-Pacific region and generally cultured in many coastal areas of Asia [20, 21]. In Thailand, *P. viridis* is intensively cultured using bamboo poles and mussel-rafting techniques in estuaries and coastal waters, especially in the upper Gulf of Thailand and several bays in Southern Thailand [22, 23]. According to previous reports, these green mussels are sensitive to several environmental changes. Extreme freshwater loading into the culture sites during rainy season can cause mass mortality and reduce the growth of the mussels [24, 25]. Although high suspended solids are usually consequences from freshwater discharge, their impacts on the mussel *P. viridis* are less known, particularly for the native mussel populations and size-specific vulnerabilities. Therefore, this study aimed to examine filtration rates of the mussel *P. viridis* (small and large sizes) under various concentrations of SP. It was also hypothesised that exposure to extreme

suspended solids probably cause some degrees of gill damage in the mussels. Gill ultrastructure of the mussels at a high concentration of SP was investigated using scanning electron microscope (SEM). The results could let one understand the mussel responses significantly beneficial to the ecological studies and the *in-situ* culture of mussels in the future.

MATERIALS AND METHODS

The experimental animals and preparation

The acclimation and experimental protocols in this study were approved by The Animal Care and Use Committee of Faculty of Science, Chulalongkorn University (Protocol Review No. 2023004). The green-lipped mussel *Perna viridis*, including small size (20 mm of shell length) and large size (60–70 mm of shell length), were obtained from Sriracha Fisheries Research Station, Faculty of Fishery, Kasetsart University. The animals were individually acclimated in plastic containers ($27 \times 37 \times 15$ cm^3) with 28 psu of aerated artificial seawater. The conditions were kept constant at water temperature of about 28 °C under a 12:12 h light/dark cycle for a week prior to the experiment. The animals were fed with a volume of 10 ml of microalgae *Isochrysis* sp. (9×10^6 cells/ml of the stock solution) every two days throughout the acclimation period. The microalgae were propagated in the laboratory, following the protocol of Ogata et al [26]. Up to half of water volume in the containers was daily changed in order to prevent elevation of nitrogenous wastes in the system.

Sediments were collected from the sampling site near the mussel cultivated zone of the Research Station. The sediments were sieved through 250 μm, and the sediment particles of less than 250 μm were collected. These sediments were dried at 180 °C in a hot-air oven prior to the experiment. To construct the SP treatments, the sediments were weighed and poured into plastic containers ($27 \times 37 \times 15$ cm^3) containing 1.5 l of artificial seawater at 28 psu with aeration. The accurate amount of SP was confirmed using a turbidity meter. A water pump was placed in each container to maintain the suspension of particles in seawater.

The experimental design and set-up

Different amounts of SP were used in the experimental laboratory. The control group was not filled with any SP, while the treatment groups were treated with 250 mg and 500 mg of SP/l. After the acclimation, the experimental animals, small and large mussels, were individually transferred to the suspended-particle treatments (five independent replications per treatment per class size). The tested mussels were fed with microalgae *Isochrysis* sp. every two days except a day before their filtration rates were measured. Water temperature and a light/dark cycle were similar to the acclimation period as mentioned in the previous section. Besides, half of seawater volume in the containers was changed every day, and the concentration of SP was adjusted every time after the exchanges of water.

Filtration rates of each tested mussel were measured at day 0 (the initial time), day 15, and day 20 after the treatments. Filtration rates were determined by the removal of microalgae *Isochrysis* sp. from seawater caused by the feeding activity of the mussels [27]. The animals were allowed to acclimate in the containers for 30 min prior to the measurement. After that, a volume of 50 ml of microalgae *Isochrysis* sp. was put into the containers. The filtration rate of the animals was calculated by the difference in the density of microalgae over time. According to several previous studies, the mussels showed different filtration rates over times. Moreover, changes in the microalgal concentrations over filtration periods can affect the filtration rates of marine bivalves [28]. In this study, therefore, the filtration rate of individual mussels was examined at 0, 10, 20, 30, 40, 50, 60, and 90 min after microalgae were added. A volume of 1 ml of seawater was sampled and kept in a microcentrifuge tube. The water samples were then quickly added with a drop of 4% neutral formaldehyde for fixing the microalgal cells. The density of microalgae in the water samples was determined using a haemocytometer (four replications per sample). The filtration rate per individual mussel was calculated using Riisgård's Eq. (1):

$$\text{Filtration rate} = \frac{v}{t} \ln\left(\frac{C_0}{C_t}\right), \tag{1}$$

where v is the volume of water in the plastic container (ml); t is a duration of a measurement; and C_0 and C_t are the concentrations (cells/ml) of microalgae *Isochrysis* sp. at the initial time ($t = 0$) and the final time (min), respectively. Hence, the unit of filtration rates was expressed in ml/min.

Filtration rates at 90 min were adopted to compare filtration rates of the mussels between SP concentrations and body sizes of the mussels. As mentioned in the previous section, we hypothesized that exposure to high SP might lead to gill damages that might influence gill functions, especially in filter-feeding activities.

At the end of the experiment, therefore, the selected mussels were euthanized using a chilling method. The gill samples of the mussels at 500 mg of SP/l ($n = 3$) were collected to further observe the changes in their gill ultrastructure using a scanning electron microscope (SEM).

Statistical analyses

Statistical analyses in this study were performed using IBM SPSS statistics (version 22; Armonk, NY: IBM Corp.), licensed by Chulalongkorn University. Differences in the filtration rates of the mussels among

the elapsed times and exposure times were analysed using repeated measure one-way ANOVA, followed by the Bonferroni test used for the multiple comparison tests. Differences in filtration rates at 90 min between SP concentrations and body sizes of the mussels were analysed using one-way ANOVA, followed by the Tukey's HSD test. The data transformation was used when the data did not show the normality and the homogeneity of variances. Significant differences were accepted at $p < 0.05$.

RESULTS

SP had effects on the filtration rates of the mussel *P. viridis* (Fig. 1). Both small and large mussels showed some significant differences in their filtration rates over time after the exposure to 250 mg of SP/l (the small size group: repeated measure one-way ANOVA, $F = 27.934$, $p < 0.05$; the large size group: repeated measure one-way ANOVA, $F = 14.039$, $p < 0.05$). After the exposure to 250 mg of SP/l, the filtration rates of both the small size and the large size groups were significantly reduced over time at day 15 and day 20 compared with day 0 (Bonferroni test; $p < 0.05$). The exposure to 500 mg of SP/l also significantly affected the filtration rates of the two groups over time (the small size group: repeated measure one-way ANOVA, $F = 101.450$, $p < 0.05$; the large size group: repeated measure one-way ANOVA, $F = 19.535$, $p < 0.05$). The Bonferroni test indicated that both groups of the mussels had significantly lower filtration rates over time at day 15 and day 20 compared with day 0 ($p < 0.05$) (Fig. 1). In the control group, filtration rates of the mussels over time were not significantly different between each elapsed time after the SP exposure. All mussels of both sizes in the control group could survive throughout the experiment without any mortality. On the other hand, there was mortality in both large and small mussels at day 15 and day 20 after the exposure to SP.

The results at day 0 (prior the exposure to SP indicated that filtration rates of the mussels were affected by the body size (one-way ANOVA, $F = 15.594$, $p < 0.05$), i.e., the large mussels had significantly higher filtration rates than the small mussels (Tukey's HSD test; $p < 0.05$) as shown in Fig. 2. At day 15 of the exposure, the filtration rates of both the large and the small mussels were significantly affected by the SP concentrations (one-way ANOVA, $F = 22.252$, $p < 0.05$). Both groups had a decrease in filtration rates after they were exposed to 250 mg and 500 mg of SP/l. However, the rates of the small mussels were significantly lower than the large mussels (Tukey's HSD test; $p < 0.05$) at the 250 mg of SP/l, and not at the 500 mg of SP/l. At day 20, both large and small mussels at 250 mg and 500 mg of SP/l had lower filtration rates compared with the control group (one-way ANOVA, $F = 62.541$, $p < 0.05$; Tukey's HSD test, $p < 0.05$). Moreover, filtration rates of the small mussels were lower than the large mussels after the exposure to 500 mg of SP/l (Tukey's HSD test, $p < 0.05$). On the other hand, filtration rates of the mussels at 250 mg of SP/l were not significantly different between the body sizes (Tukey's HSD test; $p > 0.05$).

Qualification analysis of the gill samples was investigated using a SEM (Fig. 3). In the control group, a high density of frontal, laterofrontal, and lateral cilia was found at the frontal side of the gill lamella. On the other hand, a loss of some frontal, laterofrontal, lateral cilia at the frontal side was detected in the tested mussel exposed with 500 mg of SP/l (Fig. 3). Moreover, the rest of the cilia in the experimental groups were shorter with lower density than the control.

DISCUSSION

The results in Fig. 1 demonstrated that the large and small mussels showed decreased filtration rates after the exposure to 250 mg and 500 mg of SP/l for 15 and 20 days, which were similar to what reported in previous studies that many freshwater and marine bivalves exhibited decreased filtration rates during exposure to high SP [10, 12, 29] and also consistent with another study on *P. viridis* in China. The exposure to SP could alter the filtration rates of mussels regardless of the SP concentrations [30]. Notably, our findings demonstrated that concentrations of SP affected the filtration rates of both small and large mussels, i.e., decreases in filtration rates with increasing concentrations of SP (Fig. 1 and Fig. 2). The difference in the results might be due to the longer exposure to SP in the current study. Moreover, in the control group, the large mussels showed decreases of filtration rates over elapsed time more than the small ones (Fig. 1), which could reflect the size-dependent response of the mussels to a decrease in the microalgal density during the experiment. The mussels probably reduced their filtration and valve activity during low density of microalgae in the water column, a strategy to save their energy on water pumping and filtration during low-microalgal abundance [28].

During exposure to high SP, changes in filtration rates of bivalves can be caused by several factors. Moreover, exposure to high suspended loading can result in particle clotting in the inhalant siphon and gills, leading to decreased filtration rates [31–33]. In addition to the previous reports, we hypothesised that altered filtration rates might be resulted from changes in gill structure due to its crucial roles in filter-feeding activities. Bivalve gills are considered as the secondary adaptation, the gills play important roles in filtration of food and particles in addition to gas exchange, osmoregulation, and excretion [34, 35]. In our study, gill abnormalities were detected in the selected mussels treated with 500 mg SP/l, especially the loss of cilia on the surface of the gill lamella (Fig. 3), Loss of cilia

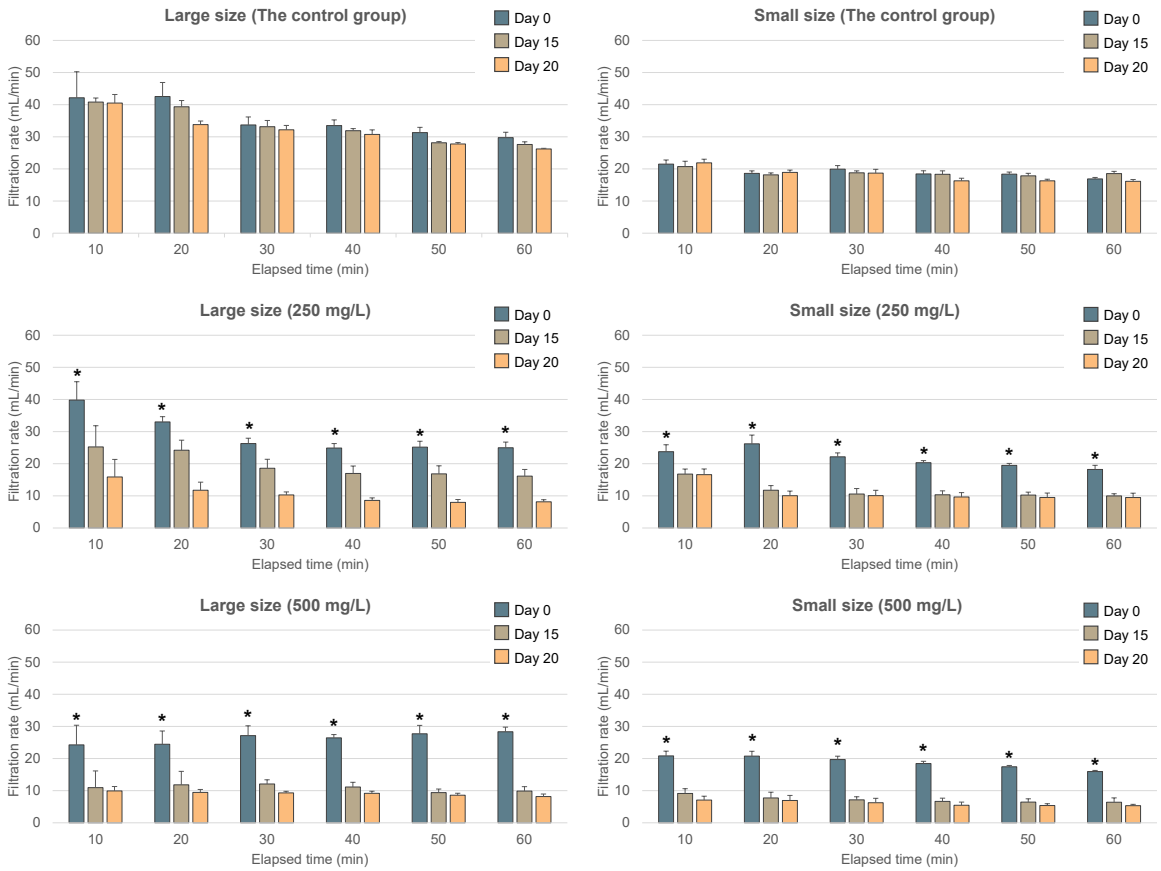

Fig. 1 Filtration rates (mean ± SE) of the large and small-size mussels *P. viridis* at day 0, 15, 20 after the treatment of 0 (the control group), 250, 500 mg of SP/l ($n = 3$–5). The asterisk above the bar chart indicates significant difference within the elapsed time assessed by the Bonferroni test ($p < 0.05$).

located at the frontal side of the gill lamella could be due to the direct contact with coarse particles in the inhaled water. Cheung and Shin [8] proposed that depletion of cilia on the gill lamella of the mussel *P. viridis* might be caused by a mechanical abrasion of sediments on the gills. Both frontal and laterofrontal cilia play important roles in filtering food and particles, capturing food, and transporting it to the mouth; while lateral cilia generate a water flow across the gills [35, 36]. Changes in the density of cilia could affect the filter-feeding process and the flow of water through the gills, resulting in decreases in filtration and water pumping rates of the tested mussels [37]. Therefore, these could explain our findings that the gill damage caused by high SP could lead to the decrease in filtration rates of the mussels after the exposure to SP for 15 and 20 days. Moreover, at day 0, the large mussels showed higher filtration rates than the small mussels (Fig. 2), implying the size-dependent effects on filtration rates of *P. viridis*, due to the differences in gill areas between the body sizes [38].

A reduction in filtration rates, which can be caused by gill damage and particle clotting in the gills, is very critical for filter-feeding bivalves. The damaged gills caused by exposure to high SP could not be repaired within several weeks [8]. Basically, changes in filtration rates refer to feeding activities and some physiological responses of the mussels. Previous studies have shown that exposure to high suspended solids can lead to reduced growth in filter-feeding mussels [11, 39]. A decrease in filtration rates caused by high SP can reduce food ingestion of bivalves, leading to reduced growth efficiency [10]. Altered filtration rates can be involved in oxygen uptake of filter-feeding bivalves in addition to food availability. The maintenance of filtration rates (ventilation rates) is very vital for the oxygen consumption of filter-feeding bivalves. Reduced filtration rates can thicken the boundary layer on the respiratory surface, resulting in a decrease in efficiency of gas exchange across the gills [40] and, subsequently, the oxygen uptake. The changes in oxygen and food availability can shift the scope for growth of the mussels, leading to reduced survival and growth performance during long-term exposure to

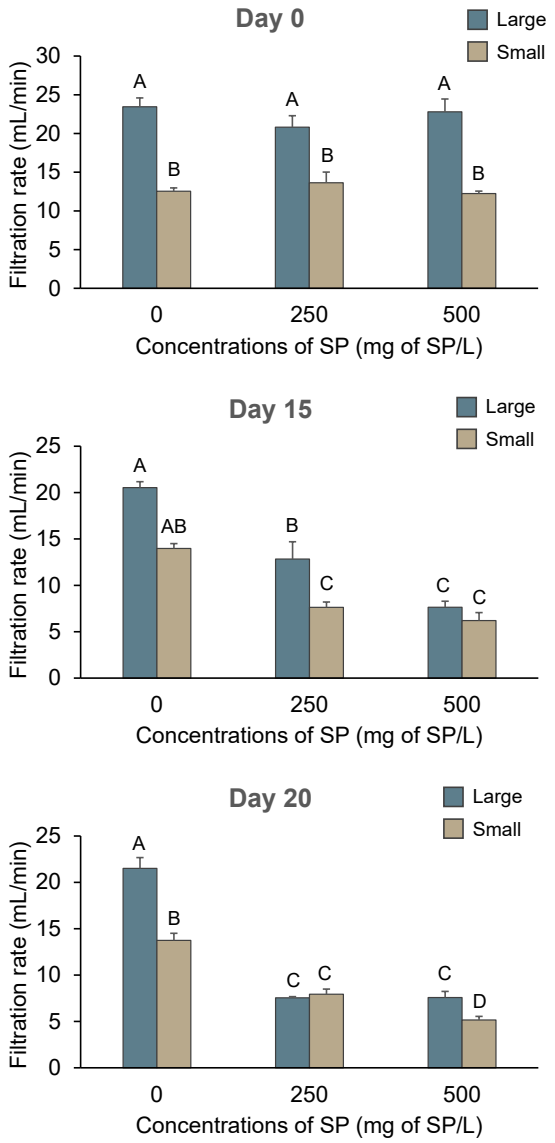

Fig. 2 Filtration rates (mean ± SE) of the large and small mussels *P. viridis* at 90 min during the measurement after they were subjected to 0 (the control group), 250, and 500 mg of SP/l for 0, 15, and 20 days. The letters above the bar charts indicate significant difference among the concentrations of SP and body sizes, which was assessed using Tukey's HSD test ($p < 0.05$).

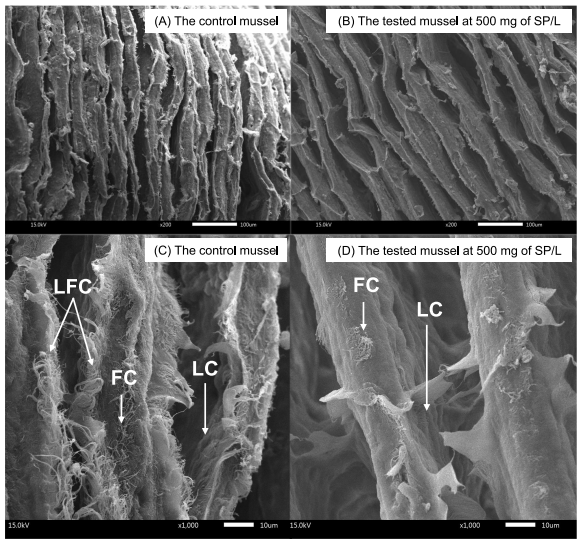

Fig. 3 The figure demonstrates the ultrastructure under SEM of the mussel gills in the control group and the tested mussels exposed to SP. Frontal views of the gill ultrastructure (200X): (A), the control mussels; and (B), the tested mussels exposed to 500 mg of SP/l for 20 days. Frontal views of the gill ultrastructure (1000X): (C), the control mussels; and (D), tested mussels exposed to 500 mg of SP/l for 20 days. Frontal cilia (FC), laterofrontal cilia (LFC), and lateral cilia (LC) are indicated in the figure.

SP [39].

Stress due to decreased filtration rates and gill damage can cause mortality of some mussels in the SP treatments. Survivorship of the rest of the mussels may depend on capabilities in particle rejection under high SP. Rejection of unfavourable particles by the labial palp, which is located in the mantle cavity, can prevent sediment feeding and enhance survival of the tested mussels during the experimental period [11]. Under high SP, notably, the small mussels seemed to exhibit less capability to maintain the filtration rates compared with the large one (Fig. 2), indicating the likely more sensitivity to high suspended loading of the small mussels compared with the large ones. Differences in maintaining the filtration rates over the exposure time could be due to the degree of gill damages and the sediment rejection activity. Moreover, maintaining scope for growth, and food availability could help filter-feeding bivalves to cope with prolonged exposure to high suspended solids [12–14]. Further studies on gill microanatomy and microstructure associated with the body size are necessary for more in-depth understanding of how the mussel responding to various SP concentrations over different exposure times. Based on our study, the exposure to high SP was likely to make the mussel *P. viridis* vulnerable. The results also further supported the FAO guide for mussel culture that suspended solids above 400 mg/l could have lethal effects on cultured mussels [32]. Prolonged exposure to high SP might have deleterious effects on cultured mussels in coastal areas, leading to reduced growth and productivity.

CONCLUSION

The current study demonstrated the effects of SP on the mussel *P. viridis*. The exposure to SP could lead to the decrease in filtration rates and the gill damages in both large and small mussels. The changes in filtration rates could be caused by the loss of cilia at the frontal side of the gill lamella; cilia play crucial roles in maintaining water flow and filter-feeding processes. Thus, high suspended solids were likely to create stressful conditions to the mussel mariculture in coastal areas, leading to reduced growth and decreased production of cultured mussels. The finding should raise some concerns over riverine runoff which might contain high amount of SP that could damage the cultured mussels, as well as the coastal ecosystems and mariculture. The results would also probably be useful for defining the suitable conditions and culture sites for mussel mariculture in the future.

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