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Seasonal Physico-Chemical Impacts on Community Structure of Microphytobenthos in a Mudflat Inside vs Outside a Breakwater System in the Inner Gulf of Thailand

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ABSTRACT. Communities of microphytobenthos in an eroded mudflat located in the Inner Gulf of Thailand were studied. This mudflat has been exposed to long-term coastal erosion for more than 30 years. A 250 m concrete breakwater system was built in 2006 to mitigate this problem. In 2015, the community structure of microphytobenthos as well as physico-chemical parameters were compared between inside or behind a breakwater (protected) and outside (unprotected) sites of this mudflat during the inter-monsoon (March) and northeast monsoon (December) periods. There were significant seasonal differences in temperature, salinity and pH in both seawater and interstitial water; values in March were lower than in December while dissolved inorganic nutrients in the water column showed the highest values in March. The sediment type was clay and clay loam at both sites of the mudflat with a higher percentage of organic matter in December than in March. However, these sediment-related parameters did not exhibit spatial differences due to the presence of the breakwater. Sediment chlorophyll a varied in the range of 30-80 mg/m2 with higher values in the unprotected mudflat in March. The temporal variations in the abundance of microphytobenthos and their predatory meiofauna were observed to be more abundant in December. Several spatial variations were observed in communities of microphytobenthos. For instance, cyanobacterial abundance in the unprotected mudflat was significantly higher than that of the protected one. The diatom *Thalassiosira* sp. was the dominant microphytobenthos in the protected mudflat while Skeletonema sp. and a cyanobacterium, *Oscillatoria* sp., was more abundant in the unprotected mudflat particularly in December. Meiofauna communities were dominated by nematodes (> 50% of total density). In March, microphytobenthos density was related to that of meiofauna abundance while abiotic factors played an important role in relation to microphytobenthos density in December. In conclusion, the environment as well as community of microphytobenthos showed strongly seasonal variations while the presence of the breakwater system played a role in modifying both physico-chemical as well as biological characteristics of this mudflat ecosystem.

KEY WORDS: microbial community, seasonal variation, breakwater system, mudflat, diatom

INTRODUCTION

Mudflats are a type of coastal ecosystem submerging only during high tides; they act as sinks of nutrients from the tidal flow and the nearby marsh (Ansari et al. , 2001). Mudflats provide nursery, foraging habitat, shelter, feeding and breeding areas for a variety of aquatic organisms including fish, crustaceans and mollusks. The fine particles of mudflat are home to benthic communities usually dominated by small-sized organisms such as microphytobenthos and meiofauna (Xuan et al, 2007). These small organisms process and recycle organic matter and act as a linkage in microbial food webs of benthic environments. These small organisms also play an important role in transferring energy to higher trophic levels by being prey to macrofauna and epibenthic organisms such as shrimp and juvenile fish (Blanchard, 1991). In addition, communities of microorganisms, mainly microphytobenthos (MPB) or benthic microalgae and their associated microbes, are responsible for the production of biofilms on surface sediments and thus affect sediment properties (Tolhurst et al., 2008 and Wooldridge et al., 2017). The abundance and diversity of MPB are key components required for sediment stability in intertidal flats (Stal and De Brouwer, 2003). At the same time, the structure and function of MPB are affected by changes in both nutrient status and herbivory of the tidal flat (Alberti et al., 2017) and also by changes in sediment particle size and composition, with organic carbon and nitrogen-content e.g., DON, PON, POC, DOC playing especially large roles.

In Thailand, mudflat areas have decreased in areal coverage due to the expansion of agricultural lands and shellfish aquaculture ponds (Barbier and Suthirathai, 2004). The loss of mudflats as well as mangrove swamps along the coast of the Inner Gulf of Thailand due to coastal erosion is also a serious issue (Jarupongsakul et al., 2009). In some mudflats, structures for mitigating coastal erosion have been established to reduce the effect of wave energy and protect the coastline. The most popular coastal erosion mitigation system for mudflat and mangrove areas is to construct bamboo fences (Paphavasit et al., 2011). These bamboo fences last for a few years but are routinely destroyed by storms in a short period of time (Jarupongsakul et al., 2009). A more permanent structure, a breakwater formed by concrete poles, was first introduced as a pilot project for Ban Khunsamut Chin, Samut Prakarn Province in 2006 because this region had undergone serious coastal erosion problems for more than 30 years. This breakwater is comprised of concrete poles, which are arranged in three rows with a length of 250 m (Fig. 1). However, it has been suggested that coastal erosion is optimally reduced when employing both hard structures (e.g., concrete or bamboo breakwaters) together with strategies that reinforce sediment particle stability, which usually involves addition and/or enhancement of biological communities in the ecosystem (Vaidya et al., 2015 and van de Graaff et al., 1998). Therefore, the establishment of mangrove swamps and/or surface microbial biofilms has emerged as critical mitigation tools to increase the stability of sediments and, by default, reduce erosion. Since our knowledge on microbial communities involved in biofilm production of mudflat ecosystems in Thailand is limited, the research reported in this study aimed to elucidate the variability in micro-phytobenthic communities in mudflats protected and unprotected by a robust breakwater system (Fig. 1). Physical and biological factors influencing micro-phytobenthos community structure were also monitored along with seasonal changes.

Study area

This study was conducted in a coastal community of Ban Khunsamut Chin, Samut Prakarn Province, about 30 kilometers south of Bangkok (Fig. 1a-1c). The area locates near the mouth of the Chao Phraya River, along the northern part of the Inner Gulf of Thailand and includes a thin strip of mangroves and an extended mudflat area. Satellite images of this area in 1984 showed that 34 years ago a temple, Wat Khun Samut Trawat

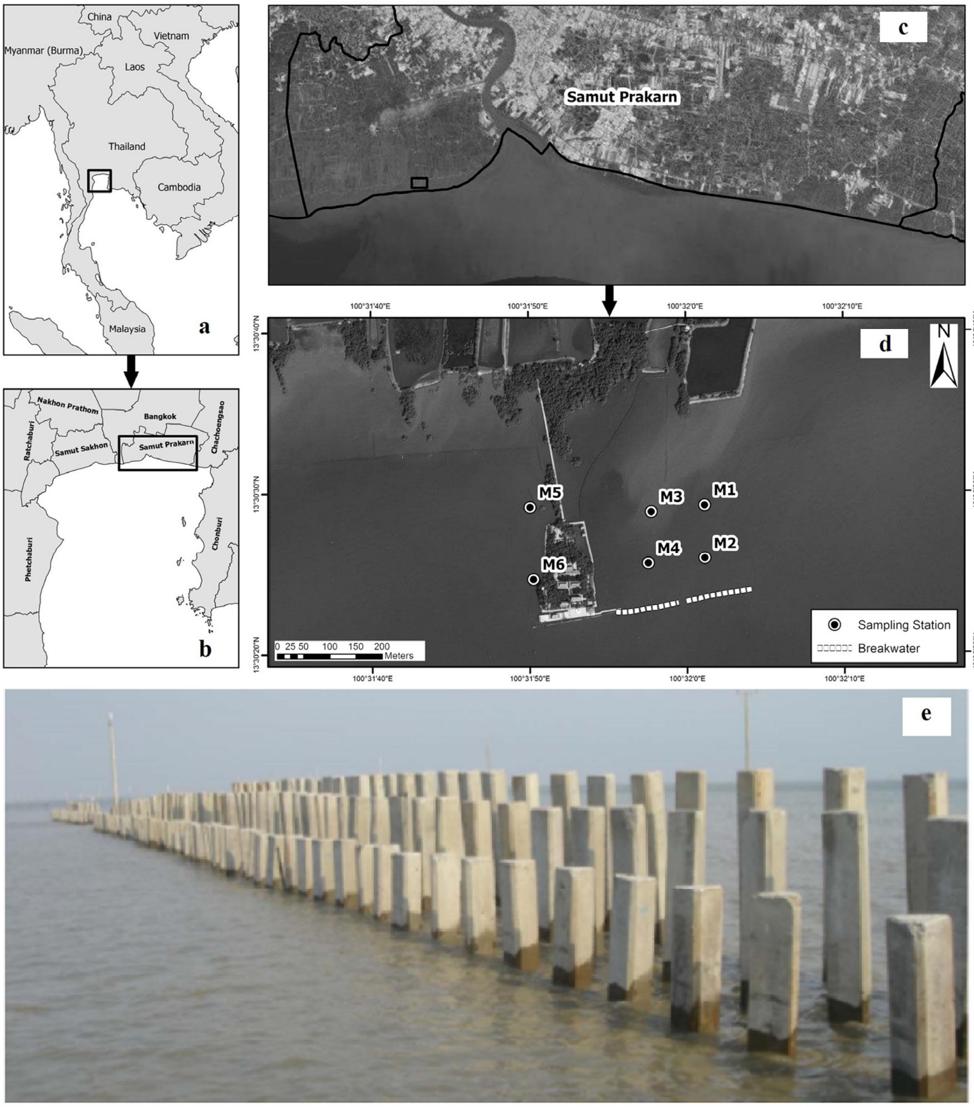

FIGURE 1. Location of Ban Khunsamut Chin, Samut Prakan Province, sampling site and images of the mudflats and breakwater structure. Maps of Thailand (a) with magnification of the study site (b); an enlarged satellite image of the study site shown in b (c); and an increasing magnification of the study site (d), with white dots representing breakwater piles. M1-M4 represent sampling sites in the protected area; M5-M6 are sampling sites in the unprotected area. Wat Khun Samut Trawat is visible as an island just west of the breakwater structure. Lowest figure (e): concrete pole breakwater structure in the coastal area of Ban Khunsamut Chin, Samut Prakarn Province.

(13°30’26.20’’N and 100°31’52.35’’E), located at the coastline but in 2016 this temple was in the sea approximately 400 m offshore of the present coast line. The breakwater structure that was studied in this report was built in 2006 only a few meters distant from Wat Khun Samut Trawat (Fig. 1d). This single point reference was then

TABLE 1. Location of sampling sites.

Area	Station	GPS location
Protected mudflat (PRO)	M1	13°30'29.20''N 100°32'1.10''E
	M2	13°30'25.90''N 100°32'1.10''E
	M3	13°30'28.80''N 100°31'57.50''E
	M4	13°30'25.60''N 100°31'57.60''E
Unprotected mudflat (UN)	M5	13°30'29.10''N 100°31'50.00''E
	M6	13°30'24.60''N 100°31'50.20''E

used to estimate shoreline erosion of >20 m/year (1967 – 2002) at the study site; this estimate is roughly consistent with detailed coastline studies of this area (Jarupongsakul et al. 2009). In 2006, an experimental coastal protection structure was established with a 250 m long concrete breakwater located 500 m from the coastline (Fig. 1d and 1e); the concrete poles were aligned in groups of three rows with the interval of ~1.5 m between rows and 1.5 m within a row along the 250 m perimeter. The poles are triangular in cross-section with each side having a width of 50 cm; each pole is 10 m in length and was placed into the sediment such that each pole was exposed about 1-2 m above mean high water of 1.39 m (Fig. 1e). The estimation of coastal erosion after the establishment of this breakwater structure was less than the period before breakwater (Jarupongsakul et al., 2009).

MATERIALS AND METHODS

Water and sediment samples were taken from four stations in the protected part of the mudflat and two stations in the unprotected part of Ban Khunsamut Chin mudflat (Fig. 1A and Table 1). Based upon the weather and hydrographic conditions of this area (Buranapratheprat et al., 2006 and Jarupongsakul et al., 2009), field samplings were conducted in two periods representing the inter-monsoon period (March, 2015) and the northwest monsoon period (December, 2015). The sampling in March was performed during low tide while that in December was held during a daytime high tide.

Physico-chemical properties of water including temperature, salinity and pH were measured at each station in situ using a YSI 600 multiprobe. Water samples for nutrient analysis were collected in triplicate from 0.5 m depth or above the sediment surface and kept frozen in polyethylene bottles for further analysis. These water samples were analyzed for ammonium-nitrogen, nitrite-nitrogen, nitrate-nitrogen, phosphate-phosphorus and silicate-silicon following Parsons et al., (1984).

At each station, sediment samples were collected in triplicate using a grab sampler. Sediment-related parameters, temperature, salinity, pH and Eh were measured. Temperature and pH were measured *in situ* using a hand-held Delta OHM field sensor device (model HD 2105. 1). Salinity was measured with a salinometer (model NS-3P, Merbabu Trading Co. , LTD) and Eh was measured with a pH-ORP meter (TRX-90, Toko Co., Japan). After the measurement of physico-chemical parameters of the interstitial water, sediment samples were stored in cleaned plastic bags for the determination of grain size by the hydrometer method (Gee and Bauder, 1986) and analysis of organic matter by the Walkley-Black method (1934). A plastic corer (3 cm id) was used to collect three samples of sediment to a depth of 1 cm; these samples were obtained at low tide in March or from the sediment collected by a grab sampler in December. These sediment samples were kept frozen for chlorophyll *a* analysis as described by Montani et al (2012) except that the measurement of extracted chlorophyll *a* was conducted by a fluorometric method (Arar and Collins, 1992) using a Trilogy Fluorometer (model TD-700 Turner Designs, USA equipped with Filter Kit PN 7000-962). Samples for analyses of meiofauna and microphytobenthos were also collected in the same manner as samples for chlorophyll *a* then preserved in a solution of neutral formalin with Rose Bengal. Fixed samples were washed with tap water and filtered onto a 63 μm mesh net for meiofauna or 20 μm mesh net for microphytobenthos. The biota samples were enumerated via light microscopy, identified and counted. Result was reported as the density of individuals/10 cm^2 or cells/ 10 cm^2 for meiofauna and microphytobenthos, respectively.

The differences in the meiofauna and microphytobenthos composition between protected and unprotected mudflats as well as sampling months were determined by Principle Component Analysis (PCA) using PRIMER 6 (Clarke and Warwick, 2001). The abundance data of microphytobenthos and meiofauna were square root transformed and the Bray-Curtis similarity index was used to explain the degree of similarity. Mann-Whitney U tests were applied to test for significance in microphytobenthos and meiofauna abundances among sampling sites and periods. Finally, a Spearman rank correlation coefficient was used to measure the relationships between biological and environmental parameters (Coolidge, 2013 and Ross, 2017).

RESULTS

Physico-chemical parameters of seawater

There were significant differences in all physico-chemical parameters measured in the seawater overlaying the two sites of this mudflat in December vs March (Table 2). Parameters measured included salinity, pH, temperature, nitrite-N, nitrate-N, ammonium-N, silicate-Si, and phosphate-P. Sampling was conducted at low tide in March and it was not possible to sample the overlaying water above the unprotected mudflat. However, it was possible to compare the overlaying waters in protected and unprotected sites in December; there were no significant differences in the physico-chemical properties of the overlaying seawater measured (Table 2).

Physico-chemical characteristics of mudflat sediment

It is possible to compare the physico-chemical properties of sediment interstitial water in two different ways; protected vs. unprotected and March vs. December (Table 2). There was only one difference in the parameters measured in March between the protected and unprotected areas; Eh was higher in the unprotected site compared to the protected one. There were four differences in the physico-chemical properties of the interstitial waters in December when comparing the protected to the unprotected sites; temperature was lower in the protected site compared to the unprotected site, while salinity, % sand, and % clay were higher in the protected site compared to the unprotected site.

There were also significant differences in the physico-chemical properties of the

TABLE 2. Physico-chemical parameters collected from a protected mudflat (PRO) and an unprotected mudflat (UNP) in March and December 2015 (n=6-12).

Parameters	March			Dec			Seasonal
	PRO	UNP	*P*	PRO	UNP	*P*	*P*
Seawater							
Temperature (ºC)	28.97±0.15	N/A	-	30.51±0.11	30.73±0.03	ns	***
pH	6.41±0.37	N/A	-	7.90±0.21	7.13±0.90	ns	***
Salinity (psu)	19.5±0.15	N/A	-	27.9±0.09	28.0±0.05	ns	***
NO_3^- -N (μm)	79.62±5.20	N/A	-	0.59±0.13	0.53±0.12	ns	***
NO_2^- -N (μm)	18.02±1.02	N/A	-	0.13±0.01	0.07±0.01	ns	***
NH_4^{3-} -N (μm)	4.70±0.45	N/A	-	2.90±0.70	1.64±0.27	ns	***
PO_4^{3-} -P (μm)	29.06±0.81	N/A	-	5.82±0.64	5.67±0.49	ns	***
SiO_3^{2-} -Si (μm)	108.36±3.28	N/A	-	15.33±4.01	12.94±4.64	ns	***
Sediment							
Temperature (ºC)	28.53±0.15	28.75±0.11	ns	29.77±0.04	30.40±0.05	***	***
pH	6.34±0.24	6.12±0.01	ns	7.37±0.08	7.42±0.03	ns	***
Salinity (psu)	20.0±1.56	19.7±0.31	ns	28.3±0.07	28.0±0.05	**	***
Eh (mv)	-216±41.18	-329±20.50	**	-259±41.17	-202±21.83	ns	ns
Sand (%)	35.28±0.55	36.48±0.26	ns	34.90±0.57	39.65±0.39	***	ns
Silt (%)	25.56±1.68	22.90±0.72	ns	24.37±1.06	26.04±1.13	ns	ns
Clay (%)	39.15±1.31	40.60±0.72	ns	40.71±1.13	34.29±0.79	**	ns
Organic matter (%)	3.83±0.07	4.06±0.04	ns	4.21±0.07	4.26±0.08	ns	***

N/A: data not available, ns: not significant, **: significant at $p < 0.05$, ***: significant at $p < 0.01$

interstitial water on a seasonal basis. Temperature, pH, salinity and % organic matter were all higher in December than in March (Table 2). The other parameters measured did not vary significantly between seasons at the two sites (Table 2). Sediment in both areas and both study periods were classified as clay and clay loam (Fig. 2). The average content of clay in both sites and both months ranged from 32 - 43% while the amount of silt tended to be lower with the average content between 21% to 31% in the protected mudflat and less than 30% in the unprotected sites. The amount of sand varied between 33% - 37% in both parts of the mudflat in March while the percentage of sand in the unprotected mudflat (39% - 40%) was significantly higher ($p < 0.01$) than in the protected site (33% - 36%) in December.

The amounts of sediment-associated organic matter in the study sites showed temporal variation with those in December higher than in March ($p < 0.01$). However, there was no difference between sediment organic matter of the protected mudflat and unprotected mudflat in each month (Table 2).

Biomass and abundance of microphyto-benthos

The amount of sediment chlorophyll *a* as a proxy of microphytobenthos biomass in both the protected mudflat and unprotected mudflats varied between 30-100 mg/m^2. In December, concentrations of chlorophyll *a*

TABLE 3. Biological parameters collected from a protected mudflat (PRO) and an unprotected mudflat (UNP) in March and December 2015. Data were average value ± SE and range (min-max). (n=6 for unprotected mudflat and n=12 for protected mudflat).

Parameters	March			Dec			Seasonal
	PRO	UNP	*P*	PRO	UNP	*P*	*P*
Chlorophyll *a*	53.99±4.68	69.11±9.68	ns	52.22±8.94	38.13±5.83	ns	ns
(mg/m^2)	(33.86-91.41)	(42.89-109.1)		(26.05-106.3)	(22.43-56.30)		
Microphytobenthos (MPB)	3,759±1,176	3,713±999	ns	24,189±6,472	41,239±5,984	***	***
($cells/cm^2$)	(199-10,489)	(1,228-6,998)		(9,156-93,677)	(22,183-62,251)		
Diatom	3,610±1162	3,713±999	ns	23,504±6,521	30,924±4,554	**	***
($cells/cm^2$)	(113-10,489)	(1,228-6,998)		(9,156-93,677)	(18,731-49,066)		
Cyanobacteria	149±67	0	**	685±380	10,316±3,020	***	**
($cells/cm^2$)	(0-777)			(0-4,620)	(1,714-21,600)		
Meiofauna	103±33	13±6	ns	143±19	118±27	ns	**
(ind./ 10 cm^2)	(0-313)	(1-43)		(4-236)	(70-231)		
Nematodes	58±17	9±5	ns	125±18	90±18	ns	***
(ind./ 10 cm^2)	(0-147)	(0-33)		(4-224)	(56-171)		
Others	45±20	3±2	ns	18±3	28±10	ns	ns
(ind./ 10 cm^2)	(0-216)	(0-10)		(0-33)	(9-60)		

N/A: data not available, ns: not significant, **: significant at $p < 0.05$, ***: significant at $p < 0.01$

in surface sediment of the protected mudflat (26 to 100 mg/m^2) varied in the same range as those in March, while the values in the unprotected mudflat were lower and had a narrower range of 22-56 mg/m^2 (Table 3). Overall, the average values of sediment chlorophyll *a* in the protected mudflat and unprotected mudflat both in March and in December were not statistically significantly different ($p > 0.05$).

The abundances of organisms/cells in the MPB showed significantly seasonal variation with the density in March much smaller than those in December (Table 3 and $p < 0.01$). In March, the density of organisms in MPB in both the protected and unprotected mudflats was in same range, around 10^3cells/cm^2. Increases in MPB densities were observed in both parts of the mudflat in December when the density varied between 10^4 and 10^5 cells/cm^2 (Table 3 and Fig. 3a). There was no significant difference between the densities in protected and unprotected mudflats in March ($p > 0.05$), however, the densities in the unprotected mudflat in December were significantly higher than the protected one ($p < 0.01$).

Twenty-five MPB taxa were identified from the mudflat sites in March and 31 taxa were identified from December samples. The diatoms including *Thalassiosira* sp., *Cyclotella* sp., *Gyrosigma*/*Pleurosigma* sp., *Nitzschia* ap. and *Surirella* sp. were dominant components of MPB in March but were sub-dominant species in December

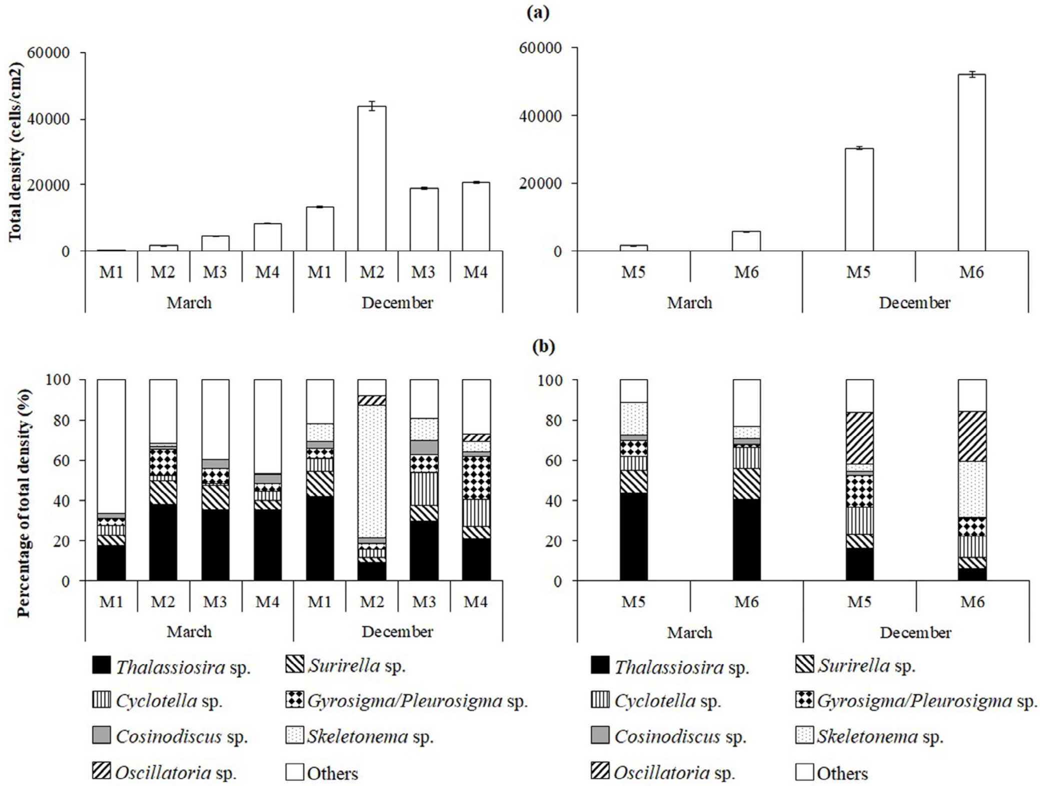

FIGURE 3. Microphytobenthos (**MPB**) assemblages in protected (M1-M4) and unprotected (M5-M6) mudflats. (a) Total density of microphytobenthos (cells/cm^2), (b) Composition of microphytobenthos expressed as proportional density of each species (%) between protected mudflat (left panel) and unprotected mudflat (right panel) in March and December**.**

(Fig. 3b). The contribution of a cyanobacterium, *Oscillatoria* sp., was noted in December at a density about 25% of total MPB in unprotected stations. A diatom, *Skeletonema* sp., was also a major component in the protected mudflat in December, when it contributed 66.3% of total densities in M2 and 27.6% in the unprotected mudflat M6. The community structure of microphytobenthos (MPB) exhibited temporal variations in diversity and abundance in December in comparison to March (Fig. 3). There was also spatial variation between protected and unprotected mudflats of the same season.

The MPB communities in December were more homogenous than those in March in that they were grouped together with approximately 65% similarity. Besides, the communities of the unprotected sites were clearly separated from the protected one due to the abundances of two dominant MPB algae, *Skeletonema* sp. and *Oscillatoria* sp. Most of MBP communities in March were 50% dissimilar to those in December except the communities in the protected mudflat

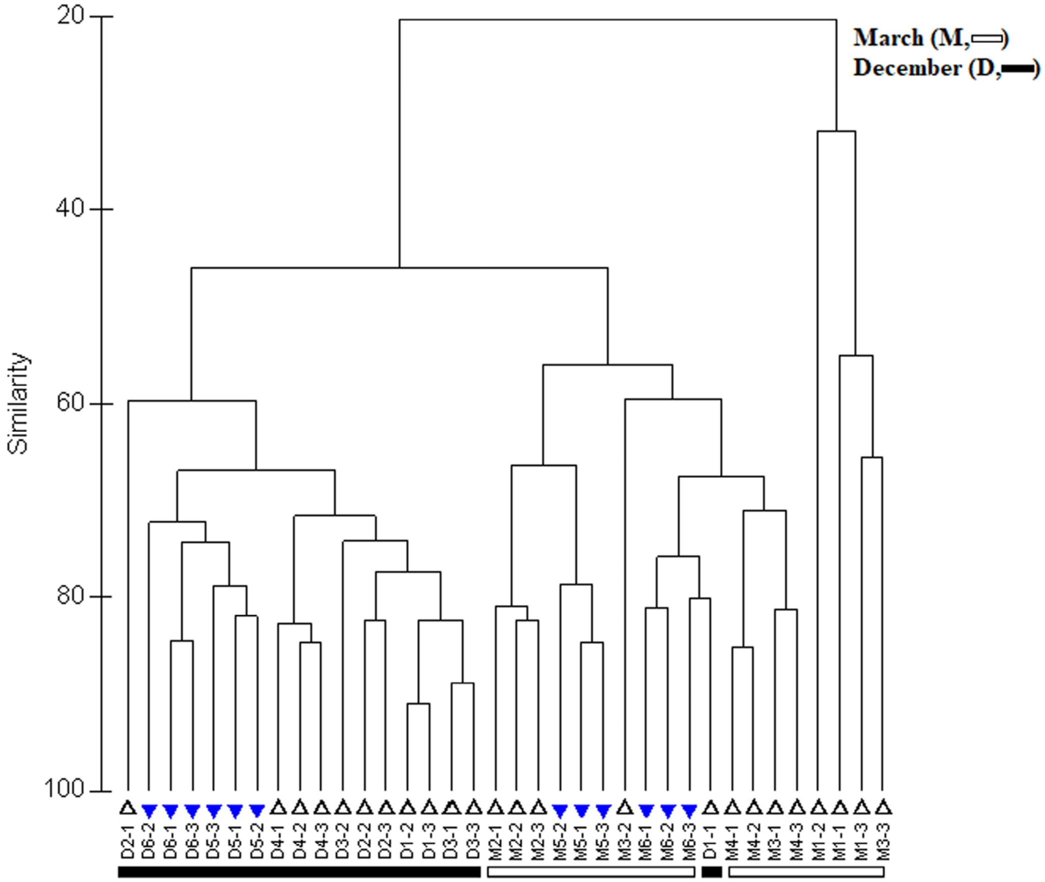

FIGURE 4. A dendogram representing microphytobenthos communities of the protected mudflat (▲) and unprotected mudflat (▼) in March (M) and December (D). The numbers after a letter (M and D) indicate the station for protected (M1-M4) and unprotected (M5-M6) mudflats and replication of samples (1,2,3) for the triplicate samples.

sites M1 and some of M3 which were dominated by *Chaetoceros* sp. and *Thalassiosira* sp. in comparison to the communities dominated solely by *Thalassiosira* in other sites (Fig. 4).

Communities of meiofauna

In March, meiofauna densities in protected mudflat sediments located near the channel (station M1 and M2) were higher than in the innermost areas (station M3 and M4) and in the unprotected mudflat (station M5 and M6). Communities of meiofauna in December were significantly higher than those in March (Table 3). The densities of meiofauna in December in both protected and unprotected parts of the mudflat had an average density >100 individuals/10 cm^2 (Table 3 and Fig. 5a). However, there was no spatial variation in meiofaunal density between the two sites of the mudflat for each season (Table 3).

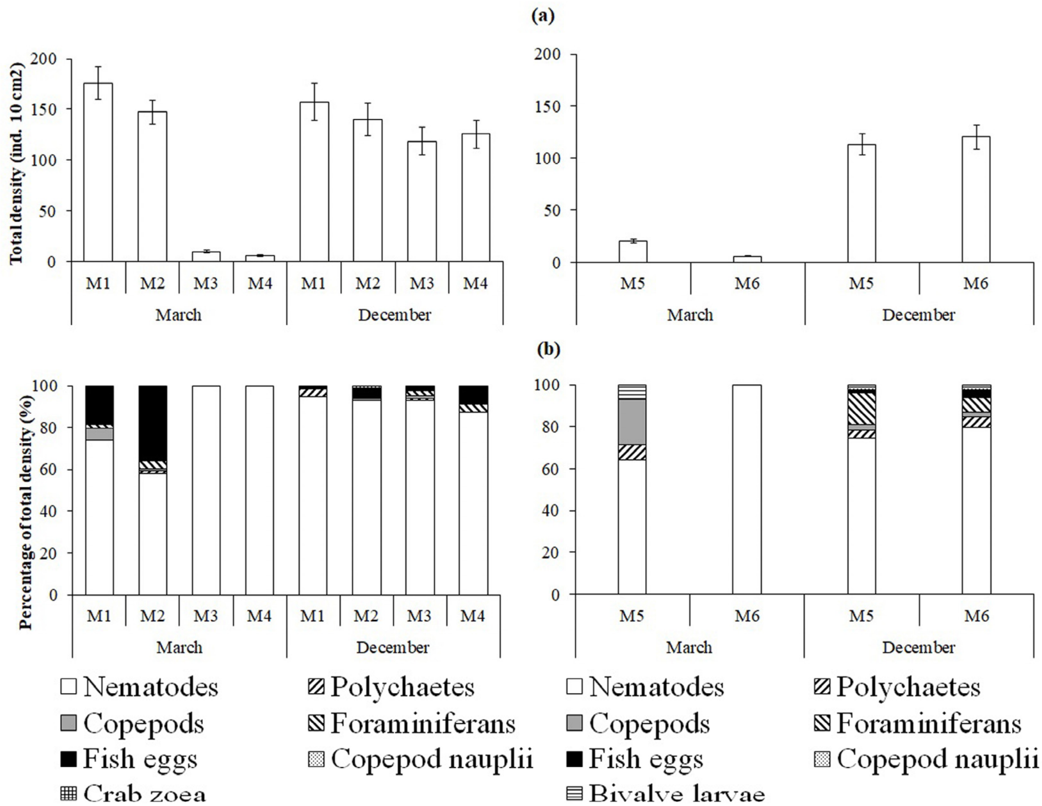

FIGURE 5. Meiofauna assemblages: (a) Total density of meiofauna (ind./ 10 cm^2), (b) Composition of meiofauna expressed as proportion density of each group (%) between protected mudflat (left panel) and unprotected mudflat (right panel) in March (M) and December (D).

Eight higher taxa of meiofauna were identified, namely nematodes, polychaetes, copepods, foraminiferans, crab zoea, fish eggs, bivalve larvae and copepod nauplii; Nematodes were the most dominant meiofauna in both protected and unprotected sites and in both seasons, contributing more than 60% of the total meiofauna density. Densities of polychaetes and bivalve larvae ranged from 0.9% to 7.1% and 1.1% to 7.1%, respectively. Other meiofauna, such as copepods, fish eggs and foraminiferans exhibited spatial and temporal variations in densities, which ranged from < 1% to 20% of the total density in both sites and both months. Crab zoea and copepod nauplii accounted for less than 1.5% of total meiofaunal densities during this study (Fig. 5b).

Community similarity analysis of meiofauna based on both composition and abundance revealed that communities of the unprotected mudflat (M5 and M6) in March with high densities of nematodes, copepods

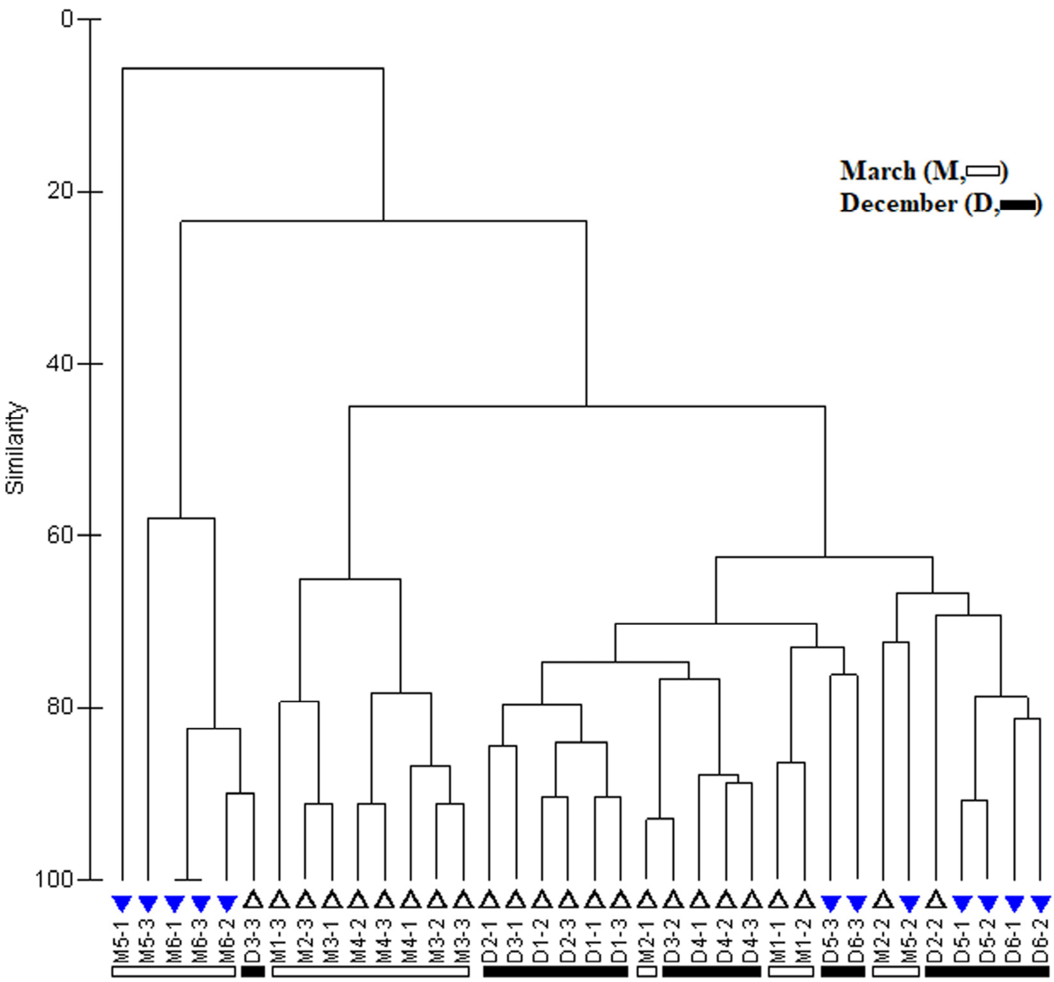

FIGURE 6. A dendogram representing meiofauna community composition of the protected mudflat (Δ) and unprotected mudflat (▼) in March (M) and December (D). Labels are as in Fig. 3.

and polychaetes were different from others with only 20% similarity. Communities of meiofauna in the protected part of this mudflat had 60% similarity due to the distinct contribution of foraminiferans and fish eggs in M1 and M2 and nematodes in M3 and M4. Meiofaunal communities of both protected and unprotected mudflat sites in December were similar at 60% similarity with the communities in the protected mudflat had >70% similarity due to the occurrence of foraminifera and fish eggs while communities in the unprotected site (M5-M6) had high contributions of foraminiferans and polychaetes and formed another cluster at 60% similarity (Fig. 6).

DISCUSSION

The presence of a breakwater structure could affect environmental conditions and hence the structure of estuarine mudflat communities. Communities of micro-organisms and meiofauna in mudflats protected by a breakwater were compared to those in adjacent, but unprotected, mudflats of Ban Khunsamut Chin (BKC); sampling was conducted in March as a representative of inter-monsoon or summer season and in December as a representative of the northeast monsoon period and was combined with analysis of sediment and over-laying seawater physico-chemical parameters. Overall, our data allowed us to compare biological community properties as a function of season, location (behind or outside the breakwater system), and physico-chemical changes. Most of the physico-chemical parameters and communities of microorganisms in protected and unprotected mudflats were not different. However, there were differences between both mudflat sites in the distribution of sediment particle size and communities of MPB (microphytobenthos) in December relative to March (Fig. 7). Our results of seasonal variations show that most of the physical parameters and communities of microorganisms in December were higher than in March.

Nutrient concentrations in interstitial water of the sediment in March were much higher than those in December in both the protected and unprotected mudflats. Seasonal differences in nutrient concentrations have been reported by other studies in the Inner Gulf of Thailand. For instance, the concentrations of NH4+ -N plus NO3- -N from the coastal water quality survey of the Pollution Control Department at the Chao Phraya River mouth located on the eastern side of our study area in April, 2015 (PCD, 2015), a month after our sampling, were quite similar to our results in March, 2015. The concentration of PO43+-P in our study was much higher than those reported by PCD; this high concentration at BKC indicated the possibility of high PO43+-P concentrations from resuspension of pore-water nutrients. Since our sampling in March was conducted during low tides, the release of nutrients from sediment to the water column might affect the concentrations of water-column nutrients. The transport of nutrients from the sediment into the water column due to tidal disturbance of sediment particles in shallow water tidal flats or during low tide has been reported in many tidal flats around the world (Percuoco et al., 2015, Sin et al., 2009, Wengrove et al., 2015, Yin and Harrison, 2000 and Yu et al., 2017).

Our results suggest that environmental conditions (e.g., temperature, pH, salinity, sediment composition) in our study area are under the influence of the monsoonal system as well as the breakwater structure. The differences in winds and hence surface current patterns affected the composition of sediments in that the sediments in December and March had different proportions of sand and clay particles. The northeast monsoon induces counter-clockwise circulation in the Inner Gulf of Thailand. This causes the transport of fine sediments along the coast and results in coastal erosion and movement of sediments towards the southwest during the period of mid-October to January (Buranapratheprat et al., 2006 and Sojisuporn et al., 2012). This resulted in the lowest clay particle (34%) and highest sand contribution (about 39%-40%) in December. The differences in sediment particles were particularly noticeable in the unprotected part of the mudflat, which points to a role of

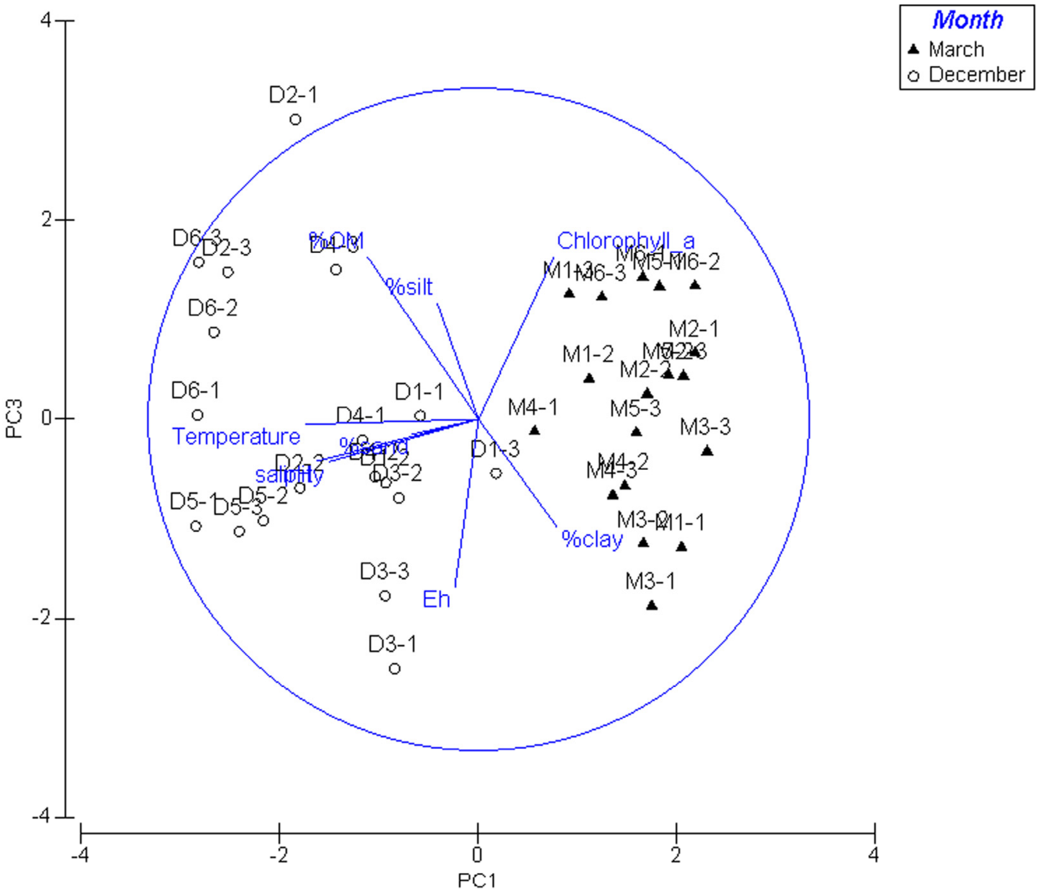

FIGURE 7. Principle component analysis (PCA) of physico-chemical parameters at protected mudflat and unprotected mudflat sites in March (M) and December (D) 2015. The principle components were the same as those shown in Fig. 2 (i.e., temperature, salinity, particle size distribution).

the breakwater structure in sediment particle composition. The presence of the breakwater provided protection against sediment transport and hence higher percentages of clay were observed in the protected mudflat for the same time period. This breakwater structure is expected to mitigate coastal erosion by reducing wave energy and contributing to increased sediment deposition. In contrast, suspended surface sediments in the silt and clay size ranges would be expected to be transported offshore from unprotected mudflats (Uehara et al., 2010). The composition of sand in unprotected mudflats in December was also higher than those reported (approximately 35%) in previous studies of the same area (Jarupongsakul et al., 2009 and Siriboon et al., 2014); these two earlier studies - observed transport of fine grain sediment offshore in the unprotected mudflat in the period of strong northeast monsoon. Both the winds and the currents change from early February where Southern Local winds blow from the south until April (Jampanil and Seigo, 2017). Sediment is transported northward and accumulated in the area by a weak clockwise water column flow during the inter-monsoon period (Buranapratheprat et al., 2006 and Sojisuporn et al., 2012), thus high percentages of clay (approximately 40%) were recorded in both mudflat sites in March (Table 2).

Overall, the distributions of sediment particle size, organic matter and chlorophyll a from the two sites in March were different from those in December. In March, sediments in the protected mudflat sites (station began with ‘‘M’’ in Fig. 6) were characterized by high percentages of clay particles while sediments in in unprotected mudflat stations had high chlorophyll a content. In December, most of the both study sites had high sand particle.

Correlation analyses between biological and environmental parameters are shown in Table 4. A Spearman’s rank correlation in March revealed that most environmental parameters showed no significant effect on biological parameters. In December, most environmental parameters significantly related to microphytobenthos (MPB), diatoms and cyanobacteria in particular. The relationship between densities of meiofauna and microphytobenthos were negative in March ($r = -0.56$, $p < 0.05$). No correlation between meiofauna and microphytobenthos densities was found in December (data not shown).

The microphytobenthos (MPB) abundances in December (northeast monsoon season) were 1 to 2 order(s) of magnitude higher than those in March (inter-monsoon period). The diversity of MPB taxa also

TABLE 4. Spearman’s rank correlation coefficients between biological and environmental parameters collected from a protected mudflat (PRO) and an unprotected mudflat (UNP) in March and December 2015 (only significant correlations were displayed).

Substrate	Parameters	MPB	Diatom	Cyanobacteria	Meiofauna	Nematode	Others nematode	Chl *a*
March sediment	Temperature (ºC)	ns	ns	**-0.57****	**-0.49****	**-0.53****	**-0.46****	
	Salinity (psu)	ns	ns	**0.47****	ns	ns	ns	ns
	Eh (mv)	ns	ns	ns	ns	ns	ns	**-0.64*****
December seawater	Salinity (psu)	ns	ns	**0.56****	ns	ns	ns	ns
	NO_2^- -N (μm)	ns	ns	**-0.58****	ns	ns	ns	ns
	NH_4^{3-} -N (μm)	**-0.64*****	**-0.60*****	ns	ns	ns	ns	ns
	PO_4^{3-} -P (μm)	ns	ns	**-0.52****	ns	ns	ns	ns
	SiO_3^{2-} -Si (μm)	ns	ns	**-0.58****	ns	ns	ns	ns
December sediment	Temperature (ºC)	**0.66*****	**0.53****	**0.77*****	ns	ns	ns	ns
	pH	**0.51****	ns	ns	ns	ns	ns	ns
	Salinity (psu)	**-0.54****	ns	**-0.62*****	ns	ns	ns	ns
	Sand (%)	**0.64*****	**-0.58****	**0.71*****	ns	ns	ns	ns
	Clay (%)	**-0.67*****	**0.53****	**-0.63*****	ns	ns	ns	ns

ns: not significant, **: significant at $p < 0.05$, ***: significant at $p < 0.01$

showed seasonal variations in that MPB communities in December were dominated by species with small cell sizes but that aggregate as filaments. These MPB taxa included a diatom, *Skeletonema* sp., which was abundant in the protected mudflat, and a cyanobacterium, *Oscillatoria* sp., which was abundant in the unprotected mudflat in December. The dominance of a filamentous cyanobacterium in the unprotected mudflat in December is consistent with the finding that filamentous cyanobacteria prefer coarser sediments such as sand rather than mud particles, which tend to favor diatom growth (Watermann et al., 1999). In addition, *Oscillatoria,* another cyanobacterium, also has a high ratio of accessory pigments (phycobilin-proteins) to chlorophyll *a* (Grossman et al., 1993, Sobiechowska-Sasim, 2014), which could explain our results showing low chlorophyll *a* but high density of MPB in the unprotected part of the BKC mudflat in December (Figs 2, 4). These two species of MPB, *Skeletonema* and *Oscillatoria*, likely impacted the communities in that high densities of microphytobenthos were recorded in December with larger variations in chlorophyll *a* concentration in comparison to March when chlorophyll *a* content varied in a narrower range. Despite these differences in chlorophyll, there was no significant difference on an average basis. Further study on biovolume of MPB may be helpful to the interpretation of the relationship between MPB abundance and biomass.

The composition of meiofauna observed in the present study as well as the dominance of nematodes throughout the study period is in agreement with previous studies in the same area (Siriboon et al., 2014). For instance, nematode-dominated meiofaunal communities were also reported in bamboo-fence protected mudflats in three coastal provinces of Thailand (Samut Songkhram Province, Samut Sakhon Province and Chachoengsao Province) and around the Gulf of Thailand (Paphavasit et al., 2011) as well as mangrove sediments elsewhere (Giere, 1993 and Coull, 1999).

Both biotic and abiotic factors play an important role in shaping the communities of microphytobenthos (MPB) in mudflats of the Inner Gulf of Thailand including the two sites studied at BKC. MPB are reported as potential food sources for meiofauna (Montagna, 1984, Riera et al., 1996, Buffan-Dubau and Carman, 2000 and Pinckney et al., 2003). Therefore, it is reasonable to expect that MPB at BKC, especially in March when meiofaunal (nematode in particular) abundance was high, was subjected to grazing pressure from meiofauna. Trophic coupling between MPB and meiofauna has been reported previously; indicated that the grazing rates of meiofauna change in response to increased primary production of benthic diatoms, with subsequent removal (i.e. grazing) of diatom biomass (Blanchard 1991 and Montagna et al., 1995). A similar trophic coupling was likely evident at the BKC sites, again, especially in March when meiofauna abundance was significantly higher. Further, the abundance of MPB may also be impacted by grazing pressure of macrofauna such as amphipods and mud snails inhabiting estuarine sediments (Blanchard et al, 2000, Hagerthey et al 2002, Herman et al, 2000, Morrisey, 1988 and Page 1997); this possibility was not covered in this study but was likely a contributing factor to MPB biomass and/or chlorophyll *a* biomass.

Based on an overview of our entire dataset, we suggest that in the period of the northeast monsoon of December, the communities of MPB were regulated by physical factors, particularly sediment composition, which was also under the influence of the breakwater. The relationship between physical disturbances and standing crops of benthic organisms has been reported in tidal flats located around the world (Aller and Aller, 1986 and Alongi, 1989) so it is reasonable to expect similar relationships at BKC. In summary, our study indicated a role of physical influences of different seasonal settings (i.e., the monsoon) together with the contribution of a man-made breakwater structure both coupled with trophic controls on the community structure of the microphytobenthos in mudflats of the Inner Gulf of Thailand.

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