The Relationship between Coastal Erosion and Chlorophyll *a* Abundance along the Western Coast of the Gulf of Thailand

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ABSTRACT

Research on the relationship between coastal erosion and related environmental factors and chlorophyll *a* abundance along the western coast of the Gulf of Thailand was carried out during the early southwest monsoon (June 2017 and May 2018), southwest monsoon (August 2017), northeast monsoon (November 2017), and dry season (March 2018). Results of chlorophyll *a* distribution indicated seasonal changes. Chlorophyll *a* levels increased during the early southwest monsoon of 2017 (from 1.04 $\mu g \cdot L^{-1}$ to 2.14 $\mu g \cdot L^{-1}$). Moreover, chlorophyll *a* concentrations along the inner part of the coastal zones (with a maximum of 42 $\mu g \cdot L^{-1}$) were higher than that in the outer zones (with an average of 2 $\mu g \cdot L^{-1}$). Across all study areas, beach slopes were widely varied (0.08-4°) over the study period. In this study, slopes that increased >4° (Thap Sakae area) coincided with an increase of chlorophyll *a*>15 $\mu g \cdot L^{-1}$ (reaching eutrophic condition). The beach slopes (S; degree°) were related to the chlorophyll *a* concentrations (Chl *a*; $\mu g \cdot L^{-1}$) by the equation: Chl $a=7.35\ S^{0.24}$ ($r=0.314$, $p<0.05$). The overall results implied that changes in the beach slopes of the western coast of the Gulf of Thailand due to monsoon-driven coastal erosion played a role in stimulation of near-shore chlorophyll *a* levels, particularly in the southwest monsoon period. Such chlorophyll *a* increases should be further utilized as an organic food source for various consumers in the coastal ecosystem. Assessment of primary production and related pelagic fishery resources, thus, should reflect the dynamics of coastal erosion that may enhance land-based nutrient inputs to the adjacent coastal ecosystem.

Keywords: Beach slope, Chlorophyll *a*, Coastal erosion, Environmental factors, Gulf of Thailand

INTRODUCTION

The coastal area around the Gulf of Thailand possesses various beach characteristics which depend on topographical, meteorological, and hydrological influences. The coastal zones are composed of several habitats, such as semi-enclosed bays, open shorelines, and mangroves. All the areas receive impacts from the southwest monsoon (particularly during May to August) and the northeast monsoon (particularly during October to February) (TMD, 2018), which have effects on coastal erosion and related resuspension regimes, along with the dynamics of the coastal zone ecosystem (Department of Water Resources, 2009). Comparatively high accumulation of biologically important nutrients in the coastal zones (Odebrecht *et al.*, 1995; Lui *et al.*, 2012; Otsuka *et al.*, 2016) can be loaded or transported into adjacent sea areas. Such nutrient increases can stimulate the production of phytoplankton chlorophyll during suitable water conditions. The increase of coastal phytoplankton

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has been recognized to be useful for several fishery resources (Subarna, 2018). The areas along the western coast of the Gulf of Thailand, particularly in the vicinity of Prachuap Khiri Khan Province, is known as a major migratory route of economically important fish species (i.e., chub mackerel; Saikliang, 2014). These areas were also recognized as the most productive in the Gulf of Thailand (Department of Fisheries, 2014).

Changing characteristics of the beach along the coastal zones are mainly influenced by wind, waves, and tidal circulation, which deposit materials on the beach in varying amounts depending on season (Department of Marine and Coastal Resource, 2018). In the coastal province of Prachuap Khiri Khan (with shoreline length of 242.34 km), beach erosion was recently recorded to reach 4.5 km per year. Such erosion regimes reflected possible roles of coastal processes in adjacent sea area. The processes were suggested to be enhanced by increasing monsoon strength due to climate change during the past decades (Department of Marine and Coastal Resource, 2014).

Chlorophyll *a* is a reflection of phytoplankton availability in pelagic waters. Phytoplankton production along the coastal zone is crucial for various species of aquatic resources, i.e., zooplankton, filter-feeding shells, and juvenile fishes (Day *et al*., 1989; 2013). Nevertheless, changes in chlorophyll concentrations are complex and depend on various parameters, including turbidity of the seawater, light conditions, wave and sea conditions, and availability of essential nutrients (Conley, 2000; Conley *et al*., 2009; Paerl, 2009). There are many reports illustrating spatial and temporal variation of chlorophyll *a* during different seasons, particularly in locations that received significant impacts of the monsoons (Buranapratheprat *et al*., 2008; Ihsan *et al*., 2018; Subarna, 2018). A recent study of the sea areas of Prachuap Khiri Khan Province along the western Gulf of Thailand showed that during the past 3-4 years, inflows from rivers along the coastal shoreline decreased significantly (Buakaew *et al*., 2018). Moreover, the levels of nutrients within a distance of 5-10 km from the shoreline were low. Nevertheless, there were also reports of phytoplankton blooms along the shoreline. Such occurrences may imply other sources of nutrients. Resuspension processes near the beach during monsoon seasons were of interest. Coastal zones with comparatively high accumulation of organic wastes and/or related nutrients should be able to provide more nutrients to further stimulate the growth of phytoplankton in the adjacent sea areas. Such monsoon-induced nutrients can be also be dispersed to surrounding areas (Odebrecht *et al*., 1995; Lui *et al*., 2012; Otsuka *et al*., 2016).

This study was, thus, carried out to investigate the roles of beach processes and their changes over the seasonal monsoons. Environmental factors related to the spatial and temporal variation of chlorophyll *a* in the sea areas were examined, with a focus on differences due to beach characteristics. Finally, factors influencing the concentration of chlorophyll *a* were analyzed. The results should be further applied to assess the stability of food conditions of the coastal zones, in terms of location and timing, to serve as feeding habitats for migratory fishes along the western coast of the Gulf of Thailand.

MATERIALS AND METHODS

Study areas

In this study, four representative areas along the western coast of the Gulf of Thailand (Figure 1) were investigated, situated in Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan districts of Prachuap Khiri Khan Province. Hua Hin (Figure 1a) was near downtown with various resorts, along a flattened-slope sandy beach. The beach sediment was mainly composed of fine to medium sand. The supratidal zone here had several concrete walls constructed as breakwaters. Kui Buri (Figure 1b) was situated within a mangrove forest and near a small river discharge. Sediments in the flattened-slope beach of the Kui Buri area were mainly composed of fine muddy clay in the subtidal zone, mixed with medium to coarse sand along the intertidal to supratidal zones. Thap Sakae (Figure 1c) was the most open-shore location with comparatively high-sloped beach. Sediments in the beach of the

Thap Sakae area were mainly composed of very coarse sand to gravel (along intertidal and surf zones), and mixed with medium sand in the supratidal zone. Bang Saphan area (Figure 1d) was composed of medium to fine sand sediment. It was located in the semi-enclosed Bang Saphan Bay and received freshwater inflows from Bang Saphan River (at a distance of ca 1 km from the sampling station).

Study periods

In this study, surveys were performed five times during early southwest (SW) monsoon (June 2017 and May 2018), SW monsoon (August 2017), northeast (NE) monsoon (November 2017), and the dry season (March 2018). These periods were determined from meteorological characteristics of the western Gulf Thailand (Thai Meteorological Department, 2018). During each survey season, investigations of the distribution of chlorophyll *a* and related environmental factors, i.e., air temperature, rainfall, wind speed and direction, erosion pattern of the beach, and water qualities were carried out.

The meteorological data, including air temperature, wind speed and direction, rainfall, and accumulated rainfall during the 1-month period prior to each survey time were gathered and analyzed for their effects on chlorophyll a and related water quality parameters (Table 1). The air temperature of the western part of the Gulf of Thailand was impacted by monsoon seasons. Mean air temperature decreased from 29.2 °C to 27.9 °C during the NE monsoon season. Thereafter, the temperature increased slightly in the early SW monsoon season (May 2018; 29.4 °C).

Average wind speeds across all study locations ranged from 11–17 knots (Table 1). The highest wind speed was found in August 2017 (17 knots) during the SW monsoon, while the lowest speed (11 knots) was found in November 2018, during the NE monsoon season. Rainfall data were analyzed separately for three zones, northward to southward: Upper (Hua Hin and Kui Buri), Middle (Thab Sakae), and Lower (Bang Saphan) regions. The average rainfall in those regions were in the ranges of 0.6-323.0, 67.7-247.3 and 33.5-409.4

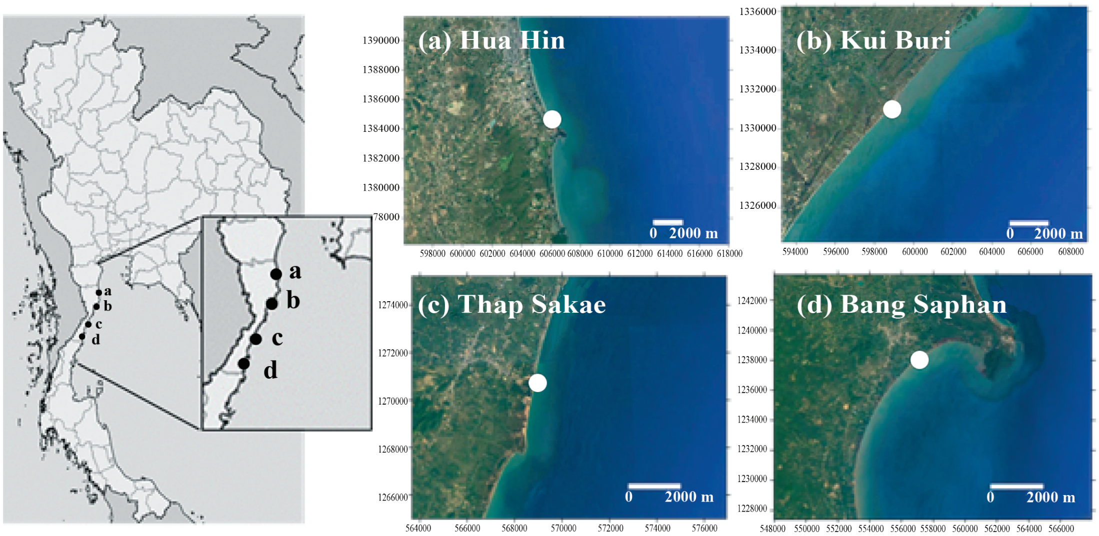

Figure 1. Study locations for investigation of changes in chlorophyll *a* and environmental factors along the western coast of the Gulf of Thailand (a; Hua Hin, b; Kui Buri, c; Thap Sakae, and d; Bang Saphan).

Table 1. Meteorological information (air temperature, wind speed and direction, and rainfall) for Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan study areas during the early SW monsoon (June 2017 and May 2018), SW monsoon (August 2017), NE Monsoon (November 2017) and dry (March 2018) season.

Sampling period	Air temperature* (°C)	Wind speed* (Knots)	Direction*	Range of accumulated rainfall* (mm·month^{-1})		
				Upper region	Middle region	Lower region
Early SW Monsoon	26.5-30.9	8-23	SE	0.0-64.4	0.0-32.3	0.0-70.1
(Jun-17)	(29.2±1.1)	15±3.8		(194.0)	(169.7)	(288.2)
SW Monsoon	26.1-30.5	7-19	SW	0.0-21.3	0.0-34.8	0.0-68.5
(Aug-17)	(29.2±1.0)	17±3.7		(0.6)	(132.4)	(214.8)
NE Monsoon	24.1-29.8	7-19	NE	0.0-95.0	0.0-88.7	0.0-107.8
(Nov-17)	(27.9±1.4)	11±3.4		(323.0)	(247.3)	(409.4)
Dry Season	26.1-29.2	11-21	SE	0.0-21.8	0.0-37.8	0.0-16.8
(Mar-18)	(27.8±0.9)	15±3.1		(27.3)	(67.7)	(33.5)
Early SW Monsoon	24.6-30.5	8-18	SE	0.0-69.0	0.0-87.0	0.0-62.8
(May-18)	(29.4±1.4)	14±2.8		(130.4)	(244.8)	(259.3)

Note: * Data from 1-month period prior to the survey times in each season (Modified from the Thai Meteorological Department, 2018)

mm·month^{-1}, respectively. During the study periods, the highest level of the rainfall was recorded in November 2017 (during NE monsoon season; 323 mm·month^{-1}). The levels decreased remarkably in the early period of dry season (March 2018).

Chlorophyll a investigation: Chlorophyll *a* concentrations in the seawater within study areas were monitored during the early SW monsoon (June 2017, May 2018), SW monsoon (August 2017), NE monsoon (November 2017) and dry season (March 2018). Water samples were collected at 0.5 m water depth along the shoreline. For chlorophyll *a* analysis, the water samples were filtered through GF/F (Whatman; pore size 0.7 µm), extracted in 5 mL of 90% acetone, and kept below 4 °C for 24 h prior to analysis. Chlorophyll *a* was analyzed by the spectrophotometric method according to Parsons *et al*. (1984).

For the study of distribution patterns of chlorophyll *a* from the sites near the shoreline to areas offshore, three stations between the four primary sampling areas were added. In addition, within each primary location (Figure 1), nine more stations at the offshore side were designed (at the water depths of 5, 10, and 15 m). Triplicate surface water samples (separated by a 2-km interval) at each depth were collected. Chlorophyll *a* concentrations in those sites were monitored during early SW monsoon (June 2017), SW monsoon (August 2017), and NE monsoon (November 2017). The samples were analyzed for chlorophyll *a* through the technique described above.

Related Water Quality Parameters: Total suspended solids (TSS) was measured by filtration of water samples through GF/C (Whatman) using freeze-drying technique to determine TSS in units of mg·L^{-1}. Measurements of water temperature, salinity, and dissolved oxygen were made at each station using multi-parameter probes (Model YSI 660QS).

Beach Erosion: A beach profile analysis (modified from the method of Andrade and Ferreira, 2006) for the surveyed locations was carried out in each survey period to monitor changes of beach slopes along with intertidal distances (from the supratidal to the subtidal distances). A comparison was made of changes in the beach slope of the study sites over time. The slopes were focused at the

Reference Distance (*Distance*$_{Ref}$; m) from the supratidal region to the maximum erosion region of each site. In that region, the *Erosion Depth* (*Depth*$_{Ref}$; m) was recorded and analyzed. In this study, the *Distance*$_{Ref}$ of Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan study sites were determined to be 15, 40, 17, and 25 m, respectively. The comparatively short *Distance*$_{Ref}$ of Hua Hin was due to the impacts of hard concrete seawalls, while at Thap Sakae this was due to its natural characteristic of having a very steep-sloped beach. The percentage of *Beach Slope* (*Slope*$_{Ref}$) at the *Reference Distance* was determined as $Slope_{Ref} = (Depth_{Ref} / Distance_{Ref}) \times 100$.

Statistical analysis

Analysis of measurements and status of their changes over sampling times was conducted by descriptive statistics through assessment of medians and standard deviations. Differences in beach slopes between locations were evaluated by a t-test ($p<0.05$). For detailed analysis of the beach slope impact, the slope levels were divided into groups, using Hierarchy Cluster Analysis combined with Ward's Method. Relationships between beach slopes, meteorological parameters, physicochemical water parameters, and chlorophyll *a* were analyzed by using Spearman's rank correlation coefficient ($p<0.05$). Accordingly, the impacts of environmental factors that coincided significantly with chlorophyll *a* were then illustrated by non-linear model using Trend Line Analysis of Excel (Version 13).

RESULTS AND DISCUSSION

In this study, changes of coastal zones in terms of beach slope, water quality, and meteorological characteristics were found to be influenced by the SW and NE monsoons that had passed through the western Gulf of Thailand. Such changes were revealed to induce variations in chlorophyll *a* levels along the western coasts (Figure 2). Results demonstrating spatial and temporal variation patterns of chlorophyll *a* and related environmental factors are as follows.

Chlorophyll a characteristics

The distribution of chlorophyll a along the western coast of the Gulf of Thailand implied both spatial and seasonal variation (Figure 2). The chlorophyll *a* levels of Kui Buri to Bang Saphan study sites along the innermost shallow zones (water depth <5 m) during the NE monsoon (November

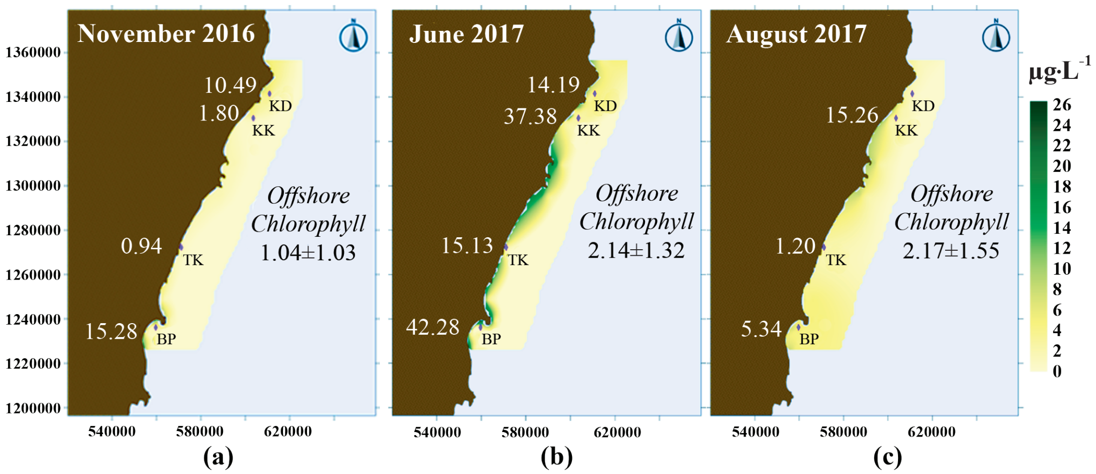

Figure 2. Surface contours of chlorophyll *a* ($\mu g \cdot L^{-1}$) concentrations during NE monsoon (a), early SW monsoon (b), and SW monsoon (c) seasons along the areas of Khao Daeng (KD), Kui Nuea (KK), Thap Sakae (TK) and Bang Saphan (BP) during 2016-2017.

2016) were low (10.49, 1.80, 0.94 and 15.28 $\mu g \cdot L^{-1}$, respectively), with an average of 6 $\mu g \cdot L^{-1}$. The levels increased to 14.19, 37.38, 15.13 and 32.28 $\mu g \cdot L^{-1}$, respectively, with an average of 26 $\mu g \cdot L^{-1}$ during the early SW monsoon (June 2017). Thereafter, during August 2017, the levels in all areas decreased to an average of 5 $\mu g \cdot L^{-1}$.

The offshore zones, with water depth of 5-15 m, had less change in chlorophyll *a*, where an overall average concentration of ca 2 $\mu g \cdot L^{-1}$ was recorded. The chlorophyll *a* levels during the NE monsoon (November 2016) had an average of 1.04 ±1.30 $\mu g \cdot L^{-1}$. The chlorophyll *a* levels increased by approximately 2 times during early and mid-SW monsoon periods (June and August 2017) to 2.14 ±1.32 and 2.17±1.55 $\mu g \cdot L^{-1}$, respectively. Such spatial and temporal variations of chlorophyll *a* have been reported to be due to impacts from coastal topography, ground water discharge, time-dependent nutrient enrichment, and circulation regimes of the sea (Kaitaranta *et al*., 2013; Menéndez *et al*., 2016; Dunn *et al*., 2017).

In this study, the levels of chlorophyll *a* were higher than in the earlier report of Traithong *et al*. (1997), who reported levels of 0.08-0.39 $\mu g \cdot L^{-1}$ at Chan Island, Prachuap Khiri Khan Province. The chlorophyll levels, nevertheless, were within the range of recent surveys (0.2-76.4 $\mu g \cdot L^{-1}$) of Lung Suan estuary and adjacent coastal areas of Chumporn Province to the south (Buakaew *et al*., 2018). In addition, chlorophyll *a* levels along the innermost water mass, particularly in the early SW monsoon (June 2017) which had the highest level of 37.38 $\mu g \cdot L^{-1}$, may reflect the impact of monsoon-driven coastal changes along the western coast of the Gulf of Thailand. Such chlorophyll abundance could imply the role of the SW monsoon on the increase of chlorophyll *a*. Shaari and Mustapha (2017) similarly emphasized the influence of the SW monsoon during June 2017 on the increase of chlorophyll *a* in Malaysian coastal waters.

The overall results of the surface distribution of chlorophyll *a* (Figure 2) and the remarkable increase along the innermost part of the coastal system reflect the meteorological functions during the SW monsoon period (Shaari and Mustapha, 2017). Analysis of meteorological information (air temperature, wind speed, and rainfall; Table 1) indicated that the temperature increased to about 32 °C, and that the wind speed increased to 15 knots during the SW monsoon (both in June 2017 and May 2018). An increase of wind speed has been reported to cause an increase in nutrients and phytoplankton along the coastal zones (Coria-Monter *et al*., 2017). During the monsoon period, moreover, the impacts of rainfall have also been indicated to enhance nutrient levels of estuarine and adjacent areas of the sea and, thus, cause an increase of phytoplankton growth (Bergamino *et al*., 2016; Buakaew *et al*., 2018; da Rocha Fanco *et al*., 2018).

Water quality characteristics

Water parameters (water temperature, total suspended solids, and salinity) of Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan study sites in all surveyed periods are depicted in Table 2, along with the chlorophyll *a* levels. Water temperatures in those survey locations were in the ranges of 28.58-33.30, 31.70-33.40, 28.83-32.2, and 29.31-34.20 °C, respectively. Overall, water temperatures showed slight seasonal changes with a decreasing trend during the NE monsoon period and an increasing trend during the SW monsoon. In this study, the Bang Saphan area, the southwest-most site characterized by an enclosed bay, had remarkable temperature changes. The temperature there was 29.31 °C during November (2016), and increased to 34.20 °C during the dry period in March (2017).

The levels of total suspended solids (TSS) of Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan study sites in all surveyed periods were in the ranges of 8.10-12.78, 12.67-328.89, 10.07-94.74, and 12.14-80.00 $mg \cdot L^{-1}$, respectively (Table 2). The coastal area of Hua Hin had the lowest TSS, while Kui Buri had the widest TSS variation over all study periods. The highest TSS of 328.89 $mg \cdot L^{-1}$ was found in Kui Buri during the dry season (March 2017). Such variation in TSS in Kui Buri is likely due to resuspension of fine muddy particles along the Kui Buri beach and adjacent coastal areas. In the Kui Buri area, wave-driven resuspension can induce more turbidity, with high amounts of suspended particulates.

Table 2. General water parameters and chlorophyll *a* levels in early SW Monsoon (June 2017 and May 2018), SW Monsoon (August 2017), NE Monsoon (November 2017), and dry season (March 2018) of Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan districts (Chl *a*: Chlorophyll *a*, Temp: water temperature, TSS: Total Suspended Solids, and Sal: Salinity).

Location	Parameter	Early SW Monsoon (June 2017)	SW Monsoon (August 2017)	Post SW Monsoon (November 2017)	Dry Season (March 2018)	Early SW Monsoon (May 2018)
Hua Hin	Chl *a* (µg·L^{-1})	5.72	5.01	3.49	2.89	3.34
	Temp (°C)	33.30	31.19	28.58	30.20	32.10
	TSS (mg·L^{-1})	N/A	12.78	N/A	11.87	8.10
	Sal (‰)	33.0	33.6	30.7	32.0	31.8
Kui Buri	Chl *a* (µg·L^{-1})	3.74	15.26	9.54	3.56	9.35
	Temp (°C)	32.00	33.40	31.70	33.10	32.87
	TSS (mg·L^{-1})	12.67	47.75	164.00	328.89	193.00
	Sal (‰)	31.0	N/A	32.2	32.5	32.2
Thap Sakae	Chl *a* (µg·L^{-1})	15.13	1.20	4.01	9.35	8.90
	Temp (°C)	30.20	29.20	29.13	28.83	32.20
	TSS (mg·L^{-1})	14.00	21.57	94.74	10.07	74.00
	Sal (‰)	34.0	35.0	30.6	32.4	31.6
Bang Saphan	Chl *a* (µg·L^{-1})	42.28	5.34	8.68	5.34	50.06
	Temp (°C)	32.67	30.29	29.31	34.20	31.80
	TSS (mg·L^{-1})	80.00	28.25	37.25	28.00	12.14
	Sal (‰)	30.0	35.1	31.6	32.0	31.7

Note: * N/A = data not available due to sampling error

The levels of water salinity of Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan areas in all surveyed periods were in the ranges of 30.7-33.6, 31.0-32.5, 30.6-35.0, and 30.0-35.1 ‰, respectively (Table 2). The salinity varied only slightly by sampling period. Across all areas, an average salinity of 32±0.68 ‰ was recorded. The salinity levels increased slightly during the dry season, except for the Kui Buri area, which showed no seasonal variation. The increases in salinity of Thap Sakae and Bang Saphan areas during August 2017 are probably due to the discharge of salt water from drying mangrove swamps near the study sites. The overall salinity results from all areas implied low freshwater inflows during the surveyed periods in 2016-2017. Such occurrence coincided with the report of very low rainfall during 2016-2017 by the Royal Irrigation Department of Thailand (2019).

Water parameters were compared to the levels of chlorophyll *a* of the shallow zones of each sampling location (Table 2). These results showed that the temperature may not have had a direct effect on chlorophyll *a*. High levels of chlorophyll *a* (*ca* 15 µg·L^{-1}) occurredin circumstances of comparatively high water temperature (*ca* 30 °C) and lower TSS (<15 mg·L^{-1}). Moreover, the decrease or increase of chlorophyll *a*, particularly during the early SW monsoons of 2017 and 2018 in all locations also implied a response to the decreasing or increasing water salinity. Thus, the combined effects of temperature, TSS, and salinity in each area were considered to influence the amount of phytoplankton production. This finding concurs with the research of Odebrecht *et al*. (1995), Shumann *et al*. (2006), and Gammal *et al*. (2017), who revealed the combined impacts of water temperature and salinity on changes of chlorophyll *a* in several coastal waters. Morais *et al*. (2003) and Cahoon *et al*. (2017) also indicated that the temperature was one of the important factors for stimulation of coastal phytoplankton growth. Qasim *et al*. (1969), Madhu *et al*. (2007) and Otsuka *et al*. (2016), in addition, revealed the importance of the turbidity of water layers to changes of phytoplankton chlorophyll.

Beach slope characteristics

Results from the measurements of beach profiles are shown in Figure 3. Along the distance from supratidal zone to the reference point (triangular mark in each graph), we found that the highest coastal erosion period was during the early SW monsoon (June 2017) with the highest beach depth at the reference points of 0.5 m (Hua Hin; Figure 3a), 0.3 m (Kui Buri; Figure 3b), 1.3 m (Thap Sakae; Figure 3c), and 0.3 m (Bang Saphan; Figure 3d), respectively. When the season changed to the NE monsoon (during November 2017), the Thap Sakae beach had apparently filled back in with sand and caused the beach depth at the reference point to be only 0.3 m lower than the reference level. The other areas had also recovered, but with smaller changes (within the ranges of 0.5 m).

Overall, beach erosion patterns were revealed to be slightly different by location ($t=4.821$, $p=0.0001$, $n=20$). In most cases, nevertheless, the SW monsoon that passed along the western coast of the Gulf of Thailand (and caused the rainy season during June to August) played the role of removing sand and related deposits from the beaches. Therefore, the beach slopes became higher after the SW monsoon. Since the rainfall amounts in all study areas were reported to be very low during the study periods (Royal Irrigation Department of Thailand, 2019), erosion along the beach intertidal zone could stimulate increases of nutrients during the disturbance and/or resuspension of fine organic particulates. Accordingly, the levels of nutrients in adjacent sea areas can also be increased and, thus, the chlorophyll levels can be later stimulated. This finding agrees with the works of Bergamino *et al*. (2016) and Coria-Monter *et al*. (2017), who illustrated that the levels of nutrients and chlorophyll in the pelagic waters can increase after a strong disturbance of the sea.

Comparison of chlorophyll a and beach slopes along study periods

In this study, temporal changes of chlorophyll *a* were compared with the levels of the beach slopes at the *Reference Distances* of the study locations (Figure 4). Study sites were clustered by slope using Hierarchy Cluster Analysis combined with Ward's Method. Based on this, the slopes of study areas were divided (92.5%, $n=20$) into two groups: low (0.082°) and high (>2°).

In this study, high beach slopes were found in Thap Sakae (Figure 4c), particularly during the early SW monsoon season (June 2017). In the Thap Sakae coastal zone, chlorophyll *a* levels were simultaneously high during that period. The increases of chlorophyll *a* levels were notably stimulated only in the Thap Sakae area (increased to 15.1 $\mu g \cdot L^{-1}$), where apparent erosion occurred and the beach slopes became higher and reached *ca* 4°. Thereafter, when the beach slope decreased to *ca* 0.3°, the chlorophyll *a* decreased to *ca* 1 $\mu g \cdot L^{-1}$. The variation of beach slopes in the Thap Sakae coastal zone was higher than the variation of chlorophyll *a*, probably due to comparatively higher dispersion of the phytoplankton cells in the area by wave action.

The beach slopes of Hua Hin (Figure 4a), Kui Buri (Figure 4b), and Bang Saphan (Figure 4d) had less temporal change (slopes were mostly <2°). Also, the levels of chlorophyll *a* were lower than those of the Thap Sakae area (Figure 4c). In these areas, the changes in chlorophyll *a* did not coincide with changes in beach slope, but instead were likely caused by other nutrient stimulation process in the water column (Odebrecht *et al*., 1995; Lui *et al*., 2012; Bergamino *et al*., 2016; Otsuka *et al*., 2016). In the Bang Saphan area, in particular, responses of chlorophyll *a* to changes of beach slopes were remarkably different. Very high levels of chlorophyll *a* (40 $\mu g \cdot L^{-1}$) were found during the SW monsoon period (June 2017) when the slope of the beach was low (*ca* 1°). Such an occurrence was considered to be due to the topography of Bang Saphan beach, which is a semi-enclosed bay with very low slopes. Moreover, comparatively

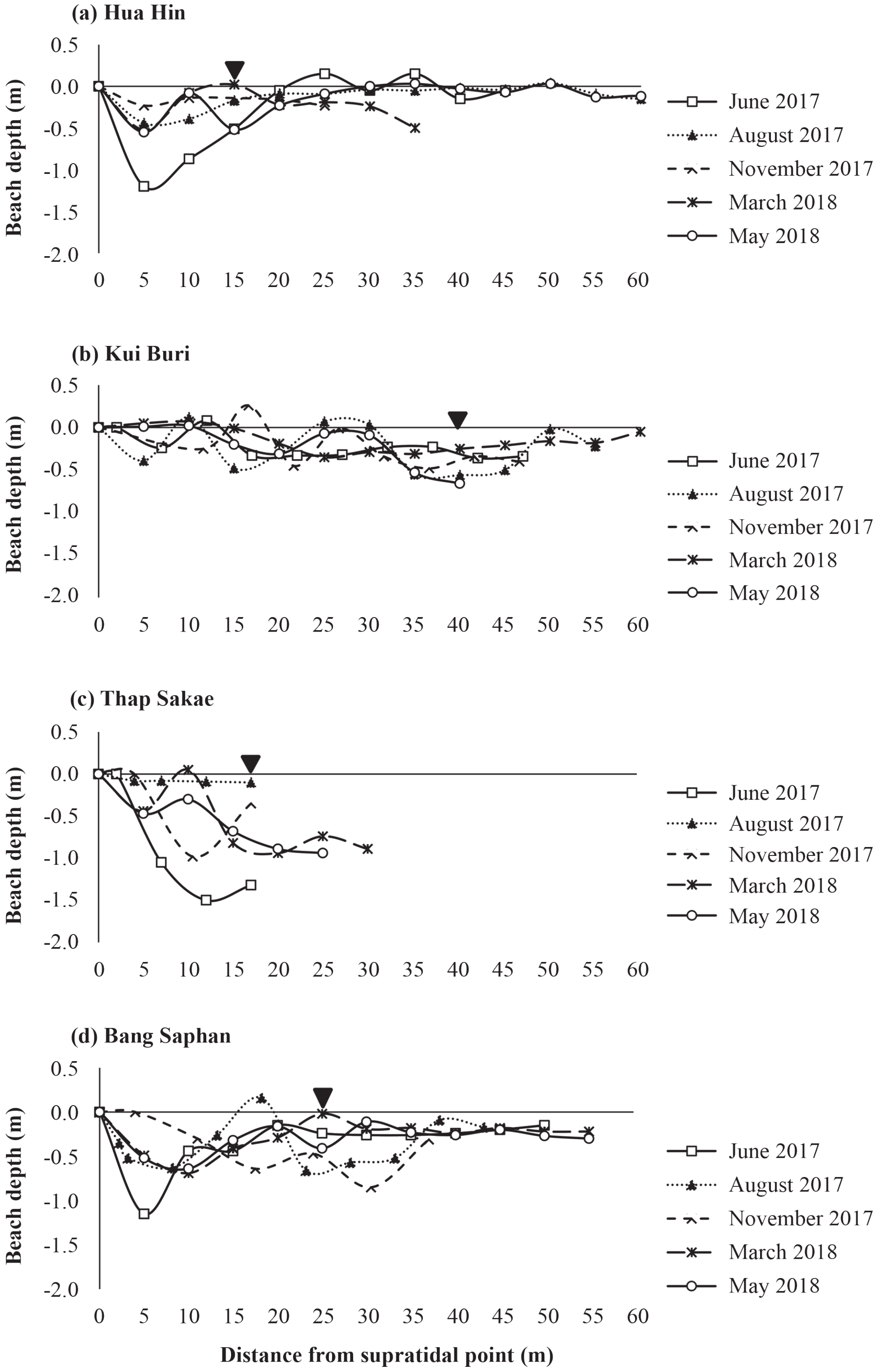

Figure 3. Beach profiles of Hua Hin (a), Kui Buri (b), Thap Sakae (c), and Bang Saphan (d) during five surveyed periods in 2017-2018 (▼ = Reference Point).

high water temperature (32 °C; Table 2) and high transparency were recorded during those periods. Such combined factors could stimulate the increases of chlorophyll *a* in the area (Qasim *et al*., 1969; Mudhu *et al*., 2007; Otsuka *et al*., 2016)

Correlations between chlorophyll a and related environmental factors

In this study, Spearman's correlations between chlorophyll *a* and slope, and correlations with other related meteorological and aquatic

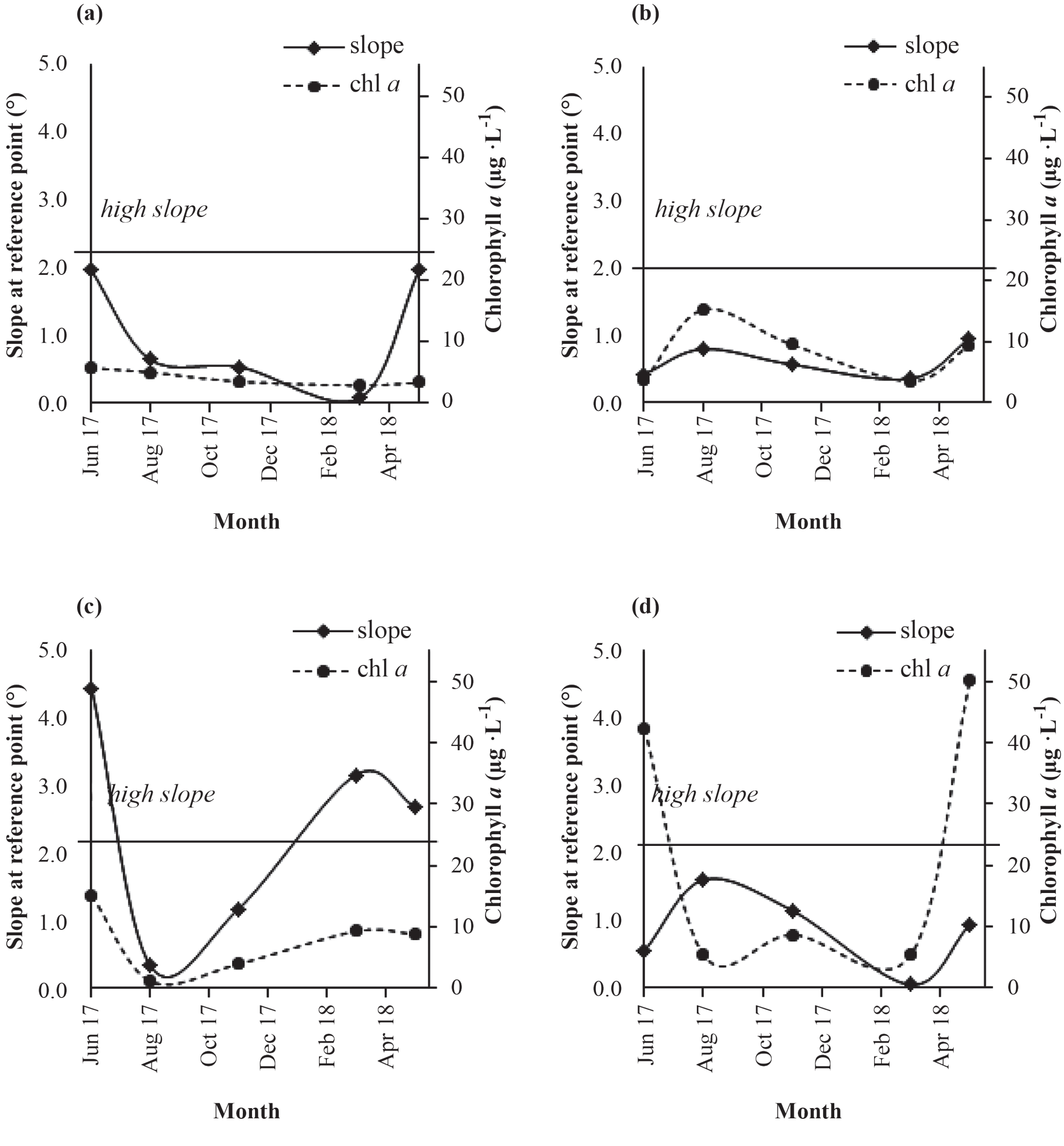

Figure 4. Seasonal changes of beach slope at reference distance (slope) and chlorophyll *a* levels (chl *a*) in the coastal areas of Hua Hin (a), Kui Buri (b), Thap Sakae (c) and Bang Saphan (d) along the Prachuap Khiri Khan coast during 2017-2018 (high slope: >2°).

environmental parameters (air temperature, wind speed, rainfall, water temperature, total suspended solids, and salinity) were analyzed and are depicted in Table 3. The correlation analysis indicated that chlorophyll *a* had an apparent correlation with slope. The other parameters (air temperature, wind speed, rainfall, water temperature, total suspended solids, and salinity) showed no significant correlation. As discussed in previous paragraphs, slopes at Hua Hin, Kui Buri, and Bang Saphan were lower than at Thap Sakae. Thus, the changes of chlorophyll *a* and related environmental conditions may be influenced and/or depended on different variables from the Thap Sakae area.

The significant correlation between chlorophyll *a* and beach slope of the four areas is of interest. Plots between chlorophyll *a* and the beach slopes of Hua Hin, Kui Buri, Thap Sakae, and Bang Saphan are presented in Figure 5, and illustrate the impact of slope on those areas. In this study, the slopes that varied by wide ranges (0.08-4°) had moderate impact on the levels of chlorophyll *a* in the adjacent sea areas.

The impact of beach slope (S) at the reference point on chlorophyll *a* (Chl *a*) can be expressed as the equation: Chl a=7.35 $S^{0.24}$ (r= 0.314, p<0.05; Figure 5). In this study, we found

Table 3. Spearman's Rho from the correlation analysis of chlorophyll *a* with beach slope (slope at reference point), meteorological data (air temperature, wind speed, average rainfall, monthly accumulated rainfall), and water parameters (water temperature, total suspended solids and salinity) in the Hua Hin, Kui Buri, Thap Sakae and Bang Saphan areas during the study period (n=18; * 2-tailed correlation significant at the 0.05 level, ** 2-tailed correlation significant at the 0.01 level).

Study Areas	**Slope at reference point**	**Meteorological factors**				**Water parameters**		
		Air temperature	**Wind speed**	**Average rainfall**	**Accumulated rainfall**	**Water temperature**	**Total Suspended Solids**	**Salinity**
All areas (n=18)	0.521*	-0.185	0.092	0.268	0.268	0.263	0.318	-0.113

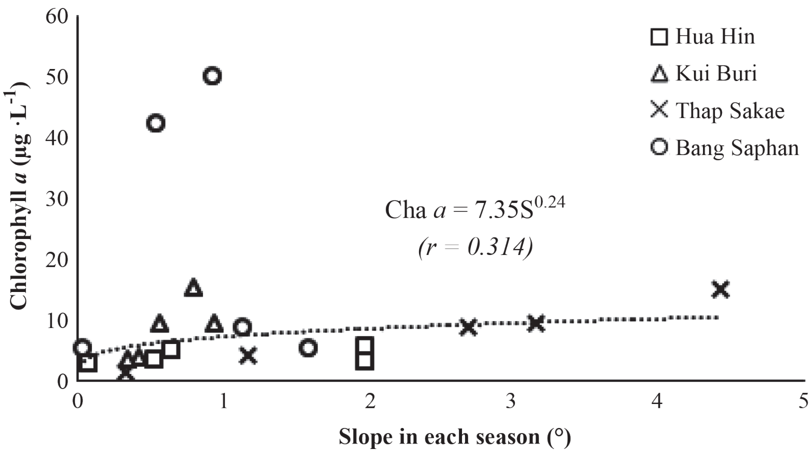

Figure 5. Plots between beach slope and level of chlorophyll *a* of the Thap Sake, Hua Hin, Kui Buri, and Bang Saphan areas along the western coast of the Gulf of Thailand.

that when the slopes increased by 3° (e.g., from 1° to 4°), the levels of chlorophyll *a* increased by approximately 3 µg·L^{-1}. In recent years, the monsoons have seemed to induce very strong winds (Demers and Therriault, 1987; Davis and Yan, 2004; Kaitaranta *et al*., 2013; Thompson *et al*., 2013; Addo, 2018; Ha *et al*., 2018). High disturbances of the beach profiles caused by these winds could stimulate increases of chlorophyll *a* in the adjacent sea areas, which may, in turn, cause eutrophic conditions at some times.

Chlorophyll *a* in the coastal zones can be further utilized as an organic food source for various consumers and benefit fishery resources in the coastal ecosystem. Therefore, assessment of the chlorophyll *a* levels that are stimulated by beach processes is of importance. Further determination of primary productions and related pelagic fishery resource production should be carefully analyzed to identify related characteristics of coastal erosion that can enhance the supply of land-based nutrients to the primary production process of the coastal ecosystem.

CONCLUSION

In this study, the roles of changes in beach slopes and related environmental factors on chlorophyll *a* production along the western coast of the Gulf of Thailand were studied. Chlorophyll *a* distributions indicated seasonal changes, with increased levels during the early SW monsoon. Moreover, chlorophyll *a* concentrations along the inner part of the coastal zones (with maximum level of 42 µg·L^{-1}) were higher than in the outer zones (with an average of 2 µg·L^{-1}). The overall results implied that chlorophyll *a* in the four study areas had an apparent correlation with the degree of beach slope, particularly in the early SW monsoon season. The other parameters (air temperature, wind speed, rainfall, water temperature, total suspended solids, and salinity) showed no significant correlations.

Across all study areas, the beach slopes had wide temporal changes (0.08-4°). The beach slopes (S; degree°) were found to relate to the chlorophyll *a* concentrations (Chl *a*; µg·L^{-1}) by the equation: Chl a=7.35 $S^{0.24}$ (r=0.314, p<0.05). The slopes that increased to levels of more than 2° (particularly the Thap Sakae area) had increases of chlorophyll *a* of more than 9 µg·L^{-1}. On the other hand, when the beach slopes were less than 2°, the level of beach slope showed no significant impact on chlorophyll *a* concentration.

The overall results implied that the changes in the beach slopes of the western coast of the Gulf of Thailand due to monsoon-driven coastal erosion can play a role in stimulation of near-shore chlorophyll *a* levels, particularly in the southwest monsoon period. The increased coastal erosion that may enhance land-based nutrients to the adjacent coastal areas was illustrated. Such chlorophyll *a* increases should be useful for related pelagic fishery resources in the coastal ecosystem.

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