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Influence of climate on seawater quality and green mussel production

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Summary: This study aimed to investigate the relationships between atmospheric parameters, seawater quality and green mussel production which were cultured in pond, estuary and coastal areas. Seawater and mussel samples were collected from mussel farms in the inner Gulf of Thailand from January to December 2019. Climate data were obtained from the Thai Meteorological Department. The correlations between selected atmospheric and seawater parameters were developed using linear and non-linear models. The influence of seawater quality on mussel production was evaluated using principal component analysis and stepwise multiple linear regression. The effects of atmospheric variation on green mussel productivity were simulated. The results showed that high air temperature and rainfall caused an increase in seawater temperature and a decrease in salinity, respectively. It was observed that the most influential factors affecting mussel production were nutrients and dissolved oxygen in ponds, temperature and salinity in estuaries, and nutrients and pH in coastal areas. The simulation indicated that mussel production can deteriorate when air temperature reaches 34°C and rainfall is higher than 200 mm per month. Our results suggest that under climate change events, locations with less riverine influence can provide higher mussel productivity. These results can be used as a guideline for farmers during a climate change event.

Keywords: air temperature; rainfall; seawater quality; climate change; cultivation area; *Perna viridis.*

Influencia del clima en la calidad del agua de mar y la producción de mejillón verde

Resumen: Esta investigación tuvo como objetivo investigar las relaciones entre los parámetros atmosféricos, la calidad del agua de mar y la producción de mejillones verdes que se cultivaron en estanques, estuarios y áreas costeras. Se recolectaron muestras de agua de mar y mejillones de granjas de mejillones en el interior del Golfo de Tailandia de enero a diciembre de 2019. Los datos climáticos se obtuvieron del Departamento Meteorológico de Tailandia. Las correlaciones entre parámetros atmosféricos y de agua de mar seleccionados se desarrollaron utilizando modelos lineales y no lineales. La influencia de la calidad del agua de mar en la producción de mejillones se evaluó mediante análisis de componentes principales y regresión lineal múltiple paso a paso. Se simularon los efectos de la variación atmosférica sobre la productividad del mejillón verde. Los resultados mostraron que la alta temperatura del aire y las precipitaciones provocaron un aumento de la temperatura del agua de mar y una disminución de la salinidad, respectivamente. Se observó que los factores más influyentes que afectaron la producción de mejillón fueron los nutrientes y el oxígeno disuelto (OD) en los estanques; temperatura y salinidad en estuarios; y nutrientes y pH en zonas costeras. La simulación indicó que la producción de mejillón puede deteriorarse cuando la temperatura del aire alcanza los 34°C y la precipitación supera los 200 mm por mes. Nuestros resultados sugieren que, bajo eventos de cambio climático, los lugares con menos influencia fluvial pueden proporcionar una mayor productividad de mejillón. Estos resultados se pueden utilizar como guía para los agricultores durante un evento de cambio climático.

Palabras clave: temperatura del aire; lluvia; calidad del agua de mar; cambio climático; área de cultivo; *Perna viridis.*

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INTRODUCTION

A higher frequency and magnitude of extreme weather events were reported during the 20th century (Hansen et al. 2006, IPCC 2013). These caused atmospheric variations, including temperature, moisture and precipitation. By the end of the 21st century (2081-2100), the IPCC (2013) predicts that the global mean surface temperature will increase by 1.5 to 2.0°C. Extreme precipitation events are becoming more intense and frequent. The areas affected by monsoon systems will increase. These weather disturbances can have devastating impacts on marine ecosystems for seawater quality and living organisms (Hader and Barnes 2019).

Many researchers have documented that surface water quality is highly sensitive to climate. Its physical, chemical and biological properties respond rapidly to climate-related changes (Coulliette and Noble 2008, Park et al. 2011, Alosairi et al. 2019). Climate change (including global warming) has led to unstable air temperature and rainfall patterns (Al-Awadhi et al. 2014). An increase in air temperature causes an increase in surface water temperature owing to the enhanced heat content of water by solar radiation (Morrill et al. 2001, Harvey et al. 2013). Rainfall events cause disturbances of water quality by diluting nutrients and other materials and increasing sediment erosion, leading to more suspended particles in the water (Pilditch et al. 2008, Park et al. 2011). Moreover, during and after the rainfall events, salinity in estuarine and coastal waters decreases significantly in response to river discharges (Valiela et al. 2012, Alosairi et al. 2019). Heavy rainfall occurring during a short period can also result in a rapid decrease in salinity caused by flash flooding. Rainfall affects the pH of seawater. In coastal areas, rainwater can input sodium and calcium ions, which come from sea salt and land dust, into seawater (Wirmvem et al. 2014, Khan et al. 2018). In contrast, in estuarine areas, heavy rainfall can dilute the alkalinity of seawater through river runoff. These changes in seawater properties could affect the health of many aquatic species, including green mussels (Goh and Lai 2014, Hader and Barnes, 2019).

Green mussel (*Perna viridis*) is a commercial bivalve species in Southeast Asia. It has been the most productive mollusc in Thailand for decades (Department of Fisheries 2020). Loss of green mussels has tremendous impacts on local income and global food security. Changes in atmospheric parameters influence seawater quality and subsequently affect green mussel growth and survival. Recent studies have documented climate change–related stressors in green mussels (Firth et al. 2011, Wendling et al. 2013, Goh and Lai 2014). The cold air temperature during the winter season can cause green mussel mortality (Firth et al. 2011). Based on the IPCC prediction that surface seawater temperature will rise as a result of global warming, experimental results to study thermal stress showed that when the seawater temperature reaches 34ºC, only 25% to 75% of mussels survive (Wendling et al. 2013). The mussels die at 8°C and 38ºC (Goh and Lai 2014). Heavy rainfall can lower the salinity in seawater. This stress results in the degradation of mussel haemocytes and lysosomal content (Wang et al. 2012). Variations in pH in seawater caused by changing rainfall patterns can affect physiology and immune responses in green mussel (Sivalingam 1977). The above studies have demonstrated the influence of seawater temperature, pH and salinity on green mussels, but none of them has evaluated green mussel production based on environmental fluctuations caused by climate variation.

We hypothesize that disturbances in atmospheric parameters such as air temperature and rainfall cause changes in seawater quality and subsequently a decrease in green mussel productivity. The novelty of the research is that it combines and links atmosphere variation, seawater quality and mussel production. A literature review reveals that no reported scientific research combines all three parameters and investigates impacts on mussel production. Moreover, differences in cultivation methods (for pond, estuary and coastal areas) can also affect green mussel production in different ways.

Therefore, this study emphasizes how climate change affects green mussels cultivated by different methods. The objectives of the study are 1) to investigate correlations between atmospheric parameters and seawater quality; 2) to evaluate the influence of seawater quality on green mussel production; and 3) to simulate the effect of atmospheric variations (air temperature and rainfall) on green mussel productivity with mussels cultured in pond, estuary and coastal areas. The results of our study can provide information to farmers on how the cultivation method used is sensitive to climate change events. They can also assist farmers and provide adaptation strategies for green mussel production under extreme weather events occurring due to global warming and climate change.

MATERIALS AND METHODS

Study area

In this study, mussel farms in the inner Gulf of Thailand, which is an important green mussel production area in Southeast Asia, were selected. Three cultivation areas and methods which are practised in Thailand (pond, estuarine and coastal areas) were chosen to investigate how each method will be affected by climate change and in which of them extreme events will have the most impact. To compare the climate change effect between these methods, Bangkhuntein (BKT), Maeklong river mouth (MK), and Sriracha (SRI) were chosen as a case study for green mussel cultivation in pond, estuary and coastal areas, respectively (Fig. 1). The farm areas, numbers of cultivation ropes and depths of each station are shown in Table 1.

The first sampling location was in Bang Khun Thian district, Bangkok (UTM unit zone 47P 655299 m E, 1497465 m N). At this location, green mussels are cultured in ponds. Juvenile mussels (shell length 2 cm) were brought from Chonburi province, Thailand. They were attached to cultivation ropes and hung on floating rafts. Seawater was circulated by opening the gate at high tide and closing the gate at low tide each day. The mussel farm is located inland at a distance of 4.69 km from the seashore. As shown in Figure 1, there are numerous ponds in this area, but most of them culture shrimp, and the few ponds that culture green mussel were selected in this study. The sampling stations at this location were BKT 1 and BKT 2, which represent a low and high density of mussel cultivation, respectively, and BKT 3, where mussels are cultivated inside a water canal where seawater can flow through all the time.

Another sampling location, where mussels are cultivated in an estuarine area, was the Maeklong river mouth, Samut Songkhram province (UTM unit zone 47P 612675 m E, 1475015 m N). This mariculture site has riverine influences. The juvenile mussels were obtained from this site. Three survey locations were selected across a wide area of the Maeklong river mouth (Fig. 1). Station MK 1 is the farthest green mussel farm from the estuary at a distance of 8.61 km east from the river mouth and 6.24 km from the shore. At this station, the mussels are cultured in horizontal racks made from rope. The mussel spats are attached to a rope and grow naturally. Station MK 2 is close to the river mouth, but the cultivation method is the same as at MK 1. Station MK 3 is at the southern boundary of the river mouth. Small mussels were brought from the mussel farms around MK 2. Then, they were attached to cultivation ropes or fishing nets and hung in long lines.

Green mussel farms in Sriracha, Chonburi province (UTM unit zone 47P 708208 m E, 1458524 m N) were selected for mussel cultivation in a coastal area. This cultivation site is outside of estuarine influences and is about 26 to 35 km south of Bang Pakong estuary. As shown in Figure 1, there are three sampling stations along the Sriracha coastal area, and each station is about 1 km from the seashore. Green mussels at all stations were cultured from floating rafts, and juvenile mussels were obtained from this site and attached to cultivation ropes.

Sampling and analysis

Green mussels and seawater samples were collected monthly during the low tide from January to December 2019. All mussels that were attached to one cultivation rope were collected from each sampling station. Epifauna and attachments were removed from the mussels. The fresh weight of the flesh of each mussel was measured using a 4-digit analytical balance. Then, the mussel production (kg m^{-2}) for each mussel farm was determined by multiplying the fresh mussels' weight by the number of cultivations ropes and dividing by the total farm area (Table 1).

At each station, a 1 L sample of seawater was collected in a glass bottle. Then, the seawater temperature, pH, salinity, conductivity and dissolved oxygen (DO) were measured in situ using a handheld multi-parameter probe (YSI 600QS, USA). Salinity was measured in practical salinity units (psu). Transparency was analysed using a Secchi disc. Seawater samples were brought to the environmental laboratory at Bansomdejchaopraya Rajabhat University, Bangkok, Thailand for chlorophyll *a* (Chl *a*), total suspended solids and nutrient concentration analysis. Chl *a* concentration was analysed as described in Parsons et al. (1984). Total suspended solids (TSS) were determined by filtering the seawater through filter paper (GF/C) and drying it in a hot-air oven at 105°C for three days. Then, the seawater sample was filtered through GF/F filter paper (pore size 0.7 µm) to remove all suspended particles and bacteria. The filtered sample was kept frozen at −20°C for nutrient analysis. Finally, concentrations of ammonium-nitrogen (NH_4^+-N), nitrite and nitrate-nitrogen ($NO_2^-+NO_3^-$-N), phosphate-phosphorus (PO_4^{3-}-P) and silicate-silicon ($Si(OH)_4$-Si) were determined using a TrAAcs 2000 segmented flow analyser (Seal Analytical, USA) (sensitivity ± 0.01 µg L^{-1}).

Data analysis

In this study, seawater quality includes only the water variables that may affect green mussel production. To investigate the correlations between atmos-

Table 1. – Characteristics of green mussel farms.

Station	Cultivation method	Farm area (m^2)	No. of cultivation ropes	Depth (m)
BKT 1	floating raft	26935	336	2.0
BKT 2	floating raft	26077	3280	2.5
BKT 3	floating raft	179	48	1.8
MK 1	horizontal rack	8064	33660	6.6
MK 2	horizontal rack	360	1680	3.0
MK 3	long-line	2000	4200	3.0
SRI 1	floating raft	1344	891	3.9
SRI 2	floating raft	1224	1460	4.5
SRI 3	floating raft	1716	1152	4.5

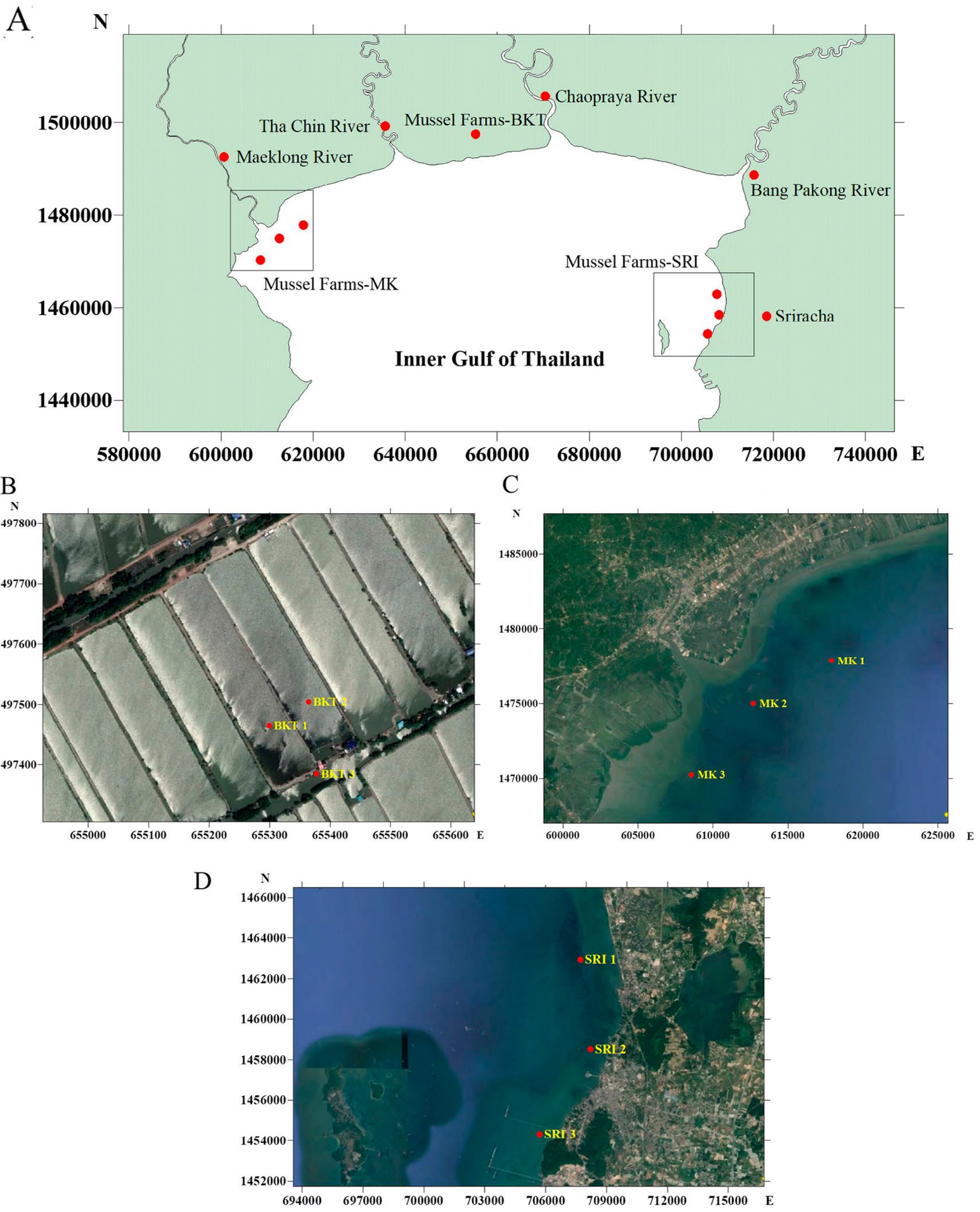

Fig. 1. – Study area: A, inner Gulf of Thailand and location map showing sampling stations for each green mussel farm; B, Bang Khun Tien (BKT); C, Maeklong river mouth (MK); and D, Sriracha (SRI). Panels B, C and D represent the pond, estuary and coastal areas, respectively.

pheric parameters and seawater quality in the study area, atmospheric data were used. The average of the highest air temperature (HAT) and the monthly total rainfall were obtained from the Thai Meteorological Department (TMD). Then, in each station, the atmospheric data were correlated with seawater parameters (temperature, pH, salinity, DO, NH_4^+-N, NO_2^-+NO_3^--N, PO_4^{3-}-P and $Si(OH)_4$-Si) from monthly field observations for one year (n=12) by model fitness (linear and non-linear) using Microsoft Excel 365 software.

Analysis of variance (ANOVA) and Turkey-HSD were used to test for the spatial and temporal variations of green mussel production and seawater quality. The sample size (n) was 108 and the degree of freedom (df) was 8 for spatial analysis and 11 for temporal analysis. Principal component analysis (PCA) was used to determine the main parameters that cause changes in the environment at each sampling site (BKT, MK and SRI). Only principal components (PCs) with an eigenvalue exceeding 1 were analysed with Varimax rotation. Then, multiple linear regressions were performed to evaluate the influence of seawater quality on green mussel production. Based on the results from PCA (PC 1) and stepwise analysis, only significant variables were used in the regression models. Moreover, cultivation duration and operation methods were different at all stations, resulting in a different age of the mussels between stations. Thus, in addition to seawater quality, cultivation time is another important parameter affecting green mussel density. Hence, to obtain reliable results, cultivation time was included in the regressions analysis. All statistical parameters were computed using IBM SPSS Statistic Version 23 for Windows.

Scenarios on effects of climate variation on green mussel production

To simulate the effects of atmospheric variation on green mussel productivity, seawater parameters were correlated with the variation in monthly rainfall or the HAT using a multiple linear regression model to evaluate the mussel production. In this study, the models were simulated under two different scenarios: 1) drought conditions; and 2) storms or rapid heavy rainfall. In the first scenario, the variation in HAT was considered with fixed rainfall of 0.1 mm (lowest data used in the models). In the second scenario, the variation in monthly rainfall was considered with fixed HAT. For both scenarios, simulations were done for 12 months of cultivation time, and the effects were assessed on the healthiest mussels that were ready for harvest.

RESULTS

Effects of air temperature and rainfall on seawater parameters

The results indicated that variations in air temperature and rainfall caused changes in seawater quality (Figs 2-5). This is explained by the model equations, as shown in the supplementary data (Table S1). The results demonstrated that in all green mussel cultivation areas a high air temperature caused an increase in seawater temperature. An increase in monthly rainfall resulted in a decrease in salinity and an increase in seawater pH, except at station MK 3. At this station, excessive rainfall may have lowered the water pH due to the amount of runoff. The correlation between rainfall and DO at each cultivation area was found to be different owing to site-specific characteristics and influence of wind, wave and pollution through river runoff. The results also showed that an increase in monthly rainfall caused a decrease in nutrient concentration. The correlations fitted well with the logarithm model, with the exception of NO_2^-+NO_3^--N and $Si(OH)_4$-Si at some stations (Figs 4-5).

Variation of green mussel production and seawater quality

Results from statistical analysis showed that green mussel production and seawater parameters in the three cultivation areas (BKT, MK and SRI) were significantly different, except for seawater temperature and Chl *a* concentration (Table 2). The pH level of seawater and DO at MK and SRI were found to be similar, and both were higher than at BKT. The highest values of salinity and conductivity were found at SRI, followed by MK and BKT, respectively. The nutrient concentrations at BKT were significantly higher than at MK and SRI, showing that BKT received more nutrient loading than the other areas. Spatial and temporal variations of green mussel production and seawater parameters in each cultivation area are shown in the supplementary data (Table S2-S4).

Results from PCA revealed that the three cultivation areas were differently affected by seawater variables. The PCs with eigenvalues higher than 1 and the variables whose loading exceeded 0.5 were mentioned. As shown in Figure 6, only PC 1 and PC 2 were emphasized because they explain most of the important variables. The first five PCs were responsible for more than 82.17% of the data scatter in the mussel cultivation in a pond (BKT). PC 1 explained 28.70% of the variance. The variables were NH_4^+-N, NO_2^-+NO_3^--N, and PO_4^{3-}-P with positive correlations and DO with a negative correlation. PC 2 explained 19.05% of the variance, comprising the negative correlation of temperature and the positive correlations of salinity and conductivity, while PC 3 explained 16.19% of the variance with TSS and transparency. PC 4 was pH and $Si(OH)_4$-Si and PC 5 was Chl *a* concentration, which accounted for 9.47% and 8.77% of the variance, respectively.

For mussel cultivation in an estuarine area (MK), salinity, conductivity, and temperature were identified as the most important component (PC 1), with 25.35% of the variance, followed by TSS, transparency and Chl *a* concentration (PC 2) with 18.0% of the variance. PC 1 was negatively correlated with temperature and positively correlated with salinity and conductivity (Fig. 6). Nutrient concentrations accounted for PC 3 ($Si(OH)_4$-Si and NO_2^-+NO_3^--N) and PC 4 (NH_4^+-N and PO_4^{3-}-P), which explained 16.53% and 12.13% of the variance, respectively. Finally, DO and pH (PC 5) accounted for 9.94% of the variance.

For the coastal area (SRI), nutrient concentrations (NH_4^+-N, PO_4^{3-}-P and $Si(OH)_4$-Si) were positively correlated and pH was negatively correlated. The most important components explained 32.32% (PC 1) and 20.56% (PC 2) of the variance (Fig. 6). PC 2 was positively correlated with NO_2^-+NO_3^--N and negatively correlated with salinity and conductivity. PC 3 comprised the temperature, DO and Chl *a* concentration, whereas PC 4 comprised TSS and transparency, and represented 15.21% and 9.64 % of the variance, respectively.

Influence of seawater quality on green mussel production

PCA and stepwise analysis were employed to determine the most important parameters affecting green mussel production in each cultivation area. The selected parameters were used in the multiple linear regression model. As shown in Table 3, each sampling station had an individual model equation with a high R-squared. This is due to differences in the seawater quality and cultivation method at each location. The results showed that DO, NH_4^+-N, NO_2^-+NO_3^--N, and PO_4^{3-}-P significantly affected green mussel productivity cultured in a pond (BKT). The mussel productivity at the estuary station (MK) was dependent on the distance from the river mouth owing to the different seawater parameters. For mussel cultivation in a coastal area (SRI), the most important factors were pH, NH_4^+-N, PO_4^{3-}-P and $Si(OH)_4$-Si.

Scenarios of effects of atmospheric variation on green mussel production

Results from model simulations on atmospheric parameters affecting seawater quality (Table S1) and the influence on green mussel production in each cultivation area (Table 3) are shown in Figure 7. For mussel cultivation in a pond (BKT 1 and BKT 3), the results showed that under drought conditions (high air temperature with negligible rainfall) the air temperature does not affect mussel production. However, mussel production tends to decrease when the air temperature increases at station BKT 2, with the largest mussel population (Fig. 7). The results also demonstrated that heavy rainfall causes a decrease in green mussel productivity, except at BKT 3, where mussels are cultured inside a water canal. The simulations revealed that a high air temperature with low rainfall sharply decreases production of green mussels cultured close to the river mouth (MK). As shown in Figure 7, in a coastal area (SRI), high air temperature did not influence mussel production. Heavy storms (rapid high rainfall) caused a decrease in mussel survival at station SRI 1, which is closer to Bang Pakong estuary than the other stations.

DISCUSSION

Seawater quality under variations of atmospheric parameters

It was found that increased air temperature resulted in a higher seawater temperature, and the correlations fitted well with simple linear regression (Fig. 2). An increase in the atmospheric temperatures is due to solar radiation and results in heat exchange processes that occur at the water surface (Morrill et al 2001). Our results are in agreement with other studies in New Zealand streams (Johnson 1971), Minnesota streams (Song et al. 1973) and the rivers of Newfoundland and Labrador, Canada (Harvey et al. 2013), where the general relation between the monthly means of the surface water and air temperature was described by linear regression. However, different sampling locations resulted in a different model because environmental conditions such as

Table 2. – Green mussel production and seawater parameters (mean±sd, n=36) in the green mussel cultivation area at Bang Khun Tien (BKT), Maeklong River Mouth (MK), and Sriracha (SRI).

				One-way ANOVA	Turkey-HSD		
Parameter	BKT	MK	SRI	Cultivation Areas	BKT	MK	SRI
GM (kg m^{-2})	0.11 ± 0.13	12.64 ± 8.29	1.03 ± 0.67	***	a	b	a
Temp (°C)	29.27 ± 2.20	29.13 ± 2.19	29.76 ± 1.80	ns	-	-	-
pH	7.68 ± 0.55	8.16 ± 0.26	8.21 ± 0.33	***	a	b	b
Sal	21.56 ± 3.52	23.91 ± 5.60	28.14 ± 3.10	***	a	a	b
Conduct (ms)	25.43 ± 2.18	25.85 ± 4.13	30.12 ± 3.00	***	a	a	b
DO (mg L^{-1})	4.87 ± 1.74	5.74 ± 0.95	5.95 ± 0.90	**	a	b	b
Trans (cm)	131.17 ± 57.32	119.09 ± 77.90	230.45 ± 98.17	***	a	a	b
TSS (mg L^{-1})	32.75 ± 32.36	26.54 ± 15.08	19.48 ± 5.91	*	b	a,b	a
NH_4^+-N (µg L^{-1})	200.01 ± 143.17	90.78 ± 73.91	67.23 ± 66.97	***	b	a	a
NO_2^-+NO_3^--N (µg L^{-1})	50.12 ± 31.44	23.63 ± 19.63	7.59 ± 8.18	***	a	c	b
PO_4^{3-}-P (µg L^{-1})	77.23 ± 59.76	13.39 ± 12.41	5.75 ± 4.83	***	b	a	a
$Si(OH)_4$-Si (µg L^{-1})	1151.98 ± 716.70	492.08 ± 261.29	657.71 ± 300.80	***	b	a	a
Chl *a* (µg L^{-1})	10.31 ± 16.21	8.24 ± 7.05	5.62 ± 7.20	ns	-	-	-

Significance level of one-way ANOVA: ***, P <0.001; **, P <0.01; *, P <0.05; ns = not significant
Groups of data from Turkey-HSD are shown as a, b and c

water depth, flow velocity, stream discharge and location were not the same.

Rainfall can increase runoff, increasing the cations in seawater and subsequently increasing the pH level. In the pond area (BKT), intense rainfall corresponded to high pH in seawater, and the plateau was found with rainfall of over 50 mm per month (Fig. 2). This can be explained by the enhancement of dissolved cations from soil erosion. At BKT, there is an embankment surrounding the cultivation pond, and this area connects to a canal. Intense rainfall can increase sediment erosion from the exposed marsh surfaces and creek banks, and thus elevate the suspended sediment concentration in water channels (Pilditch et al. 2008). As a result of increased suspended solids, enhanced solubility of Na^+, K^+, Ca^{2+}, and Mg^{2+} in a water body is observed (Budhavant et al. 2009). Therefore, more suspended-solid loading can cause high dissolved cations and saturation. In the estuary (MK) and coastal (SRI) areas, high pH levels were observed with increased rainfall. Probable sources of cations were soil erosion and atmospheric deposition. Rainfall washes off aerosols and deposits them into seawater. Budhavant et al. (2009) found that rainwater was alkaline throughout the year. Other studies (Wirmvem et al. 2014, Khan et al. 2018) also indicated that rainwater contains many cations from sea salt (Na^+) and land dust (NH_4^+, Ca^{2+}, and Mg^{2+}). These cation fluxes in seawater cause an increase in pH. However, at station MK 3, heavy rainfall caused a decrease in the pH of seawater. This area is south of the Maeklong river mouth and is influenced by strong winds from the land. Rainwater in this area may be more acidic than in other areas owing to aerosol pollutants (NO_3^- and SO_4^{2-}) from human activity (Khan et al. 2018), indicating that this area is sensitive to anthropogenic stress.

This study found that high rainfall caused a decrease in salinity that can be described by simple linear regression (Fig. 3, Table S1). In estuarine and coastal areas, the salinity of seawater is diluted by river water. In addition, intense rainfall events cause water discharges, decreasing the salinity. This phenomenon has been widely observed in coastal ecosystems, as shown by recent research carried out on the pacific coast of Panama (Valiela et al. 2012), in the Depeng lagoon, Taiwan (Meng et al. 2017), and in the northwest Arabian Gulf (Alosairi et al. 2019). These studies confirmed that rainfall decreases salinity at the sea surface. The present study provides site-specific model equations for evaluating seawater salinity caused by variations in rainfall (Table S1).

Rainfall can cause an increase or decrease in DO. Our results revealed that at sampling stations MK 1 and SRI 3 intense rainfall resulted in high DO in seawater. This is because there were more wind and waves than at other stations. This finding is in line with a study on gas exchange across an air-water interface by Liss (1973), who reported that the exchange of oxygen between the air and surface water increased as a result of higher wind velocity and breaking of the water surface. In contrast, at some sampling stations (MK 2, MK 3, SRI 1, and SRI 2), rainfall caused oxygen depletion in seawater (Fig. 3). These areas were influenced by water discharges from the Maeklong and Bang Pakong river mouths, which may be polluted with suspended sediments and dissolved organic matter. In agreement with previous studies, heavy rainfall events increase waste-

Table 3. – Multiple linear regression model equation of each sampling station.

Model equation	Multiple R	R-squared	Adjusted R-squared	Standard error
$GM_{BKT\,1} = 0.0028D - (7.4261 \times 10^{-6})A + 0.0003P + (3.9282 \times 10^{-6})N + 0.0027Ct - 0.0708$	0.9885	0.9772	0.9202	0.0021
$GM_{BKT\,2} = -0.0016T - 0.1167pH + 0.0031S + 0.0079D + 0.0056Ct + 0.8119$	0.9187	0.8439	0.7139	0.0183
$GM_{BKT\,3} = -0.0683D - 0.0012A + (1.7320 \times 10^{-5})N + 0.0019P - 0.0380Ct + 1.0635$	0.9334	0.8711	0.7101	0.0741
$GM_{MK\,1} = -0.0009T - 0.1387pH + 0.0385S + 0.0865D - 0.0017P + 0.0013A - 0.0001N + 2.9414Ct + 1.8603$	0.9128	0.8332	0.7359	0.2487
$GM_{MK\,2} = -1.1487T + 18.3636pH - 0.2184S - 4.2752D + 0.0871Ct - 75.1478$	0.7742	0.5994	0.2656	4.6909
$GM_{MK\,3} = -0.1655D + 0.0088P - 0.0031Si + 0.6674Ct - 3.4299$	0.8425	0.7098	0.4776	1.8867
$GM_{SRI\,1} = 0.0039T - 0.5995pH + 0.1369S - 0.3015D + 0.3022Ct + 2.4448$	0.9676	0.9363	0.8725	0.2975
$GM_{SRI\,2} = -0.4718pH - 0.0020A + 0.2629P - 0.0038Si - 0.0344Ct + 6.8927$	0.8562	0.7331	0.5106	0.3273
$GM_{SRI\,3} = 0.1698pH - 0.0043A + 0.0161P - 0.0009Si - 0.0085Ct - 0.5888$	0.9185	0.8437	0.7135	0.0797

Note: *GM* is green mussel production (kg m^{-2}); *T* is seawater temperature (°C); *pH* is pH level of seawater; S is salinity; *D* is dissolved oxygen (DO) (mg L^{-1}); *A* is ammonium-nitrogen (NH_4^+-N) (µg L^{-1}); *N* is nitrite and nitrate-nitrogen (NO_2^-+NO_3^--N) (µg L^{-1}); *P* is phosphate-phosphorus (PO_4^{3-}-P) (µg L^{-1}); *Si* is silicate-silicon ($Si(OH)_4$-Si) (µg L^{-1}); and *Ct* is cultivation time (months) water discharges (Park et al. 2011) and faecal coliform bacteria (Coulliette and Noble 2008). Consequently, this phenomenon enhances decomposition processes that require oxygen, resulting in oxygen depletion. In the pond area (BKT), it was found that an increase in rainfall increases DO; however, with rainfall over 50 mm per month, DO became steady. With high rainfall, dispersion of suspended sediments and organic matter occurred, so DO did not increase continuously.

The results of this study also revealed that rainfall causes a decrease or increase in nutrient concentrations. During high rainfall periods, low nutrient contents were observed in the pond area (BKT), with the exception of silicate-silicon. Sipaúba-Tavares et al. (2007) also reported that rainfall positively affected a pond's water quality. In an unpolluted pond, high rainfall tends to lower the nutrient concentration owing to an increase in the water flow. However, it was found that silicate-silicon increased with high rainfall. This is because heavy rainfall increases sediment erosion from the creek banks (Pilditch et al. 2008), dissolving silicon content into the water body. In estuarine (MK) and coastal (SRI) areas, nutrient concentrations tend to decrease with high rainfall, and the correlation between these two parameters fitted the logarithm model (Figs 4-5, Table S1). Although rainfall caused excessive nutrient loading through river runoff, it has a short-term impact. These nutrients can be effectively absorbed by phytoplankton (Meng et al. 2017). The concentrations returned to their normal levels within five days after rainfall (Xu et al. 2019). Moreover, the concentrations of dissolved ions tend to be higher during dry periods (Park et al. 2011) as a result of high water evaporation. In this study, high nitrite nitrate-nitrogen and silicate-silicon with intense rainfall were found in the estuarine area (MK). This is because DO during weather disturbances can induce nitrification processes that transform ammonium to nitrite and nitrate. In addition, as observed for the pond area (BKT), rainfall causes an increase in suspended solids, which are the main source of silicate-silicon in seawater. Thus, the amount of rainfall affects the nutrient variability. The

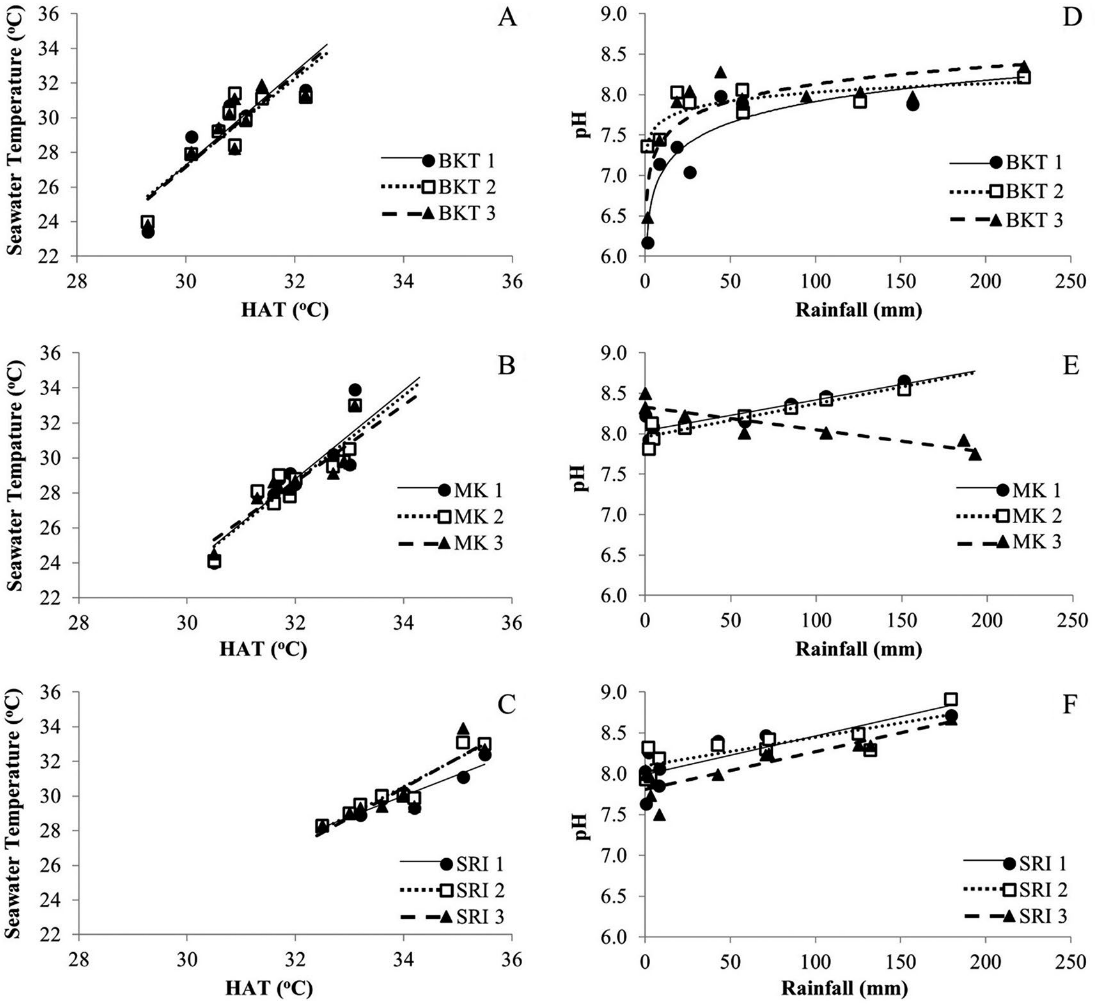

Fig. 2. – Correlation between the average of the highest air temperature (HAT) and seawater temperature (A, B and C), and correlation between rainfall and pH of seawater (D, E, and F) at each sampling station in the pond area of Bangkhuntein (BKT), the estuary area of the Maeklong river mouth (MK) and the coastal area of Sriracha (SRI) based on monthly measurements from January to December 2019.

model developed in this study (Table S1) can predict nutrient concentrations with variations in rainfall. This can assist the estimation of seawater quality during atmospheric disturbances such as typhoons, depressions and tropical storms.

Influential seawater parameters for green mussel production

It was found that seawater quality in pond, estuary and coastal areas was significantly different and affected green mussel production in different ways. Research on green-lipped mussel *Perna canalicus* by Ren et al. (2019) found that there were site-specific influences on the mussel filtration, ingestion, respiration and growth rates owing to differences in environmental conditions. Results from PCA revealed that the most important parameters affecting the environmental variability in a pond (BKT) were NH_4^+-N, NO_2^-+NO_3^--N, PO_4^{3-}-P and DO. These parameters were considered by multiple linear regression to estimate the mussel production at stations BKT 1 and BKT 3, where the mussels are cultured in low density and in a water channel, respectively. In these areas, nutrients are important factors because they are sensitive areas that receive pollutant loading from anthropogenic activities such as residences, restaurants, local industry and shrimp farms. Excessive nutrients affect green mussel production by inducing large phytoplankton blooms (Riani et al. 2018), which are a dominant dietary source for mussels (Irisarri et al. 2014). However, extreme ammonia concentrations (2.0 mg L^{-1}) are toxic to green mussels because they reduce lysosomal integrity (Fang et al. 2008), and the concentration in BKT was closer to this level than at other locations (Table 2). Furthermore, in the pond, water circulation significantly influenced the available DO in the water column. High water flows result in an increase in the oxygen concentration; this results in high growth and survival rates of green mussels (Sanjayasari and Jeffs 2019). Therefore, good mussel productivity could be found with high nitrite and nitrate-nitrogen, phosphate-phosphorus, oxygen

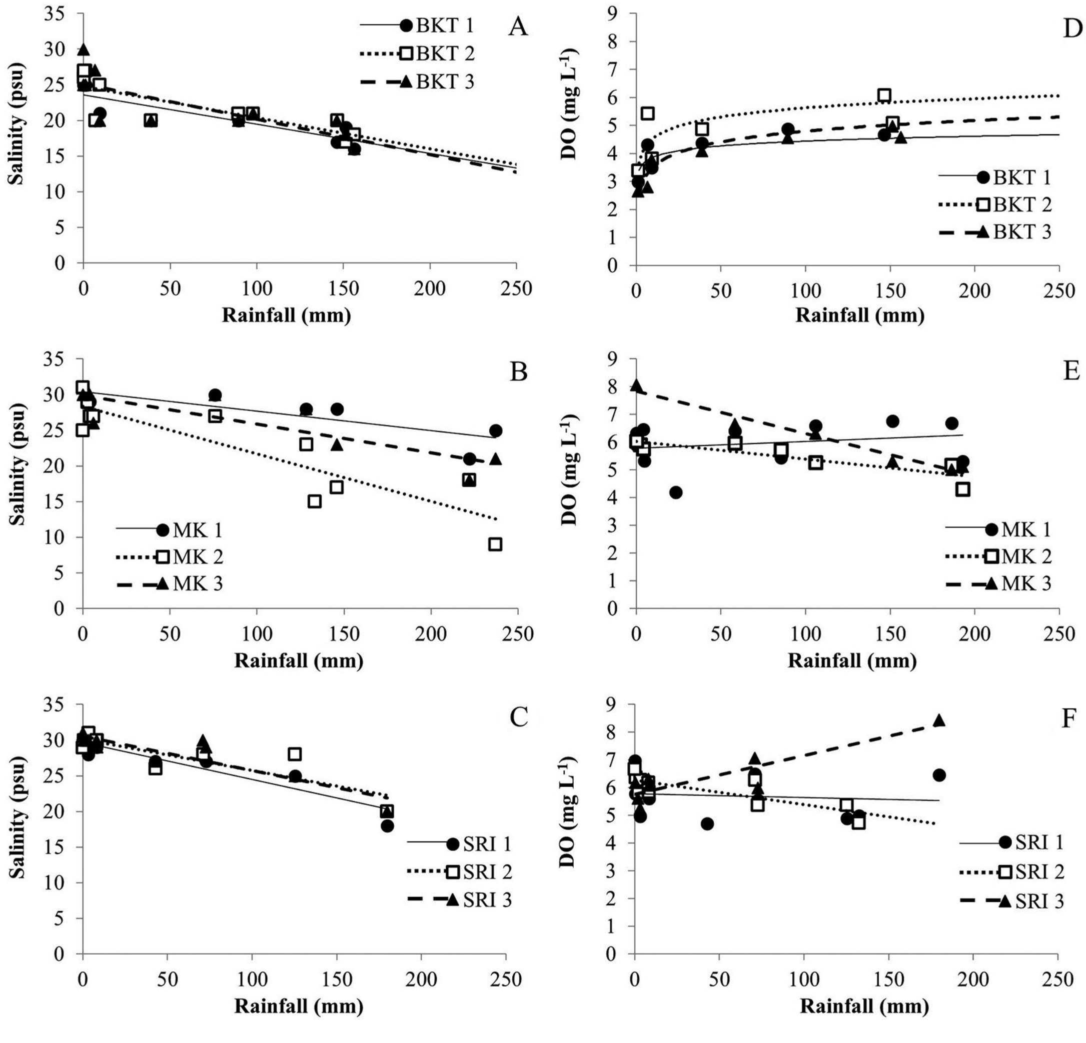

Fig. 3. – Correlation between rainfall and salinity (A, B and C), and correlation between rainfall and dissolved oxygen (DO) (D, E, and F) at each sampling station in the pond area of Bang Khun Tien (BKT), the estuary area of the Maeklong river mouth (MK), and the coastal area of Sriracha (SRI) based on monthly measurements from January to December 2019.

and low ammonium-nitrogen concentrations. Results from multiple linear regression demonstrated that the model parameters at station BKT 2 differed from those at the other stations (Table 3). At BKT 2, there was less water circulation, and seawater quality depended on the air temperature. High air temperature caused an increase in water temperature (Fig. 2), leading to higher water vaporization and denser cations in the water column (Park et al. 2011). This influences salinity and the pH level of seawater. The lethal level of these parameters can be reached faster than that of nutrient concentrations. Therefore, at this station, temperature, salinity and pH were included in the model instead of nutrients, which had less influence.

In an estuarine area (MK), our results from PCA demonstrated that variation of temperature and salinity were the most important parameters. Salinity and temperature are affected by freshwater discharges through river runoff. In line with our findings, Sasikumar and Krishnakumar (2011) also found that in a riverine influenced area, water discharges can transport significant amounts of particulate matter into coastal waters, leading to variations in seawater temperature and salinity. These parameters significantly affect green mussel growth and survival (Wendling et al. 2013). Hence, in the present study, they contributed to the mussel productivity model equations. Our results indicated that in an offshore area (MK 1), the riverine areas had less influence and the abundance of nutrients became a more important factor. Therefore, NH_4^+-N, $NO_2^-+NO_3^-$-N, and PO_4^{3-}-P were the main factors in the mussel production model. These nutrients are essential for phytoplankton growth, which corresponds to mussel integrity (Irisarri et al. 2014). Unlike at other stations, $Si(OH)_4$-Si was found to be a significant variable affecting green mussel production at MK 3. Intensive suspended solids led to dissolved silicate in the water body. This influences the mussel production by providing essential nutrients for phytoplankton, especially diatoms and dinoflagellates, which are major food sources for mussels (Irisarri et al. 2014).

In this study, the dominant parameters affecting

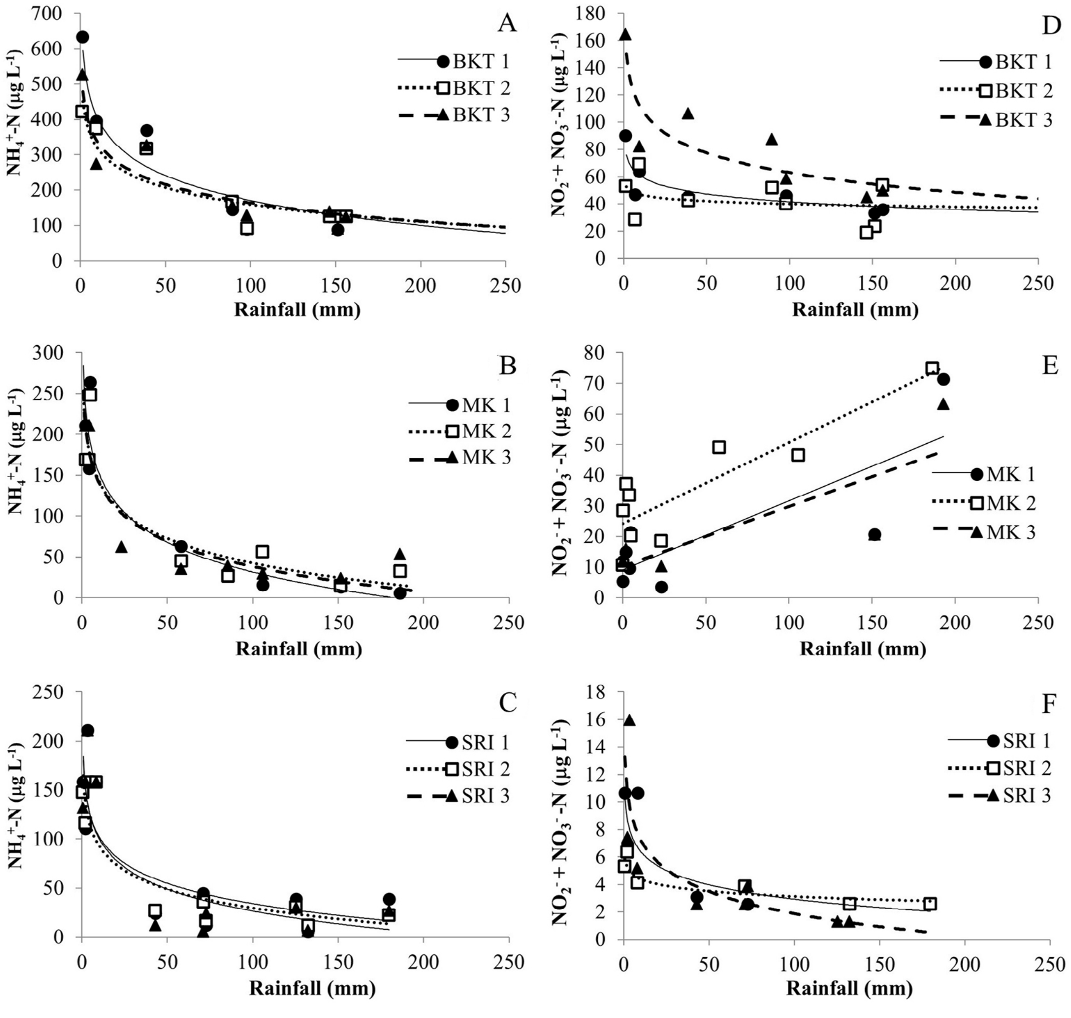

Fig. 4. – Correlation between rainfall and ammonium-nitrogen (NH_4^+-N) (A, B and C), and correlation between rainfall and nitrite and nitrate-nitrogen ($NO_2^-+NO_3^-$-N) (D, E, and F) at each sampling station in the pond area of Bang Khun Tien (BKT), the estuary area of the Maeklong river mouth (MK) and the coastal area of Sriracha (SRI) based on monthly measurements from January to December 2019.

environmental variability in a coastal area (SRI) were pH, NH_4^+-N, PO_4^{3-}-P and $Si(OH)_4$-Si. These variables were found to have a significant effect on green mussel production. This is because the study area is located farther from the river mouth. There was less input of freshwater, and the riverine influences were reduced along the coast. Therefore, temperature and salinity become less impactful factors. Seawater quality in this area is associated with precipitation and water circulation inside the inner Gulf of Thailand. The amount of rainfall affects the variation of pH levels in seawater (Fig. 2). Extremely low or high pH levels cause unhealthy green mussels (Sasikumar and Krishnakumar 2011), and tremendous die-offs can occur (Sivalingam 1977). Low pH levels (<7.3) induce physiological and biochemical stress in bivalves, such as immune deterioration (Sui et al. 2016, Wu et al. 2016), lowered clearance rates, reduction of absorption efficiency, decline of scope for growth and increased excretion rates (Gu et al. 2019). Moreover, a decrease in pH has negative effects on the calcification ability of other mussel species (Duarte et al. 2014, Fitzer et al. 2014). The results demonstrated that unlike at other stations, the significant variables affecting green mussel production at SRI 1 were seawater temperature, pH, salinity and DO, which can be influenced by river runoff (Sasikumar and Krishnakumar 2011). This is because SRI 1 has more riverine influences because it is located closer to the Bang Pakong river mouth than the other stations.

Impact of atmospheric variation on green mussel production

The results of the simulations indicated that at all sampling stations variations in air temperature and rainfall influence green mussel production in different ways. For mussels cultured in a pond, drought strongly affected green mussel production (Fig. 7). A high air temperature caused an increase in seawater temperature (Fig. 2). A very low or absence of rainfall caused a decrease in pH and DO and an increase in ammonia concentration (Figs 2-4). Consequently, the immune-related functions

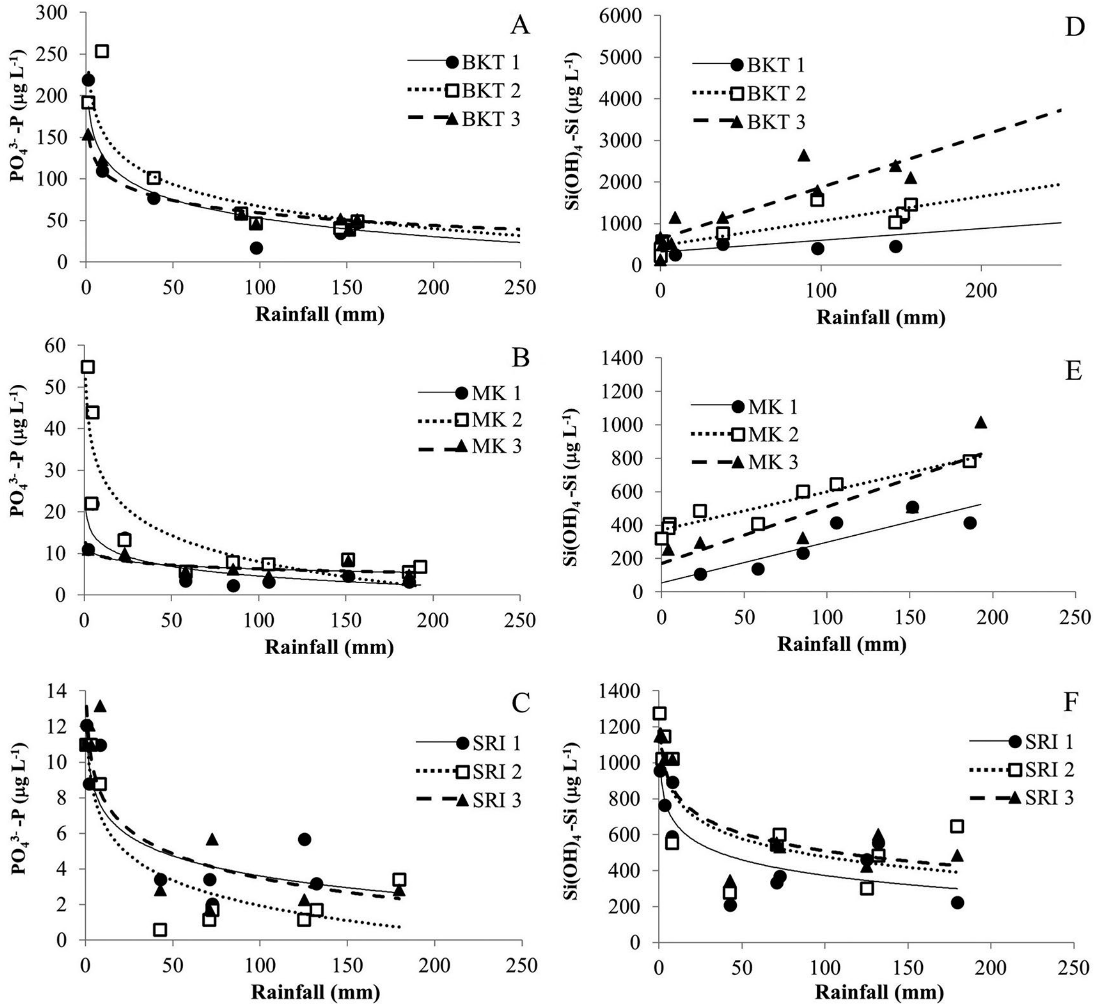

Fig. 5. – Correlation between rainfall and phosphate-phosphorus (PO_4^{3-}-P) (A, B and C), and correlation between rainfall and silicate-silicon ($Si(OH)_4$-Si) (D, E, and F) at each sampling station in the pond area of Bang Khun Tien (BKT), the estuary area of the Maeklong river mouth (MK) and the coastal area of Sriracha (SRI) based on monthly measurements from January to December 2019.

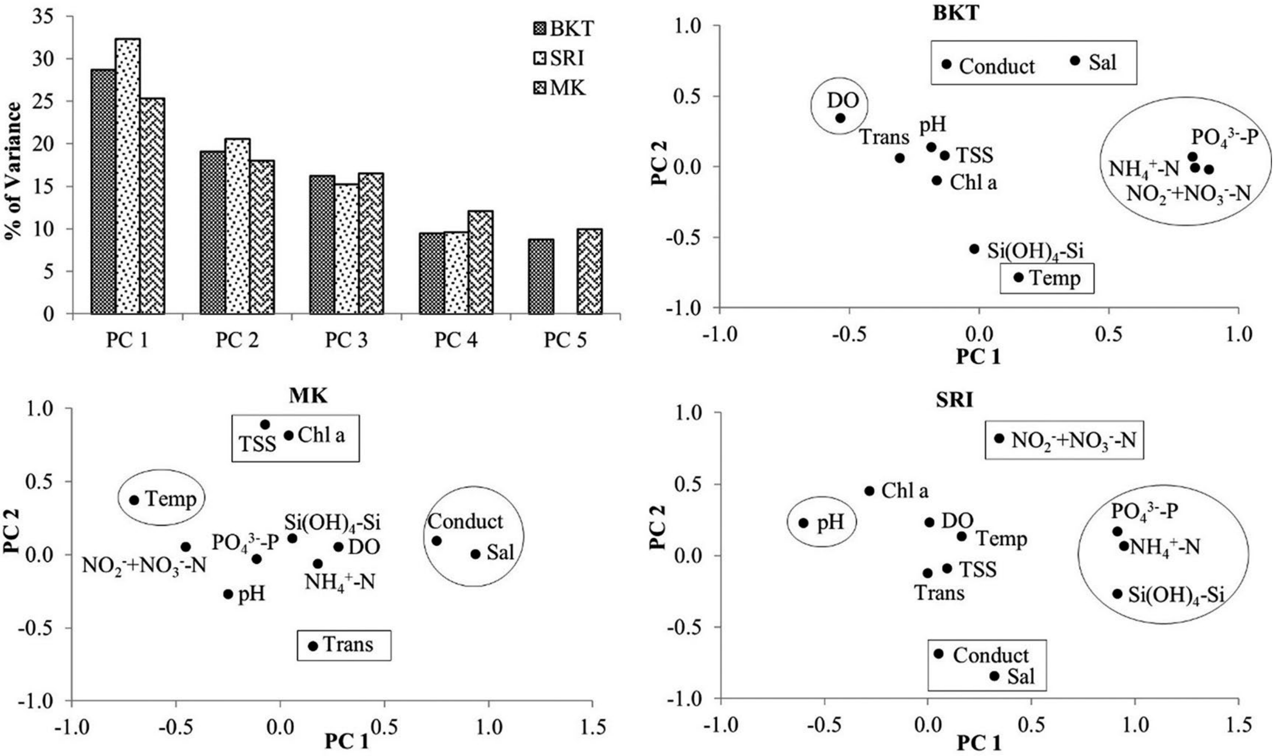

Fig. 6. – Bar chart and scatter plots showing the results of principal component analysis (significant factor of PC 1 [circle] and PC 2 [square]) for seawater variables [temperature (Temp), pH, salinity (Sal), conductivity (Conduct), dissolved oxygen (DO), transparency (Trans), total suspended solids (TSS), ammonium-nitrogen (NH_4^+-N), nitrite and nitrate-nitrogen ($NO_2^-+NO_3^-$-N), phosphate-phosphorus (PO_4^{3-}-P), silicate-silicon ($Si(OH)_4$-Si), and chlorophyll a (Chl *a*)] at the three sampling sites [Bang Khun Tien (BKT), Maeklong river mouth (MK) and Sriracha (SRI)].

and metabolism of green mussels were reduced (Fang et al. 2008, Donaghy and Volety 2011, Wang et al. 2011). However, when mussels were cultured in a water canal (BKT 3), the seawater temperature was not a significant variable for mussel production. This is because thermal stress can be reduced by enhanced aeration in seawater (Wang et al. 2011). Although our results showed that there was not much difference in DO between pond stations (BKT) (Fig. 3), water can effectively flow through the mussel body at BKT 3, and there is minimal oxygen competition between living organisms. Increasing the water flow can provide positive effects on green mussel growth and survival (Sanjayasari and Jeffs 2019).

Based on simulation results, drought did not influence green mussel production in estuary (MK) and coastal (SRI) areas (Fig. 7). This is because, although seawater temperature was found to be linearly dependent on the air temperature (Fig. 2 and Table S1), it was not a significant variable for mussel production (Table 4). However, there was a negative effect at the mussel farm that was closest to the river mouth (MK 2). This is because the seawater temperature was an influential parameter in this area. The results are in line with those of White and Toumi (2014), who found that seawater temperature fluctuates when there is a tremendous flux of freshwater from rivers. This fluctuation can affect mussel immunity and integrity (Donaghy and Volety 2011, Goh and Lai 2014), and subsequently mussel production

Scenarios of green mussel production under variations of rainfall showed that intense rainfall resulted in a decrease in production of green mussel cultured in a pond (Fig. 7). As shown in Figures 4-5, high rainfall corresponded to nutrient reduction. The lack of essential nutrients was not suitable for phytoplankton growth. Consequently, there was not sufficient available food for green mussels (Irisarri et al. 2014). The mussels that were cultured in a water canal (BKT 3) were found to be more productive than those in a pond (BKT 1 and BKT 2). The mussel production increased with an increase in rainfall and become steady when rainfall was over 50 mm per month (Fig. 7). Although there were fewer available nutrients during intense rainfall, the multiple regression analysis indicated that mussel production depends more on DO than on the other parameters (Table 3). A high water flow rate enhances the aeration of seawater and promotes mussel growth (Sanjayasari and Jeffs 2019).

Surprisingly, the simulations revealed that heavy rainfall did not affect green mussels that were cultured in the estuary area (Fig. 7). The multiple linear regression analysis showed that for mussel cultivation far from shore the seawater quality did not change (much) during intense rainfall. This is because there is less impact from river runoff in this area. However, the mussel production next to the river mouth (MK 2) was found to be higher when rainfall increased (Fig. 7). This can be explained by the enhancement of phytoplankton during heavy rainfall events. Heavy storms cause ex-

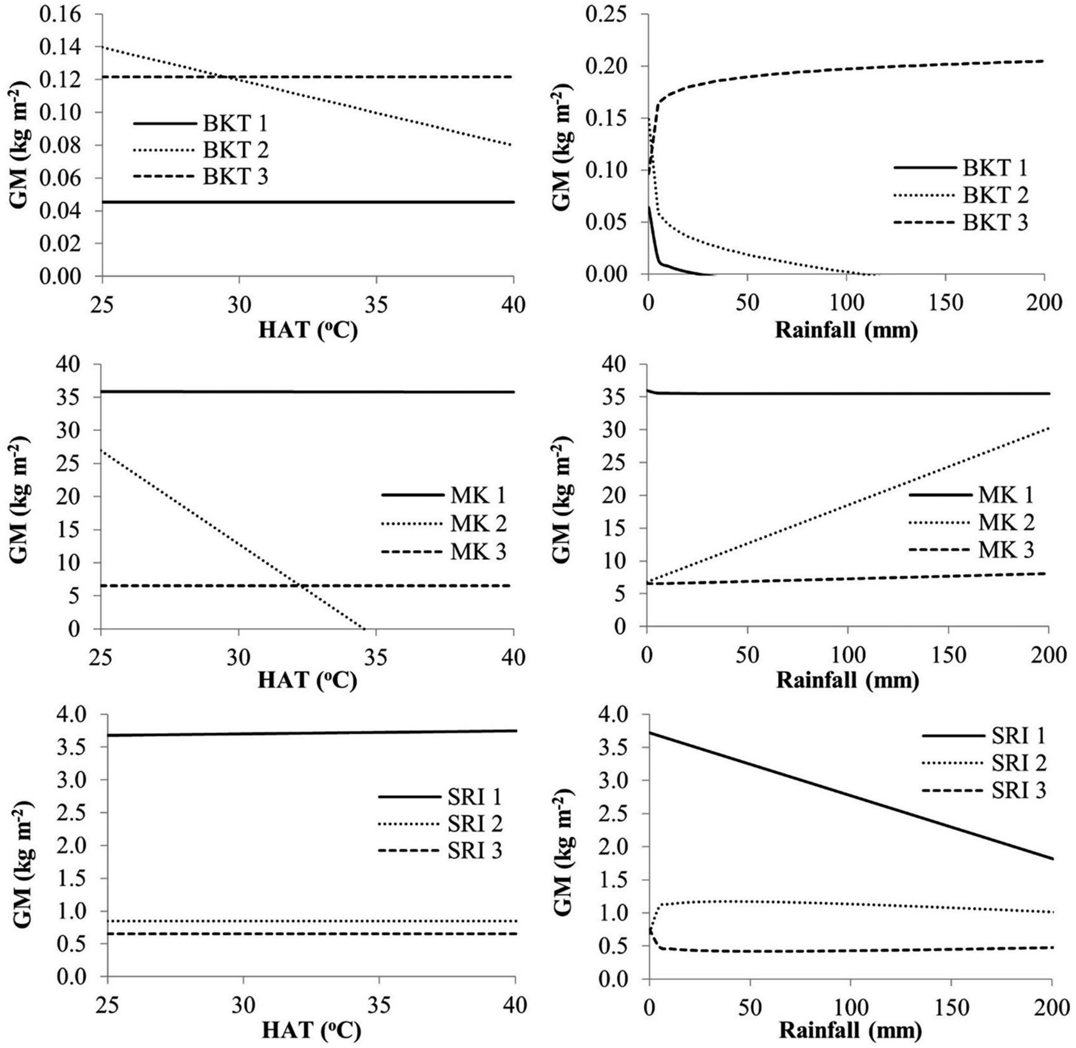

Fig. 7. – Simulations of green mussel production (GM) based on variations of the average of the highest air temperature (HAT) and rainfall in the pond area of Bang Khun Tien (BKT), the estuary area of the Maeklong river mouth (MK) and the coastal area of Sriracha (SRI).

cessive nutrients in an estuary through river runoff. These nutrients were effectively absorbed by phytoplankton (Meng et al. 2017, Xu et al. 2019). Then, this phytoplankton was filtered by green mussels as their dominant dietary source (Irisarri et al. 2014). Finally, enhanced green mussel production was observed.

For a coastal area, green mussel production was not affected by heavy rainfall, except at SRI 1 (Fig. 7). The regression analysis indicated that the pH of seawater was the most important parameter affecting mussel production. However, it did not change (much) with variations in rainfall. Therefore, almost consistent mussel production was found. The simulation results demonstrated that the mussel production dramatically decreased with intense rainfall at the farm that was closest to the river mouth (SRI 1), where higher fluctuations in seawater salinity were observed than at the other stations. A magnitude decrease in salinity causes physiological changes in green mussels, such as decreased clearance rates, closed valves (McFarland et al. 2013), and reduced immune responses (Wang et al. 2012). Finally, fewer mussels can be found due to high mortality (Firth et al. 2011).

The results of field observation demonstrated that the estuary area (MK) had significantly the highest green mussel production (Table 2). However, simulation results showed that during climate disturbance, coastal areas (SRI) are suitable for green mussel culture owing to low fluctuations in temperature and salinity. Variation of these parameters can significantly reduce mussel production and often occurs in the area which is close to the river mouth (Sasikumar and Krishnakumar 2011, White and Toumi 2014). Therefore, the location far from shore is less impacted by climate change than locations near the river mouth.

Although some simulations showed that variations in air temperature or rainfall do not affect green mussel production, there are threshold limits. To estimate atmospheric parameters that cause the death of green mussels, the threshold levels of seawater quality (Table 4) were employed in the model equations (Table S1), which were developed from the correlations between

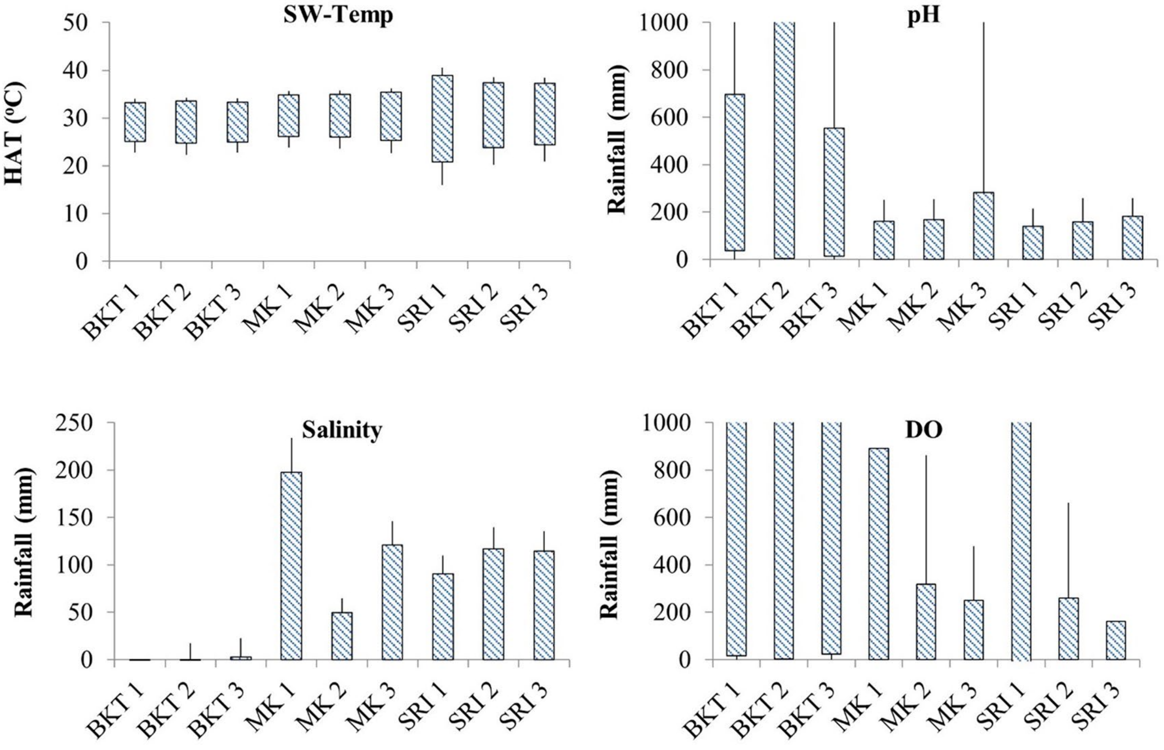

Fig. 8. – Bar charts representing (from top to bottom), the maximum lethal level, upper survival level, lower survival level and minimum lethal level of atmospheric parameters (average of the highest temperature (HAT) and rainfall) that were estimated from seawater temperature (SW-Temp), pH, salinity, and dissolved oxygen (DO) in the pond area of Bang Khun Tien (BKT), the estuary area of the Maeklong river mouth (MK) and the coastal area of Sriracha (SRI).

atmospheric parameters and seawater quality (Figs 2-5). When the air temperature and rainfall reached the threshold levels of seawater quality, high mortalities of green mussels were observed (Fig. 8). When these atmospheric parameters were beyond the maximum and minimum lethal levels, large green mussel mortality was observed. According to Figure 8, the mussels can die-off when the air temperature reaches 34.01°C, 35.64°C and 38.39°C for cultivation in the pond, estuary and coastal areas, respectively. Intense rainfall higher than 204.48, 200.24, and 283.18 mm per month can deteriorate the mussel production in the pond, estuary and coastal areas, respectively. These results can assist green mussel farmers to adapt their operation when weather disturbances occur. The results of the study can guide farmers to select a proper location for mussel cultivation under extreme climate events. During climate disturbance, the coastal zone is the most suitable for mussel cultivation because the lethal levels of air temperature and rainfall are higher than in estuary and pond areas (Fig. 8). In addition, these lethal levels also can be used as warning levels. When air temperature and rainfall reach these levels, green mussels should be harvested to avoid mass mortality. Finally, the farm operators can use our results to plan their cultivation period with less impact of climate variation on green mussel production. For instance, to reach a higher production of mussels under climate change, the cultivation should not start when the air temperature is above the lethal levels (Fig. 8). The findings of our study can provide scientific information to enhance the efficiency of the farm and can be used as a climate change adaptation tool for shellfish farmers. Our suggestion for further study is to increase the number of replications together with controlled cultivation methods, such as mussel density, location, depth, distance from shore, cultivation rope, etc., in order to increase the accuracy of the model. In addition, more yearly data or several cultures could enhance the reliability of the model.

CONCLUSIONS

It can be concluded that climate change affects green mussel productivity differently according to the cultivation area. Atmospheric parameters affect seawater quality in pond, estuary and coastal areas in different kinetics. A high air temperature significantly increased the seawater temperature. Intense rainfall results in a decrease in salinity and an increase in pH except at MK 3, where the pH of water can be lowered by a high quantity of river runoff. Increased DO was found during heavy rainfall. However, it decreased with excessive suspended sediments and dissolved organic matter caused by water discharges. Rainfall caused variations in nutrient concentrations that were diluted under unpolluted conditions and concentrated by the dispersion of domestic waste and soil erosion. Additionally, results also indicated that the most influential seawater parameters on green mussel production in pond, estuary and coastal areas were different. This can be explained by the results of PCA and the multiple linear regression analysis. Nutrients and DO significantly affected the mussels cul-

Table 4. – Limits of seawater parameters that cause death and threaten the survival of green mussels (Firth et al. 2011, Goh and Lai 2014, Sivalingam 1977, Wendling et al. 2013).

Seawater parameter	Maximum lethal level*	Upper survival level	Lower survival level	Minimum lethal level*
Temperature (°C)	38.00	36.00	14.00	8.00
pH	9.00	8.65	7.54	3.50
Salinity	80.00	65.00	25.00	24.00
DO (mg L^{-1})	-	8.00	4.00	0.50

Note: *Lethal level is the level of seawater parameters that causes 50% to 100% die-off of green mussels.

tured in a pond. In an estuary, temperature and salinity were influential factors due to freshwater input caused by river runoff. Nutrient and pH levels were found to be more important in coastal waters. Finally, the cultivation areas most sensitive to droughts and heavy storms were ponds, followed by estuary and coastal areas. Drought conditions with high air temperature and negligible rainfall strongly affected the mussel production in the pond. Tropical storms cause intense rainfall that significantly affects mussel production close to the river mouth. This study suggests that cultivating in a coastal area or a large distance from the river mouth can effectively produce green mussels under extreme weather events caused by climate change.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available through the online version of this article and at the following link: http://scimar.icm.csic.es/scimar/supplm/sm05232esm.pdf

Table S1. – Simple linear regression and logarithm model equations and coefficient of determination (R2) show correlations between atmospheric parameters and seawater parameters in each sampling station at Bangkhuntein (BKT), the Maeklong river mouth (MK) and Sriracha (SRI).

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Table S4. – Spatial and temporal variation of green mussel production and seawater parameters in the mussel cultivation areas at Sriracha (SRI) by using one-way ANOVA and Turkey-HSD.

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Influence of climate on seawater quality and green mussel cultivation

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Table S1. – Simple linear regression and logarithm model equations and coefficient of determination (R^2) show correlations between atmospheric parameters and seawater parameters in each sampling station at Bangkhuntein (BKT), the Maeklong river mouth (MK) and Sriracha (SRI).

Equation	R^2	Equation	R^2
$T_{BKT1} = 2.6753(AHT) - 52.986$	$R^2 = 0.7074$	$A_{BKT1} = -101.40\ln(R) + 637.28$	$R^2 = 0.9090$
$T_{BKT2} = 2.4945(AHT) - 47.59$	$R^2 = 0.7454$	$A_{BKT2} = -69.46\ln(R) + 478.61$	$R^2 = 0.8717$
$T_{BKT3} = 2.634(AHT) - 51.855$	$R^2 = 0.7494$	$A_{BKT3} = -75.00\ln(R) + 508.88$	$R^2 = 0.8829$
$T_{MK1} = 2.5276(AHT) - 52.091$	$R^2 = 0.7621$	$A_{MK1} = -52.42\ln(R) + 272.73$	$R^2 = 0.8908$
$T_{MK2} = 2.4532(AHT) - 49.874$	$R^2 = 0.8169$	$A_{MK2} = -43.53\ln(R) + 242.78$	$R^2 = 0.8336$
$T_{MK3} = 2.1928(AHT) - 41.565$	$R^2 = 0.7790$	$A_{MK3} = -44.47\ln(R) + 242.92$	$R^2 = 0.8814$
$T_{SRI1} = 1.2173(AHT) - 11.377$	$R^2 = 0.8820$	$A_{SRI1} = -29.76\ln(R) + 171.12$	$R^2 = 0.7063$
$T_{SRI2} = 1.6318(AHT) - 24.948$	$R^2 = 0.9107$	$A_{SRI2} = -27.61\ln(R) + 156.72$	$R^2 = 0.7975$
$T_{SRI3} = 1.7192(AHT) - 27.999$	$R^2 = 0.8137$	$A_{SRI3} = -32.21\ln(R) + 174.79$	$R^2 = 0.7133$
$pH_{BKT1} = 0.3787\ln(R) + 6.1702$	$R^2 = 0.8532$	$N_{BKT1} = -8.232\ln(R) + 79.446$	$R^2 = 0.7588$
$pH_{BKT2} = 0.1556\ln(R) + 7.3110$	$R^2 = 0.7038$	$N_{BKT2} = -2.982\ln(R) + 53.669$	$R^2 = 0.1225$
$pH_{BKT3} = 0.3040\ln(R) + 6.7289$	$R^2 = 0.7649$	$N_{BKT3} = -20.84\ln(R) + 158.95$	$R^2 = 0.8296$
$pH_{MK1} = 0.0038(R) + 8.0392$	$R^2 = 0.8430$	$N_{MK1} = 0.2253(R) + 9.136$	$R^2 = 0.6540$
$pH_{MK2} = 0.0041(R) + 7.9575$	$R^2 = 0.8761$	$N_{MK2} = 0.2648(R) + 24.129$	$R^2 = 0.7654$
$pH_{MK3} = -0.0028(R) + 8.331$	$R^2 = 0.8208$	$N_{MK3} = 0.1947(R) + 10.276$	$R^2 = 0.6859$
$pH_{SRI1} = 0.0047(R) + 7.9888$	$R^2 = 0.6688$	$N_{SRI1} = -1.501\ln(R) + 9.8385$	$R^2 = 0.7181$
$pH_{SRI2} = 0.0035(R) + 8.0932$	$R^2 = 0.6700$	$N_{SRI2} = -0.552\ln(R) + 5.6547$	$R^2 = 0.7882$
$pH_{SRI3} = 0.0046(R) + 7.8071$	$R^2 = 0.7854$	$N_{SRI3} = -2.325\ln(R) + 12.577$	$R^2 = 0.6390$
$S_{BKT1} = -0.0411(R) + 23.605$	$R^2 = 0.6379$	$P_{BKT1} = -31.99\ln(R) + 200.02$	$R^2 = 0.8777$
$S_{BKT2} = -0.0439(R) + 24.778$	$R^2 = 0.6474$	$P_{BKT2} = -38.33\ln(R) + 243.27$	$R^2 = 0.7533$
$S_{BKT3} = -0.0496(R) + 25.142$	$R^2 = 0.6118$	$P_{BKT3} = -21.57\ln(R) + 158.26$	$R^2 = 0.9434$
$S_{MK1} = -0.0274(R) + 30.415$	$R^2 = 0.6852$	$P_{MK1} = -3.345\ln(R) + 19.965$	$R^2 = 0.6171$
$S_{MK2} = -0.0665(R) + 28.316$	$R^2 = 0.7873$	$P_{MK2} = -9.063\ln(R) + 49.76$	$R^2 = 0.7841$
$S_{MK3} = -0.0402(R) + 29.865$	$R^2 = 0.7032$	$P_{MK3} = -1.312\ln(R) + 12.297$	$R^2 = 0.6364$

Equation	R^2	Equation	R^2
$S_{SRI1} = -0.0519(R) + 29.697$	$R^2 = 0.8428$	$P_{SRI1} = -1.625\ln(R) + 11.086$	$R^2 = 0.7575$
$S_{SRI2} = -0.044(R) + 30.138$	$R^2 = 0.7345$	$P_{SRI2} = -2.059\ln(R) + 11.414$	$R^2 = 0.8379$
$S_{SRI3} = -0.0481(R) + 30.517$	$R^2 = 0.8055$	$P_{SRI3} = -1.967\ln(R) + 12.541$	$R^2 = 0.7388$
$D_{BKT1} = 0.2497\ln(R) + 3.2924$	$R^2 = 0.5765$	$Si_{BKT1} = 2.8139(R) + 318.30$	$R^2 = 0.7107$
$D_{BKT2} = 0.4723\ln(R) + 3.4519$	$R^2 = 0.6880$	$Si_{BKT2} = 5.9321(R) + 463.79$	$R^2 = 0.7265$
$D_{BKT3} = 0.5528\ln(R) + 2.2477$	$R^2 = 0.8659$	$Si_{BKT3} = 12.407(R) + 626.85$	$R^2 = 0.7802$
$D_{MK1} = 0.0025(R) + 5.7695$	$R^2 = 0.0608$	$Si_{MK1} = 2.438(R) + 54.633$	$R^2 = 0.7759$
$D_{MK2} = -0.0064(R) + 6.0290$	$R^2 = 0.7557$	$Si_{MK2} = 2.297(R) + 369.44$	$R^2 = 0.8922$
$D_{MK3} = -0.0153(R) + 7.8423$	$R^2 = 0.9633$	$Si_{MK3} = 3.4005(R) + 168.67$	$R^2 = 0.7645$
$D_{SRI1} = -0.0014(R) + 5.7808$	$R^2 = 0.0146$	$Si_{SRI1} = -125.6\ln(R) + 951.33$	$R^2 = 0.7260$
$D_{SRI2} = -0.0087(R) + 6.2643$	$R^2 = 0.6362$	$Si_{SRI2} = -145.2\ln(R) + 1145.6$	$R^2 = 0.7047$
$D_{SRI3} = 0.0139(R) + 5.7621$	$R^2 = 0.7842$	$Si_{SRI3} = -140.1\ln(R) + 1155.2$	$R^2 = 0.8350$

Note: R is rainfall (mm); AHT is average the highest air temperature (°C); T is seawater temperature (°C); pH = pH level of seawater; S is salinity (psu); D is dissolved oxygen (DO) (mg L^{-1}); A is ammonium-nitrogen (NH_4^+-N) (µg L^{-1}); N is nitrite and nitrate-nitrogen (NO_2^- +NO_3^--N) (µg L^{-1}); P is phosphate-phosphorus (PO_4^{3-}-P) (µg L^{-1}); Si is silicate-silicon ($Si(OH)_4$-Si) (µg L^{-1})

Table S2. – Spatial and temporal variation of green mussel production and seawater parameters in the mussel cultivation areas at Bangkhuntein (BKT) by using one-way ANOVA and Turkey-HSD.

			Turkey-HSD														
	One-way ANOVA		Spatial Analysis			Temporal Analysis-BKT											
Parameter	Station	Month	BKT 1	BKT 2	BKT3	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GM (kg m^{-2})	***	ns	a	a	b	-	-	-	-	-	-	-	-	-	-	-	-
Temp (°C)	ns	***	-	-	-	c	e,f	d,e	g	e,f,g	b	g	d	f,g	d,e	c	a
pH	*	*	a	b	a,b	a,b	a	a,b	a,b	a,b	a,b	a,b	b	b	a,b	a,b	a,b
Sal (psu)	ns	***	-	-	-	c,d	c,d	b	a,b	a,b	a,b	a,b	a,b,c	a,b	a,b	b,c	d
Conduct (ms)	ns	***	-	-	-	a,b	b,c	b,c	b,c	a	c,d	a,b	a,b,c	a,b	a	a,b	c,d
DO (mg L^{-1})	ns	**	-	-	-	a	a,b	a,b	a,b,c	a,b,c	a,b,c	a,b,c	a,b,c	a,b,c	a,b	a,b,c	c
Trans (cm)	***	ns	a	b	c	-	-	-	-	-	-	-	-	-	-	-	-
TSS (mg L^{-1})	***	ns	a	a	b	-	-	-	-	-	-	-	-	-	-	-	-
NH_4^+-N (mg L^{-1})	ns	***	-	-	-	c	b	b	b	a	a	a	a	a	a	a	a
NO_2^-+NO_3^--N (mg L^{-1})	*	ns	a,b	a	b	-	-	-	-	-	-	-	-	-	-	-	-
PO_4^{3-}-P (mg L^{-1})	ns	***	-	-	-	c	a,b,c	b,c	a,b,c	a,b	a	a	a	a	a	a	a
$Si(OH)_4$-Si (mg L^{-1})	ns	*	-	-	-	a,b	a	a,b	a,b	b	a,b	a,b	a,b	a,b	a,b	a,b	a
Chl *a* (mg L^{-1})	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: Significance level of one-way ANOVA: *** = P < 0.001; ** = P < 0.01; * = P < 0.05; ns = not significant

Table S3. – Spatial and temporal variation of green mussel production and seawater parameters in the mussel cultivation areas at the Meaklong River Mouth (MK) by using one-way ANOVA and Turkey-HSD.

			Turkey-HSD														
	One-way ANOVA		Spatial Analysis			Temporal Analysis-MK											
Parameter	Station	Month	MK 1	MK 2	MK 3	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GM (kg m^{-2})	***	ns	b	b	a	-	-	-	-	-	-	-	-	-	-	-	-
Temp (°C)	ns	***	-	-	-	f	b	b,e	g	e	d,e	c,d,e	b,c,d	b,c,d	d,e	b,c	a
pH	ns	**	-	-	-	a,b	a	a,b	a,b	a	a,b	a,b	a,b	a,b	b	a,b	a,b
Sal (psu)	ns	**	-	-	-	b,c	b,c	a,b,c	a,b	a,b	a,b,c	b,c	a,b,c	a,b	a	a,b,c	c
Conduct (ms)	*	ns	b	a	a,b	-	-	-	-	-	-	-	-	-	-	-	-
DO (mg L^{-1})	ns	**	-	-	-	a,b	a,b,c	a,b,c	b,c	a,b,c	b,c	a,b,c	a,b,c	a,b,c	a,b,c	a	c
Trans (cm)	**	ns	b	a	a	-	-	-	-	-	-	-	-	-	-	-	-
TSS (mg L^{-1})	ns	*	-	-	-	a	a,b	a,b	a,b	a,b	a,b	b	a,b	a,b	a,b	a,b	a,b
NH_4^+-N (mg L^{-1})	ns	***	-	-	-	f	e,f	e	d	b,c,d	a,b,c	a,b	a,b	a,b	a	a,b,c	c,d
NO_2^-+NO_3^--N (mg L^{-1})	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PO_4^{3-}-P (mg L^{-1})	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$Si(OH)_4$-Si (mg L^{-1})	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chl *a* (mg L^{-1})	**	ns	a	a,b	b	a	a,b	a,b	a,b	a,b	b	a,b	a,b	a,b	a,b	a,b	a,b

Note: Significance level of one-way ANOVA: *** = P < 0.001; ** = P < 0.01; * = P < 0.05; ns = not significant

Table S4. – Spatial and temporal variation of green mussel production and seawater parameters in the mussel cultivation areas at Sriracha (SRI) by using one-way ANOVA and Turkey-HSD.

			Turkey-HSD														
	One-way ANOVA		Spatial Analysis			Temporal Analysis											
Parameter	Station	Month	SRI 1	SRI 2	SRI 3	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GM (kg m^{-2})	**	ns	a	a	b	-	-	-	-	-	-	-	-	-	-	-	-
Temp (°C)	ns	***	-	-	-	b,c,d,e	d	c	f	f	e	b,c,d,e	e	b	b,c,d	b,c	a
pH	ns	*	-	-	-	a	a,b	a	a	a,b	a,b	a,b	a,b	b	a,b	a,b	a,b
Sal (psu)	ns	***	-	-	-	c,d	d	c,d	c,d	b	b,c,d	b,c	b,c,d	a	d	c,d	c,d
Conduct (ms)	ns	***	-	-	-	b,c	b,c	c	b,c	b,c	b,c	b,c	a,b	a	c	b,c	c,d
DO (mg L^{-1})	ns	***	-	-	-	a,b,c	a,b,c	a,b,c	a,b,c	a,b	b,c,d	a	a,b,c	d	a	a,b,c	c,d
Trans (cm)	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TSS (mg L^{-1})	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NH_4^+-N (µg L^{-1})	ns	***	-	-	-	b	b	c	b,c	a	a	a	a	a	a	a	a
NO_2^-+NO_3^--N (µg L^{-1})	ns	ns	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PO_4^{3-}-P (µg L^{-1})	ns	***	-	-	-	c,d	b,c,d	a	b,c,d	d	a	a	a	a,b,c	a,b	a	a
$Si(OH)_4$-Si (µg L^{-1})	ns	***	-	-	-	b	b	b	b	a	a	a	a	a	a	a	a
Chl *a* (µg L^{-1})	ns	***	-	-	-	a	a,b	a,b	a,b	a,b	a,b	a,b	b,c	c	a,b	a	a

Note: Significance level of one-way ANOVA: *** = P < 0.001; ** = P < 0.01; * = P < 0.05; ns = not significant