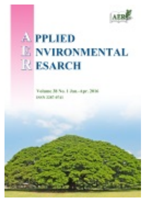
App. Envi. Res. 43(2) (2021): 77-92

Applied Environmental Research

Journal homepage : http://www.tci-thaijo.org/index.php/aer



Consequence of Seawater Intrusion on Soil Properties in Agricultural Areas of Nonthaburi Province, Thailand

Napaporn Phankamolsil[1], Kiattisak Sonsri[1], Yutthana Phankamolsil[2,*]

[1] Department of Soil Science, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom 73140, Thailand

[2] Environmental Engineering and Disaster Management Program, Mahidol University, Kanchanaburi Campus, Saiyok, Kanchanaburi 71150, Thailand

[*] Corresponding author: yutthana.pha@mahidol.ac.th

Article History

Submitted: 23 June 2020/ Revision received: 27 September 2020/ Accepted: 8 December 2020/ Published online: 27 April 2021

Abstract

Seawater intrusion associated with climate change and sea level rise (SLR) has been postulated for the last decade that causes negative impact on worldwide environmental resources. In Thailand, however; the information pertaining to its effect on soil properties in agricultural areas has not been clearly reported yet. Hence, this study aimed to investigate the seawater intrusion effect on soil properties in agricultural areas of Nonthaburi Province, Thailand. Five study locations, which anticipated to be affected by seawater intrusion, were selected based on the different distances from the Chao Phraya River. Soil morphological properties were recorded, besides undisturbed soil samples at depth of 0–15 and 15–30 cm as well as disturbed soil samples at depth of 0–15, 15–30, 30–60, 60–90 and 90–120 cm were collected to determine the soil physical and chemical properties. Additionally, the soil electrical conductivity (EC_e) and sodium adsorption ratio (SAR) analyses demonstrating soil salinity and sodicity were monthly conducted from March 2018 to February 2019 and their annual average values were calculated. The results revealed that all soils were deep to very deep, consisted of silty clay, clay textures, and its field soil pH varied from 6.0–8.0. Soil saturated hydraulic conductivity rating exhibited that it was very slow to moderate. EC_e and SAR values of these soils ranged from 0.21–4.38 dS m^{-1} and 8.29–41.89 consecutively, which trended to increase from its annual average during March and April 2019 as well as July and August 2019. These results suggested that seawater intrusion could be presumptively regarded as a co-factor affecting the variability of soil salinity and sodicity occurring at the interval of insufficient freshwater content for forcing seawater. The implementation strategies for freshwater management and planning are required to prevent future potential seawater intrusion.

Keywords: Sea level rise; Seawater intrusion; Salinity; Sodicity; Soil permeability; Land uses

https://doi.org/10.35762/AER.2021.43.2.6

Introduction

Climate change has been presently concerning as one of the vastly pivotal matters confronting the world due to its large-scale hazard influencing the remarkably powerful impact on various affairs, particularly in weather pattern fluctuations, utmost weather, human health hazards, wildlife and also ecosystem impacts. A number of previous literatures have been notably revealed that human activities; for instance, the fossil fuels burning and the forests clearing led to the releasing of the massive quantities of greenhouse gases (GHGs) into the Earth's atmosphere affecting to the climate change that prevalent provenances on different timescales from decades to many millions of years [1–2]. In addition, it can be obviously seen that carbon dioxide (CO_2) and other GHGs are able to officially act as the positive radiative causing the earth energy budget has significantly increased, resulting in the rising global surface temperature [3]. Harvard Business School [2] has also disclosed that the Earth's average surface temperature has evidently been accelerated to raise since the Industrial Revolution; especially, during the period between 1880 and 2015, the average global surface temperatures escalated to 0.9°C. Furthermore, the future global average surface warming alterative projections have been performed by the Intergovernmental Panel on Climate Change (IPCC), which unveiled that global average surface temperatures would be between 2.5 and 4.7°C higher by 2100 compared to pre-industrial levels [4].

Evidently, SLR is compellingly considered as the climate change impact because its causable processes comprising thermal expansion, supplying water to the oceans through melting glaciers, ice caps, and polar ice sheets, changing in ocean, atmospheric circulations, natural and human-induced, and changing in groundwater levels are also logically associated with the climate change occurrence [2, 4–6]. According to precedent publication since approximately 1870, sea level rates have distinctly been accelerated [2]. During the 20th century, based on tidal gauges, the average rate was 1.7 mm a^{-1} and then has precipitately increased to 3.2 mm a^{-1} [7–10]. As a result of SLR, intervening variables in the hydrological cycle impacting the amount of on land stored water [11] either the water surface in lakes, rivers, artificial reservoirs, marshes or subsurface water such as groundwater, liquid water trapped in soils, and permafrost have been affected [5].

Seawater intrusion, the encroachment of saline water into freshwater regimes, is one of the most imperative environmental problems caused by both natural and anthropogenic processes, particularly the influence of SLR associated with climate change. From that reason, it can be delineated as the seawater level rising results in the increase of saline water heads at the ocean boundary, which is the logical consequence of enhanced seawater intrusion [12]. The detrimental seawater intrusion impacts are mainly the reduction in available freshwater storage volume, contamination of production wells, degradation of groundwater quality [13–14]. Moreover, the contaminated seawater source usage containing high amount of salt concentration for irrigation can negatively affect to the crop productivity reduction and alter the soil physicochemical properties leading to soil deterioration [15].

The accumulation of soluble salts in the surface or near-surface soil horizon is widely postulated as the crucial soil contaminant problem confronted in both developed and developing countries which well-known as salt affected soils [16–17]. This problematic soil is one of the most violent environmental factors imposing worldwide restrictions on plant growth, crop cultivation, crop productivity, and food quality because the crop plants are generally sensitive to salinity caused by high concentration of soluble salts in soil [16, 18–20]. Additionally, it was reported that the average yields of all important crops decreased down to between

20% and 50% in some areas because of drought and high soil salinity, environmental conditions which will exacerbate in many regions affected by global climate change [20]. The salt affected soils formation areas cover worldwide almost 1 billion ha representing about 7% the earth's continental extent. In addition, these soils are usually widespread in arid or semi-arid zones where the precipitation supply is inadequate to leach and remove the salts in conjunction with high evaporation that can also increase the concentration of salts in soils [20–21]. In Thailand, the total extent areas faced by salt affected soils are approximately 2.302 million ha which can be divided into three major locations comprising of the northeast plateau basin, the coastal area, and the central plain where each location is regulated by different environmental conditions [22].

Recently, the other causation of salt affected soils has been regarded to accelerate by the seawater intrusion in accordance with the rising in sea level [15, 23], in particular when seawater has transited into the soil and freshwater systems causing secondary salinity. Conforming to the present situation, seawater from the Gulf of Thailand especially during spring tides, has transported and intruded to the Chao Phraya River, which is the imperative water resources of Thailand. Furthermore, in order to prevent this problem, an appropriate technique has been suggested that freshwater should be used to force the seawater back to the Gulf of Thailand [24]. Nonetheless, the available freshwater content was inadequate to extrude the seawater flow because the drought phenomenon had occurred in Thailand since 2015 until the summer in 2016. Hence, the electrical conductivity (EC_w) of this river has occasionally increased, impacting on the agricultural areas located either adjacent to the river or direct water usage from the river. In Nonthaburi province, located directly nearby the Chao Phraya River, agricultural areas are likely to be one of the areas faced by seawater intrusion causing such negative impacts on the growth and yield of economic crops. Therefore, the contribution of this study, we intended to examine the influence of seawater intrusion on soil properties in agricultural areas in Nonthaburi Province, Thailand. To accomplish this objective, soil morphological characteristics, soil physical and chemical properties were elucidated. Moreover, the EC_e and SAR analyses indicating the variability of soil salinity and sodicity, were monthly carried out respectively during the study period.

Materials and methods

1) The study location

The agricultural areas in Nonthaburi Province, UTM coordinates from 1530605 to 1532747 N and 47 0647406 to 0659292 E, were selected as the investigated locations for this study (Figure 1). This province, the approximately total areas 622.3 km^2, is one of the central region provinces of Thailand that located directly in northwest of Bangkok on the Chao Phraya River. Pertaining to agricultural practices, land use characteristics of these study sites are mostly tropical fruit orchard and paddy field. In terms of geological setting, these study sites are characterized by the lower central plain, of which flat, low-lying area surrounded by mountains in the west, north, and east. In the southern part, it is also connected to the shoreline of the Gulf of Thailand which the sedimentary basin contains the thick sequence of Quaternary sediments [25]. The study site elevation is approximately 2 m above mean sea level. For these study locations, their climatic conditions are characterized as tropical savanna, Aw (Köppen climate classification), which has an annual temperature of 27 to 30°C. The rainy season extends from mid-May to mid-October with an average annual precipitation of 903 mm for the central region [26].

Figure 1 The study sites in agricultural areas of Nonthaburi Province, Thailand.
Remarks: Satellite images were obtained from Google Earth [27].

2) Soil collection and characterization

Soil samples were obtained from five selected locations based on the different distances from Chao Phraya River. Each soil from study locations was generally classified as Inceptisols according to the USDA soil taxonomy [28] and soil profiles to a depth of 120 cm were scrupulously described by the genetic horizons according to the standard field methods [29–30]. For undisturbed soil samples, undisturbed soil cores were collected at depth of 0–15 and 15–30 cm to analyze the soil saturated hydraulic conductivity. In terms of disturbed soil samples, all soil samples at depths of 0–15, 15–30, 30–60, 60–90 and 90–120 cm were extracted by using the hand auger in order to analyze the soil particle size distribution, soil properties related with soil salinity and sodicity, namely EC_e, and SAR, respectively. Likewise, these soil samples had been collected from March 2018 to February 2019 to determine EC_e and SAR.

3) The soil preparation and analysis

Prior to the analysis of soil particle size distribution, EC_e, and SAR, the samples were air-dried, eliminated the plant debris, gently pulverized, and sieved through 2 mm. Soil saturated hydraulic conductivity was determined by using falling-head method [31]. The pipette method was performed to examine the soil particle size distribution [32]. Then, soil texture was classified using soil textural triangle classes [33]. The EC_e in saturation paste extracts was measured according to the method described by the United States Department of Agriculture (USDA) using conductivity meter [34]. The SAR was evaluated from the saturation extract cations Na^+, Ca^{2+} and Mg^{2+} measuring by atomic absorption spectrophotometry and subsequently calculated as the following to U.S. Salinity Laboratory Staff [34] as shown in Eq. 1:

$$\text{SAR} = \frac{[Na^+]}{\sqrt{[Ca^{++}]+[Mg^{++}/2}} \qquad \text{(Eq. 1)}$$

Where Na^+, Ca^{++} and Mg^{++} are expressed in meq L^{-1}. To illustrate the variability of soil salinity and sodicity, both EC_e and SAR values were calculated every single month as the annual mean at each study location. Subsequently, the differences in EC_e and SAR values between the annual mean and each month were compared.

Results and discussion

1) Environmental conditions and soil morphological characteristics

The relief of whole study locations was flat, possessing the slope from less than 1 % (N4 and N 5) to 1% (N1–N3). There was the elevation gradient approximately 2 m above mean sea level. These originated from marine sediments mixed with riverine alluvium and developed under landform of young delta plain with former tidal flats [35–36]. In terms of land use types, these soils were mainly used to cultivate the tropical fruit orchard comprising mango (N1), durian, lime tree and banana (N2), durian, Marian plum and banana (N3), and paddy field (N4 and N5). From the sea distances, N1-N5 was approximately 39.8, 39.7, 38.2, 40.8, 40.9 km, respectively, and approximately 0.5, 0.8, 6.5, 11.1, 12.33 km, respectively from the Chao Phraya River.

Table 1 Soil morphological characteristics of agricultural soils in the study areas

Horizon	Depth (cm)	Color		Texture	Consistence (Wet)	Field pH
		Matrix	Mottle			
N1						
Ap	0–20	10YR 4/4		C	VS/VP	6.5
Bw1	20–40	10YR 4/3		C	VS/VP	6.0
Bw2	40–65	10YR 3/4		C	VS/VP	6.0
Bw3	65–80	10YR 4/4		C	VS/VP	6.5
Bg1	80–105	10YR 4/3, 10YR 5/2	7.5YR 5/8	C	VS/VP	7.0
Bg2	105–120+	10YR 5/3, N5/0	7.5YR 6/8	C	VS/VP	7.5
N2						
Ap	0–20	10YR 3/3		C	VS/VP	6.5
Bw1	20–50	10YR 4/4		C	VS/VP	6.5
Bw2	50–70	10YR 3/4		C	VS/VP	6.5
Bg1	70–100	10YR 4/3, 10YR 6/1	10YR 5/8	C	VS/VP	7.5
Bg2	100–120+	10YR 4/1	10YR 8/8	C	VS/VP	8.0
N3						
Ap	0–30	10YR 4/4		C	VS/VP	6.5
Bg1	30–50	10YR 4/3, 10YR 5/2		C	VS/VP	6.5
Bg2	50–70	10YR 5/2	10YR 5/4	C	VS/VP	7.0
Bg3	70–90	10YR 5/2	10YR 6/8	C	VS/VP	7.0
Bg4	90–120+	10YR 4/1	10YR 4/6	C	VS/VP	7.0
N4						
Apg	0–20	10YR 3/1	2.5YR 4/6	C	VS/VP	6.5
Bg1	20–35	10YR 5/1	10YR 6/8	C	VS/VP	7.0
Bg2	35–60	2.5Y 5/1, 2.5Y 4/1	7.5YR 6/8	C	VS/VP	7.0
Bg3	60–90	5Y 6/1	10YR 7/8	C	VS/VP	7.0
Bg4	90–120+	N6/0	7.5YR 6/8	C	VS/VP	7.0
N5						
Apg	0–25	10YR 5/1, 10YR 7/2	10YR 6/8	SiC	MS/MP	7.5
Bg1	25–45	10YR 6/1, 10YR 5/3	10 YR 5/8	SiC	MS/MP	7.0
Bg2	45–60	10YR 6/1	10YR 5/6	SiC	MS/MP	7.0
Bg3	60–90	10YR 5/1	10YR 6/6	SiC	MS/MP	7.0
Bg4	90–120+	10YR 5/1	10YR 4/6	SiC	MS/MP	7.0

Texture: C = clay; SiC = silty clay

Consistence: VS = very sticky; VP = very plastic; MS = moderately sticky; MP = moderately plastic

The morphological characteristics of agricultural soils in the study areas are shown in Table 1. The results indicated that these soils were deep to very deep, having topsoil thickness between 20 and 30 cm. These soil matrix colors were mainly mixed including brown, yellow and gray. Generally, the topsoil seemed to be darker than the subsoil indicating that the topsoil presumably contained higher amount of organic matter content than subsoil due to more input of plant residue materials in the topsoil compared to subsoil [37–38]. The thermal organic matter stability in the topsoil was mainly associated with the amount of organic matter, which represented the balance between factors influencing inputs, i.e., litter in-mixing, fine root density, and outputs, i.e., waterlogging [39].

In general, the low chroma value (≤ 2) and appearance mottling suggest that the soils have progressively poor drainage and profile development under water-saturated conditions which have induced reduction processes imposed over many years [40–41]. In this study, the soil used for the paddy field has been found low chroma value and mottling in the topsoil. In the meantime, those soils in the topsoil of any orchards were not observed (Table 1). For this study, it indicated the difference effects on land uses and its management practices on soil morphological features. Soil texture, according to field method, was silty clay and clay leading to poor drainage which affected the soil color and caused mottling. The wet condition consistence is usually divided into stickiness and plasticity [30]. This study showed that the main stickiness and plasticity of these soils were very sticky and plastic, respectively. Whereas, moderately sticky and plastic characteristics were shown in N5. Regarding to the field soil pH, it was found that field soil pH ranged from 6.0 to 8.0 from these study sites. The difference of field soil pH was probably affected by either erratic or complicated formation of soil parent materials, especially sediment or alluvium [42].

2) Selected soil physical properties

The depth functions of soil particle size distribution of agricultural soils in the study sites revealed that clay particle was the vastly main composition of soil particles (Figure 2). The amount of clay particle at depth of 0–15, 15–30, 30–60, 60–90, 90–120 cm was 472–604, 408–604, 446–618, 532–581, 456–601 g kg^{-1}, respectively. In addition, it could be clearly seen that sand, silt and clay particles showed erratic variations with the depth functions. It might be resulted by the erratic formation of depositional soil layers due to their soil parent materials, i.e. marine sediments mixed with riverine alluvium [42], which also reflected the presence of sedimentary layers deposited under a regime where transport conditions became more energetic over time [43]. Concerning to the soil texture, the distribution of sand, silt and clay particles was utilized to determine soil texture using soil textural triangle classes as shown in Figure 3. All soil samples from each study location were categorized as groups of fine-textured soils, namely, clay texture types in accordance with the physiographic positions and parent materials of soils [29, 38, 44].

In the study areas, the saturated hydraulic conductivity of agricultural soils is exhibited in Table 2. The results demonstrated that saturated hydraulic conductivity of these soils at depth of 0–15 and 15–30 cm ranged from $1.72 \times 10^{-4} – 3.37$ and $2.58 \times 10^{-4} – 3.72$ cm h^{-1}, respectively indicating that these soils had the saturated hydraulic conductivity rating between very slow and moderate [45]. This condition presumably originated from 2 main factors comprising (1) the obviously dominant content of clay and silt particles of these soils resulted in the small amount of macropores in these soils [46–47], (2) the influence of high sodium adsorption ratio caused the dispersion of soil particles, especially clay particle resulting in the decrease of macropores and water infiltration in these soils [48–49].

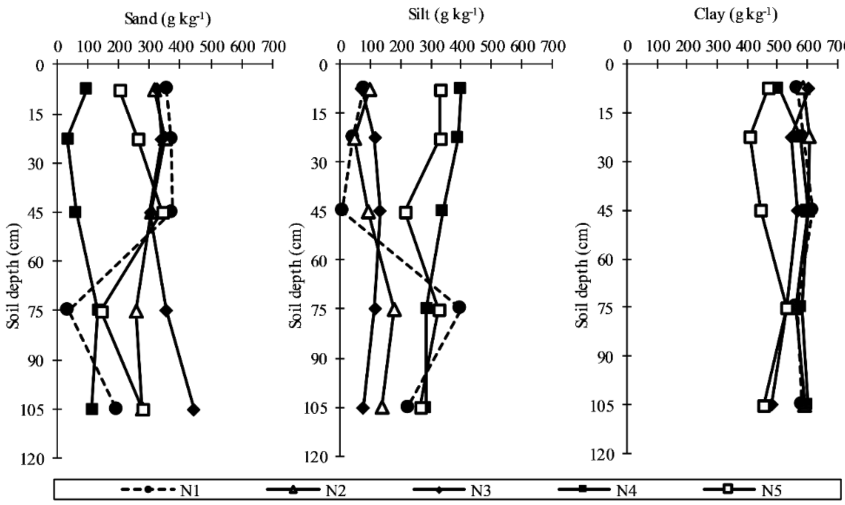


Figure 2 Distribution of sand, silt and clay particles of agricultural soils in the study areas.

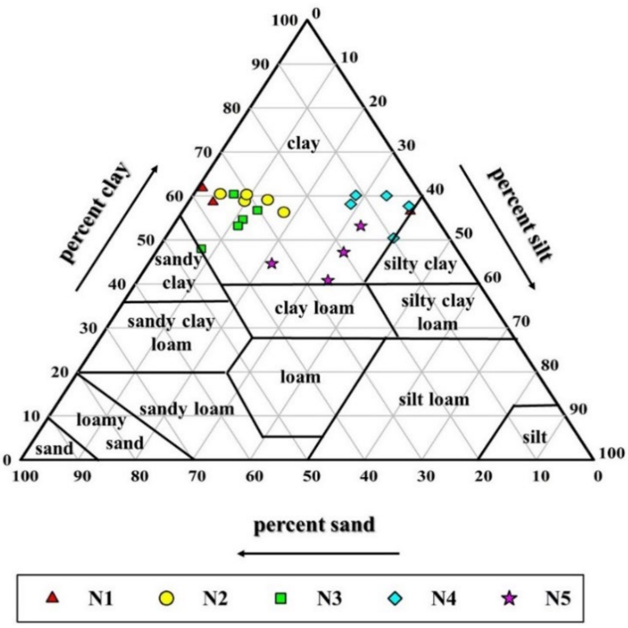


Figure 3 Soil textural triangle classes of agricultural soils in the study areas.

Table 2 Saturated hydraulic conductivity at depth of 0–15 and 15–30 cm for agricultural soils in the study areas

Locations	Depth (cm)	Ks (cm h^{-1})
N1	0–15	3.36608
	15–30	3.72205
N2	0–15	0.00017
	15–30	0.00026
N3	0–15	0.32949
	15–30	0.45847
N4	0–15	0.00103
	15–30	0.00034
N5	0–15	0.00503
	15–30	0.00103

3) Soil electrical conductivity (EC_e)

Basically, the EC_e is universally used as the standard parameter for soil salinity assessment [50]. Whenever soils possess the EC_e values up to 4 dS m^{-1} demonstrating that those soils are affected by salts based on the classification of salt affected soils defined by Brady and Weil [51] called saline soils. This study observed that the EC_e values of these agricultural soils ranged between 0.21 and 4.38 dS m^{-1}, and it generally exhibited very large considerable variation among study locations, soil depths, and soil collected time (Figure 4). In terms of study locations, the

EC_e values from N4 and N5 were more than 4 dS m^{-1} in some soil horizons during some periods of soil collection indicating that the soils were affected by salts or saline soils. Besides the other locations; for example, the EC_e values of N1 were more than 2 dS m^{-1} which sufficiently considered to negatively affect plant growth [41, 51]. Since the plant responses to soil salinity are complex phenomena that depend upon many factors [52], e.g. land uses. In the paddy field, (N4 and N5) tended to possess the EC_e values higher than the other locations cultivated with tropical fruit orchard; however, rice is more tolerant to salinity when compared to mango, citrus, and banana while durian is sensitive [53]. Hence, the risk assessment of salinity level is essential in order to consider the land uses which may be useful for future agricultural management planning. In addition, it can be noticed that the salt influence intensity was not correlated with the distances from the Chao Phraya River because the farthest location (N5) revealed the highest EC_e values compared to the other locations. Concerning to the distances of each location from the sea, the adjacency of their distances was also observed. This situation was presumably caused by water utilization managed by the agriculturists, which directly used the water from the Chao Phraya River through the branch canal trail intruded by seawater [54]. The seawater intrusion in agricultural areas affecting soil salinity was also observed in the case of Erfandi and Rachman [55] who found that most paddy fields in the North Coast of Java, Indramayu were potentially affected by seawater intrusion.

According to soil depth functions, the EC_e values of subsoil in most sites for this study generally seemed to be higher than topsoil. This observational result might be probably associated with groundwater system contained soluble salts [56] owing to the intrusion of seawater in agreement with Arslan and Demir [15] who reported that groundwater was significantly affected by seawater intrusion in Bafra Plain, Turkey. Another reason might be their soil parent materials which were marine sediments mixed with riverine alluvium. Those sediments are usually high concentration of exchangeable sodium and soluble salts e.g., $NaCl$, Na_2SO_4, $CaCl_2$, $CaSO_4$, $MgCl_2$ and $MgSO_4$; thus, it could be able to transport and accumulate in soil profile resulted in an increase of EC_e values [57–59]. Nonetheless, the topsoil of N5 appeared that there was higher than subsoil which was perhaps associated with the flowing water from the Chao Phraya River through the branch canal trail used by the cultivators while that water source was potentially influenced by the intrusion of seawater. In regard to the soil collection in different periods, the EC_e values of most study locations trended to increase from its annual average during March and April 2019, then gradually rose in July and August 2019. As those periods result, there were likely to experience the small amount or deficiency of precipitation [60]; hence, the occurrence of seawater intrusion phenomenon during those periods possibly resulted in the movement of soluble salts through surface water by draining from the Chao Phraya River for cultivation usage by the agriculturists induced salt accumulation in the soil profile. Furthermore, the small amount or deficiency precipitation interval, especially in dry season, soluble salts contained in groundwater and potentially intruded by seawater, seemingly accumulated in the upper soil profile by upward movement groundwater because of evaporation higher than precipitation [61–62]. However, the EC_e values of many study locations generally seemed to decrease between September and October 2019 owing to the precipitation for those periods that exhibited to increase.

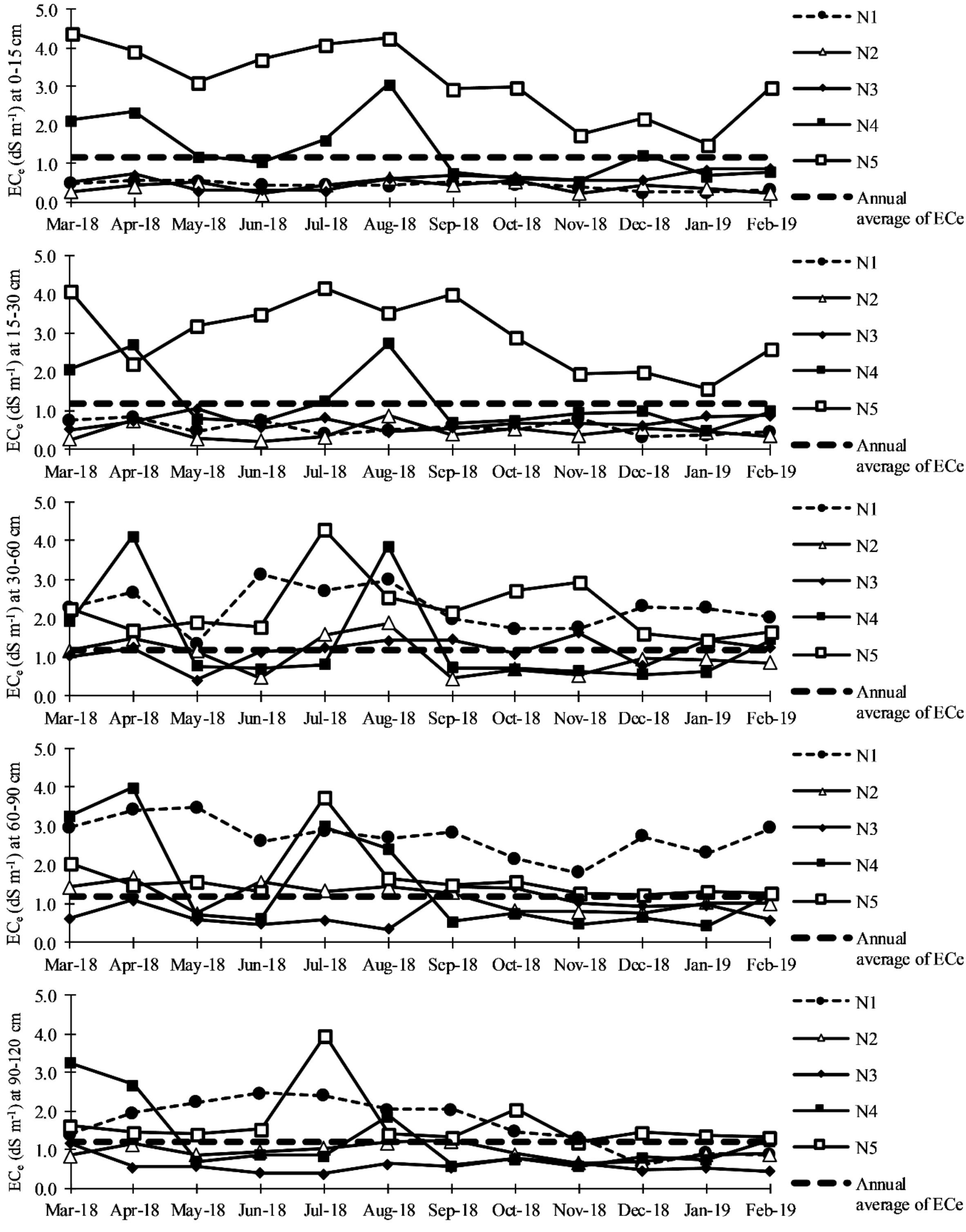


Figure 4 Depth functions exhibiting the variability of EC_e from March 2018 to February 2019.

4) Sodium adsorption ratio (SAR) of soils

This present study exposed that SAR values ranged between 8.29 and 41.89 (Figure 5). Moreover, it evidently demonstrated that some soil horizons during some periods of soil collection from most study sites possessed the SAR values more than 13 expressing that those soils were influenced by sodium. In particular, N1 where SAR values obtained in April 2019 were higher than other locations, namely 41.89. In theoretical, whenever soils have the SAR values up to 13 and EC_e values less than 4 dS m^{-1}

suggesting that those soils are salt affected soils containing sodium accumulation higher than that standard named sodic soils or soil sodicity. Consequently, it is able to influence on plant growth restriction when it is applied for cultivation. As stated in N4 and N5, the EC_e values were up to 4 dS m^{-1} and SAR values up to 13 in some soil horizons during some periods of soil collection indicated that those soils could be categorized as saline-sodic soils [51].

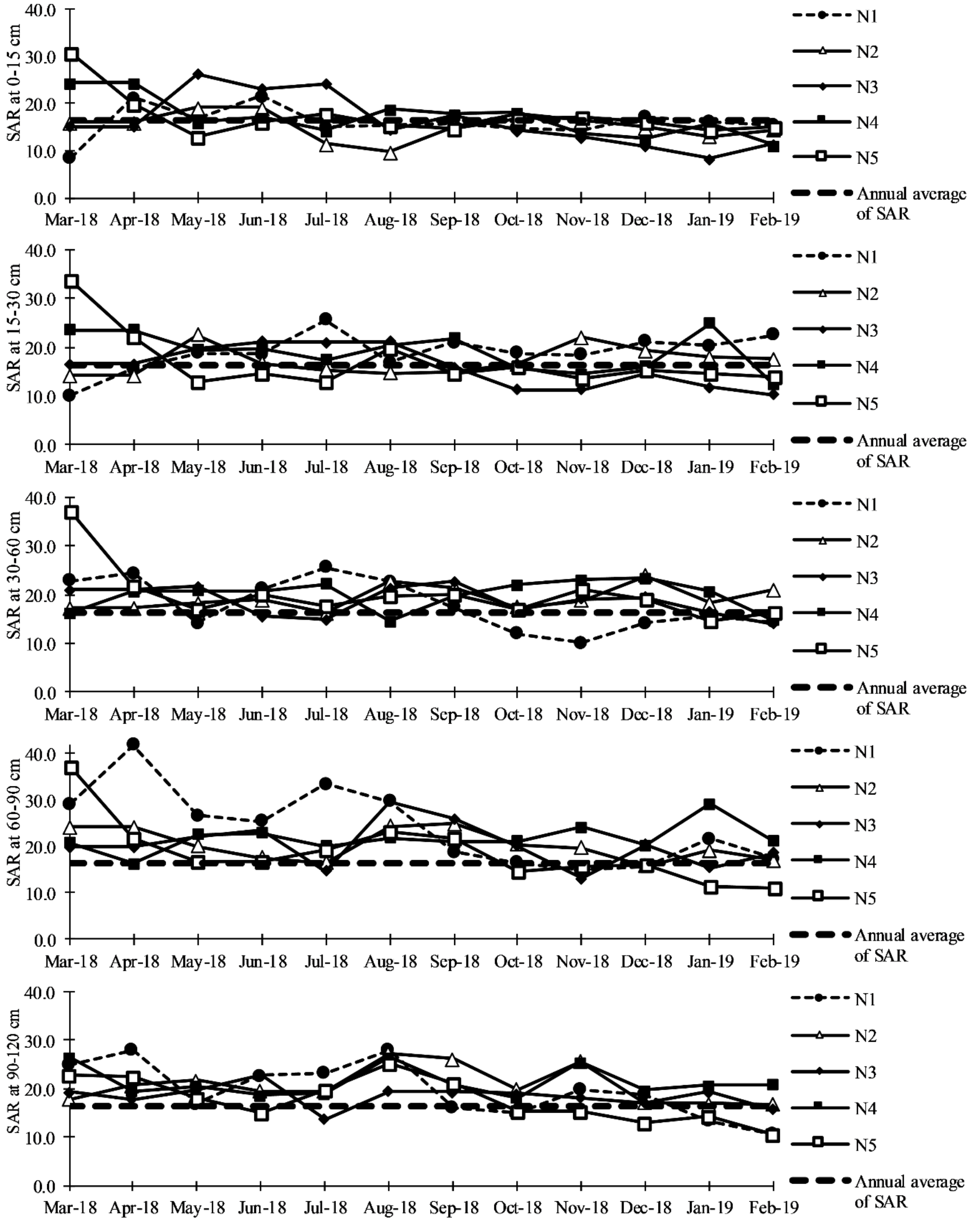


Figure 5 Depth functions exhibiting the variability of SAR from March 2018 to February 2019.

Concerning the depth functions of soils, the subsoil of most study sites trended to raise the SAR values when compared to the topsoil which perchance associated with their soil parent materials that were marine sediments mixed with riverine alluvium. Those sediments are usually high concentration of exchangeable sodium and soluble salts, e.g., NaCl, Na_2SO_4, $CaCl_2$, $CaSO_4$, $MgCl_2$ and $MgSO_4$ resulted in the sodium accumulation in soil profile and increasing in SAR values [57–59]. Previous research papers have additionally mentioned that the majority salts found in salt affected soils were NaCl influencing the increase in SAR values [61, 63]. Besides, the water management was conducted by the agriculturists, which directly drained the water from the Chao Phraya River through the branch canal trail in which the water sources were potentially influenced by the seawater intrusion presumably leading to sodium addition in the natural soil systems continually. In general, sodium ion (Na^+) is such a cation that can remain for a prolonged period while an anion; for example, chloride ion (Cl^-) is easier leached out from natural soil systems than Na^+ caused the sodium accumulation in natural soil systems. Particularly, fine-textured soils resulted in increasing SAR values more than that standard [64–65]. The tendency changes of SAR values displayed that there were likely to raise its annual average during March and April 2019, then rose in July and August 2019 identically to the EC_e values, whereas it trended to decline from its annual average during November and December 2019. Based on this observation, the fluctuation of SAR values could be considered that it was presumptively associated with the precipitation content, irrigation management from water resources that was possibly affected by seawater intrusion for cultivation, and groundwater transportation contained soluble due to the presumable seawater intrusion at those period times [64, 66–68]. The seawater intrusion impacts were also reported by Arslan and Demir [15] demonstrating that the relationship between seawater intrusion and SAR of groundwater values was observed, and the quality of groundwater decreased with an increase in the mixing percent of seawater.

Conclusions

This present study exposed that all agricultural soils were deep to very deep consisting of silty clay and clay texture. The field pH of these soils varied from 6.0–8.0 as well as soil saturated hydraulic conductivity rating exhibited that there was very slow to moderate. Concerning to EC_e and SAR values, the results indicated that these agricultural soils in the study locations were salt affected soils. From most study locations, the EC_e and SAR variabilities indicated that there were likely to increase from its annual average at the interval of March and April 2019 as well as July and August 2019, which possibly related to the small amount of precipitation and the potential seawater intrusion through surface water and/or groundwater sources during those periods. Therefore, it would be able to reveal that seawater intrusion might be considered as a co-factor influencing the variability of soil salinity and sodicity which appeared during the freshwater insufficiency to force back the seawater. Therefore, it caused the seawater encroachment through groundwater and/or water utilization of agriculturists for cultivation. In addition, land uses are still imperative to consider which may result in the different variabilities in soil salinity and sodicity due to differences in management practices causing the contrasting impacts on plant growth and yield owing to divergences in salt tolerance. Because the climate change associated with SLR resulting in seawater intrusion, is still concerned, the implementation strategies for freshwater management and planning are required to prevent future potential seawater intrusion such as releasing higher amount of water more than the average minimum flow during the potential period of seawater intrusion. Furthermore, long-term soil salinity and sodicity monitoring in agricultural areas potentially intruded by seawater should be persuaded to completely enlighten and be aware of the issue assisted in order to gain more future alternative solutions.

Acknowledgements

This research was financially supported by the Kasetsart University Research and Development Institute (KURDI), and the National Research Council of Thailand (NRCT). The authors wish to thank the agriculturists for allowing us to collect soil samples for this study. Our appreciation is also expressed to the anonymous reviewers who provided valuable and constructive suggestions.

References

[1] Haunschild, R., Bornmann, L., Marx, W. Climate change research in view of bibliometrics. PLoS ONE, 2016, 11(7), e0160393.

[2] Harvard Business School. Climate change in 2017: Implications for business. PCD. No. 9-317-032. Boston: Harvard Business School Publishing. 2017. [Online] Available from: https://www.hbs.edu/environment/Documents/Climate_Change_2017.pdf [Accessed 4 December 2018].

[3] Shukla, J.B., Verma, M., Misra, A.K. Effect of global warming on sea level rise: A modeling study. Ecological Complexity, 2017, 32, 99–110.

[4] IPCC. Climate change 2007: Synthesis report. 1st edition. Geneva, Switzerland: IPCC, 2007, 43–54.

[5] Noone, K.J. Sea-level rise. *In:* Noone, K.J., Sumaila, U.R., Diaz, R.J. Managing ocean environments in a changing climate. Amsterdam: Elsevier, 2013, 97–126.

[6] Adedeji, O., Reuben, O., Olatoye, O. Global climate change. Journal of Geo-science and Environment Protection, 2014, 2, 114–22.

[7] Church, J.A., White, N.J. Sea-level rise from the late 19th to the early 21st century. Surveys in Geophysics, 2011, 32, 585–602.

[8] Woodworth, P.L., Gehrels, W., Nerem, R.S. Nineteenth and twentieth century changes in sea level. Oceanography, 2011, 24(2), 80–93.

[9] Carless, S.J., Green, J.A.M., Pelling, H.E., Wilmes, S. Effects of future sea-level rise on tidal processes on the Patagonian Shelf. Journal of Marine Systems, 2016, 163, 113–124.

[10] Pickering, M.D., Horsburgh, K.J., Blundell, J.R., Hirschi, J.J.M., Nicholls, R.J., Verlaan, M., Wells, N.C. The impact of future sea-level rise on the global tides. Continental Shelf Research, 2017, 142, 50–68.

[11] Church, J.A., Monselesan, D., Gregory, J.M., Marzeion, B. Evaluating the ability of process based models to project sea-level change. Environmental Research Letters, 2013, 8, 1–8.

[12] Werner, A.D., Simmons, C.T. Impact of sea-level rise on sea water intrusion in coastal aquifers. Groundwater, 2009, 47 (2), 197–204.

[13] Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., ..., Barry, D.A. Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources, 2013, 51, 3–26.

[14] Sae-Ju, J., Chotpantarat, S., Thitimakorn, T. Hydrochemical, geophysical and multivariate statistical investigation of the seawater intrusion in the coastal aquifer at Phetchaburi Province, Thailand. Journal of Asian Earth Sciences, 2020, 191, 104165.

[15] Arslan, H., Demir, Y. Impacts of sea-water intrusion on soil salinity and alkalinity in Bafra Plain, Turkey. Environmental Monitoring and Assessment, 2013, 185, 1027–1040.

[16] Chhabra, R. Classification of salt-affected soils. Arid Land Research and Management, 2004, 19(1), 61–79.

[17] Farifteh, J. Imaging spectroscopy of salt-affected soils: Model-based integrated method. Ph.D. Thesis, Utrecht: Utrecht University, 2007.

[18] Feng, G.L., Meiri, A., Letey, J. Evaluation of a model for irrigation management under saline condition: I. Effects on plant growth. Soil Science Society of America Journal, 2003, 67, 71–76.

[19] Fan, Y., Ge, T., Zheng, Y., Li, H., Cheng, F. Use of mixed solid waste as a soil amendment for saline-sodic soil remediation and oat seedling growth improvement. Environmental Science and Pollution Research, 2016, 23, 21407–21415.

[20] Shrivastava, P., Kumar, R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi Journal of Biological Sciences, 2015, 22(2), 123–131.

[21] Fullen, M.A., Catt, J.A. Soil management: Problems and solutions. New York, USA: Oxford University Press Inc., 2004, 27–47.

[22] Arunin, S., Pongwichian, P. Salt-affected soils and management in Thailand. Bulletin of the Society of Sea Water Science Japan, 2015, 69, 319–325.

[23] Van-Camp, L., Bujarrabal, B., Gentile, A.R., Jones, R.J.A., Montanarella, L., Olazabal, C., Selvaradjou, S.K. Reports of the technical working groups established under the thematic strategy for soil protection. Volume II Erosion. EUR 21319 EN/2. Luxembourg: Office for Official Publications of the European Communities. 2004.

[24] Royal Irrigation Department. Report on the vigilance and monitoring of water quality regarding salinity. 30/2016. Bangkok, Thailand: Royal Irrigation Department, Ministry of Agriculture and Cooperatives. 2016.

[25] Songtham, W., Musika, S., Mildenhall, D.C., Cochran, U.A., Kojevnikova D. Development of the lower central plain of Thailand with history of human settlements: Evidence from pollen, spores and diatoms. Journal of Geological Resource and Engineering, 2015, 2, 98–107.

[26] Thai Meteorological Department. Climate of Thailand. Bangkok, Thailand: Meteorological Department, Ministry of Information and Communication Technology. 2015.

[27] Google Earth. The location of Nonthaburi province. Google Earth website, 2018. [Online] Available from: https://www.google.com/earth/index.html. [Accessed 29 August 2018].

[28] Soil Survey Staff. Key to soil taxonomy. 12th edition. Washington, DC, USA: United State Department of Agriculture, Natural Resource Conservation Service, 2014, 173–209.

[29] Soil Survey Division Staff. Soil Survey Manual Handbook No. 18. 5th edition. Washington, DC, USA: United State Department of Agriculture, United States Government Printing Office, 2017, 83–233.

[30] Kheoruenromne, I. Soil Survey Laboratory Manual. 6th edition. Bangkok, Thailand: Department of Soil Science, Faculty of Agriculture, Kasetsart University, 2009, 61–106.

[31] Klute, A., Dirksen, C. Hydraulic conductivity and diffusivity: Laboratory methods. *In:* Kulte, A. 2nd edition. Methods of soil

analysis. Part I. Physical and mineralogical methods. Wisconsin: American Society of Agronomy, 1986, 687–734.

[32] Kilmer, V.J., Alexander, L.T. Method of making mechanical analysis of soils. Soil Science, 1949, 68, 15–24.

[33] Soil Survey Division Staff. Soil Survey Manual Handbook No. 18. 4th edition. Washington, DC, USA: United State Department of Agriculture, United States Government Printing Office, 1993, 433–480.

[34] U.S. Salinity Laboratory Staff. Diagnosis and improvement of saline and alkali soils, Handbook No. 60. Washington, DC, USA: United State Department of Agriculture. 1954, 7–33.

[35] Office of Soil Survey and Land Use Planning. Characterization of established soil series in the Central Plain region of Thailand reclassified according to Soil Taxonomy 2003, Handbook No. 520. Bangkok, Thailand: Land Development Department. 2004.

[36] Department of Mineral Resources. Geological mapping of Nonthaburi Province. Department of Mineral Resources website, 2007. [Online] Available from: http://www.dmr.go.th/download/pdf/Central_East/Nonthaburi.pdf. [Accessed 4 December 2019].

[37] Khongnonglan, T. Distribution and variability of Kula Ronghai series in Khorat Basin. MSc Thesis, Bangkok: Kasetsart University, 2013.

[38] Chuaychoo, J. Properties and agricultural potential of acid sulfate soils under tropical monsoonal climate. MSc Thesis, Bangkok: Kasetsart University, 2014.

[39] Matteodo, M., Grand, S., Sebag, D., Rowley, M.C., Vittoz, P., Verrecchia, E.P. Decoupling of topsoil and subsoil controls on organic matter dynamics in the Swiss Alps. Geoderma, 2018, 330, 41–51.

[40] Prakongkep, N., Suddhiprakarn, A., Kheoruenromne, I., Smirk, M., Gilkes, R.J. The geochemistry of Thai paddy soils. Geoderma, 2008, 144(1–2), 310–324.

[41] Wongpokhom, N., Kheoruenromne, I., Suddhiprakarn, A., Smirk, M., Gilkes, R.J. Geochemistry of salt-affected aqualfs in Northeast Thailand. Soil Science, 2008, 173(2), 143–167.

[42] Wisconsin Department of Transportation. Geotechnical manual website, 2017. [Online] Available from: https://wisconsindot.gov/Documents/doing-bus/eng-consultants/cnsltrsrces/geotechmanual/gt-02-04.pdf [Accessed 29 April 2019].

[43] Gerrard, J. Soil geomorphology: An integration of pedology and geomorphology. 1st edition. London, UK: Chaman & Hall, 1992.

[44] Poulton, S.W., Raiswell, R. Chemical and physical characteristics of iron oxides in riverine and glacial meltwater sediments. Chemical Geology, 2005, 218(3–4), 203–221.

[45] O' Neal, A.M. A key for evaluating soil permeability by means of certain field clues. Society of America Journal, 1952, 16(3), 312–315.

[46] Goldberg, S., Forster, H.S. Flocculation of reference clays and arid-zone soil clay. Soil Science Society of America Journal, 1990, 54(3), 714–718.

[47] Miller, W.P., Newman, K.D., Frenkel, H. Flocculation concentration and sodium/calcium exchange of kaolinitic soil clays. Soil Science Society of America Journal, 1990, 54(2), 346–351.

[48] Marshall T.J., Holmes J.W. Soil Physics. London, UK: Cambridge University Press, 1979, 329–338.

[49] Ilyas, M., Miller, R.W., Qureshi, R.H. Hydraulic conductivity of saline-sodic soil after gypsum application and crop-

ping. Soil Science Society of America Journal, 1993, 57(6), 1580–1585.

[50] Visconti, F., de Paz, J.M. Electrical conductivity measurements in agriculture: The assessment of soil salinity. *In:* Cocco, L. New trends and developments in metrology. London: IntechOpen, 2016, 99–126.

[51] Brady, N.C., Weil, R.R. The nature and properties of soils. 14th edition. New Jersey, USA: Prentice Hall, Inc., 2008, 421–461.

[52] Hussain, N., Ali, A., Sarwar, G., Mujeeb, F., Tahir, M. Mechanism of salt tolerance in rice. Pedosphere, 2003, 13(3), 233–238.

[53] Arunin, S. Soil Salinity in Thailand. Bangkok, Thailand: Land Development Department, Ministry of Agriculture and Cooperatives, 1996, 113–137.

[54] Sonsri, K., Phankamolsil, N. The properties of soil as impacted by sea level rise in the dry season: A case study of Nonthaburi Province, Thailand. IOP Conference Series: Earth and Environmental Science, 2019, 230, 012107.

[55] Erfandi, D., Rachman, A. Identification of soil salinity due to seawater intrusion on rice field in the northern coast of Indramayu, West Java. Journal of Tropical Soils, 2011, 16(2), 115–121.

[56] Poochai, K., Phankamolsil, N., Poolsab, P., Sonsri, K. Influences of brine shrimp farming on chemical properties of soil and water in the surrounding areas that possess coarse to medium textured soils. In Proceedings of the 13th International Conference of the East and Southeast Asia Federation of Soil Science Societies, Nong Nooch Tropical Garden, Pattaya, Thailand, 12–15 December 2017, 137–144.

[57] Keren, R. Salinity. *In:* Summer, M.E. Handbook of soil science. Boca Raton: CRC Press, LLC, 2000, G-3-G21.

[58] Mengel, K., Kirkby, E.A. Principles of plant nutrition. 5th edition. Dordrecht, Netherlands: Kluwer Academic, 2001, 62–64.

[59] Havlin, J.L., Beaton, J.D., Tisdale, S.M., Nelson, W.L. Soil fertility and fertilizers: An introduction to nutrient management. 7th edition. New York, USA: Pearson Prentice Hall Inc., 2005.

[60] Thai Meteorological Department. The precipitation of Thailand website, 2019. [Online] Available from: http://hydromet.tmd.go.th/Reports/report-rfyear.aspx?fbclid=IwAR0RnEPHu-p2uYPgpXsZSoLaMOGcWCLsuURLXlg9pQQfWrZqngWwsT8ul_o. [Accessed 6 June 2019].

[61] Patcharapreecha, P., Topark-Ngarm, B., Goto, I., Kimura, M. Studies on saline soils in Khon Kaen region, Northeast Thailand I. Physical and chemical properties of saline soils. Soil Science and Plant Nutrition, 1989, 35(2), 171–179.

[62] Iwai, C.B., Oo, A.N., Topark-ngarm, B. Soil property and microbial activity in natural salt affected soils in an alternating wet-dry tropical climate. Geoderma, 2012, 189–190, 144–152.

[63] Wongpokhom, N. Variability of natural soil system as affected by salinity levels in Thailand. Ph.D. Thesis, Bangkok: Kasetsart University, 2007.

[64] Sparks, D.L. Environmental soil chemistry. 2nd edition. San Diego, USA: Academic Press, 2003, 285–300.

[65] Poolsab, P., Phankamolsil, N., Poochai, K., Sonsri, K. Distribution and accumulation of salt from brine shrimp farm in fine textured soil. In Proceedings of the 13th International Conference of the East and Southeast Asia Federation of Soil Science Societies, Nong Nooch Tropical Garden, Pattaya, Thailand, 12–15 December 2017, 137–144.

[66] Gupta, R.K., Abrol, I.P. Salt-affected soils: Their reclamation and management

for crop production. Advances in Soil Science, 1990, 11, 223–288.

[67] Shahid, S.A., Zaman, M., Heng, L. Introduction to soil salinity, sodicity and diagnostics techniques. *In:* Zaman, M., Shahid, S.A., Heng L. Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques. Cham: Springer Nature, 2018, 1–42.

[68] Szabolcs, I. Salt-affected soils. Boca Raton, USA: CRC Press, LLC., 1989.