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Research article

Fractionated organic carbon in relation to soil aggregates and other soil properties in humid, tropical lowland, salt-affected soils

Kanokpon Boonrit[†], **Somchai Anusontpornperm**[†,*], **Suphicha Thanachit**, **Wittaya Jindaluang**

Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand

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Abstract

Importance of the work: The understanding of the relationships among soil properties, soil aggregates, and fractionated organic carbon (OC) in tropical, lowland, salt-affected soils (SASs) is unclear and requires further investigation.

Objectives: To investigate the proportion of OC fractions in relation to water stable aggregates (WSAs) and other soil properties in selected SASs.

Materials & Methods: Lalerng Phimarn and Non Thai transects were chosen with four soils along each toposequence (LP1–LP4 and NT1–NT4, respectively). Fractionated OC, WSAs and other soil properties were analyzed.

Results: All SASs were classified as Typic Natraqualfs with silt+clay and with sand particles dominating in the soils of the LP and NT transects, respectively. Only aggregates < 0.50 mm were detected in these SASs. Dissolved OC was almost undetectable. Particulate organic matter was positively and negatively correlated with the sand (r = 0.783, $p < 0.01$) and clay (r = -0.812, $p < 0.01$) contents, respectively. This fraction was adversely affected by electrical conductivity (r =-0.706, $p < 0.01$) and the sodium adsorption ratio (r = -0.741, $p < 0.01$). The OC bound to silt+clay increased with increasing WSA5 (0.1–<0.25 mm; r = 0.542, $p < 0.015$) and mean weight diameter (r = 0.525, $p < 0.01$) and was positively correlated with OM (0.650, $p < 0.01$), total N (r = 0.544, $p < 0.05$) and extractable Ca (r = 0.526, $p < 0.05$). The chemically resistant OC had a positive correlation with WSA7 (< 0.053 mm; r = 0.686, $p < 0.01$) and clay content (r = 0.581, $p < 0.05$).

Main finding: Sodium overcame OM and induced WSA breakdown in these SASs. The s+c dominated, while the particulate OM was equally dominant in the sandier SASs. The chemically resistant carbon fraction was vital for C sequestration in the SAS subsoil.

[†] Equal contribution.
[*] Corresponding author.
E-mail address: somchai.a@ku.ac.th (S. Anusontpornperm)

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Introduction

Salt affected soils (SASs) occur in more than 100 countries, with their worldwide extent estimated to be about 1 billion ha and thus posing a global risk for agriculture (Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, 2015). These problem soils have increased nearly 831 million hectares in the past decade (Martinez-Beltran and Manzur, 2005). In Thailand, SASs cover 2.30 million ha, with inland SASs making up 1.90 million ha of the SAS total, generally used for jasmine rice cultivation or other cash crops (Arunin and Pongwichian, 2015). SASs have high concentrations of dissolved mineral salts, including carbonates, chlorides, sulfates and bicarbonates of calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^{+}) in their profiles (Qadir et al., 2000; Manchanda and Garg, 2008). These dissolved salts adversely affect crop production (Rengasamy, 2010; Wong et al., 2010). Generally, SASs are classified based on their electrical conductivity of the saturation extract (ECe), the sodium adsorption ratio (SAR), the exchangeable sodium percentage (ESP) and pH (Richard, 1954; Bohn et al., 2001; Rengasamy, 2010, Weil and Brady, 2016). There are three major types of SAS: saline soils, all containing high levels of soluble salts and characterized by having high ECe values (> 4 dS/m); sodic soils, having high levels of exchangeable sodium with SAR > 13 or ESP > 15, or both; and saline-sodic soils, in which both soluble salts and exchangeable sodium are high, (ECe>4 dS/m, SAR>13 and ESP>15) (Richard, 1954; Ghasemi et al., 1995). A combination of salinity and sodicity severely affects soil properties and plant growth in saline-sodic soils; thus, these soils are considered the most degraded form of SAS (Rengasamy, 2002).

Soil salinity lowers the ability of a plant to take up water efficiently, particularly jasmine rice that is widely planted in northeast Thailand (Clermont-Dauphin et al., 2010), with this plant being poisoned by various ions, such as sodium and chlorine, that are present in substantial soluble amounts (Dobermann and Fairhurst, 2000; Cha-um et al., 2009). Sodium, a dispersing agent, leads to the soil structure becoming unstable and compacted, which restricts the root elongation of growing plants (Ghassemi et al., 1995; Singer and Munns, 2006) because exchangeable Na^{+} in the soil solution and at exchange sites contributes to repulsive charges that disperse clay particles (Bronick and Lal, 2005), resulting in low soil hydraulic conductivity and leading to a risk of soil erosion on slopes, as cited by Sparks (2003). It is widely known that SAS particles are dispersed and weakly aggregated due to the presence of highly soluble salts (Warrence et al., 2006). Most of the water-stable aggregates (WSAs) in SASs are microaggregates (Nelson and Oades, 1998), which induce good development of capillary pores and upward movement of salts together with water; thereafter, salt accumulates in the surface soil (Daliakopoulos et al., 2016). Thus, it is an essential goal to enhance the amount of WSAs during SAS improvement (Franzluebbers et al., 2000).

Organic matter (OM) is considered as the main binding material for soil WSAs by enhancing aggregation through the bonding of primary soil particles (Bronick and Lal, 2005). Both the quantity and quality of soil organic matter (SOM) are closely related to the distribution and stability of WSAs (Tisdall and Oades, 1982; Elliott, 1986; Six et al., 2000). Usually, humic substances are considered as the major binding agents of microaggregates, while plant roots and microbial hyphae are the main glue components for macroaggregates (Tisdall and Oades, 1982; Oades and Waters, 1991; Puget et al., 1995; Six et al., 2000). A study in northeast Thailand revealed that the content of WSAs in SASs decreased with depth within the soil profile as did the clay and OM contents (Kaewmano et al., 2009) while Kantrikrom et al. (2020) showed that SOM contributed to the formation of large WSAs and a larger mean weight diameter (MWD) of WSAs, whereas ECe and SAR decreased the stability of large aggregates in SASs in the same region. However, the SOM content in SASs is relatively low due to the limited plant productivity and carbon input, while soil salt can also inhibit SOM decomposition through slowing transformation of organic substrates and reducing microbiological activity levels (Kaur et al., 2000; Rasul et al., 2006).

Humid tropical SASs can have different soil properties such as texture and the SAR, which lead to different strategies of remediation. The aggregate stability of 56 salt-affected soil samples from the North-east Plateau, Thailand was in the range 3–91% while saturated paste electrical conductivity (EC_e) varied in the range 0.6–16.2 dS/m, with the aggregate stability having the strongest correlation with pH, followed by exchangeable K, cation exchange capacity (CEC), clay content, extractable acidity and OM, respectively (Kaewmano et al., 2009). This clearly demonstrated that the soil OC, in relation to aggregations in SASs with different soil textural classes, can likely be variable. For example, the formation of large WSAs and a larger MWD of WSAs was positively affected by SOM but adversely affected by the ECe and SAR (Kantrikrom et al., 2020). This was due to stable organic carbon (SOC) enhancing clay flocculation and favoring the formation of bonds with clay particles and some cations (Tisdall and Oades, 1982; Six et al., 2004; Abiven et al., 2009). Nonetheless, SASs are usually composed of low SOC stocks (Wong et al., 2010; Setia et al., 2013), whereas high SARs in SASs could trigger clay dispersion that destabilizes the soil structure (Warrence et al., 2006). These outcomes suggest that the negative impacts of SAR and EC_e on soil aggregations in SASs might be overcome to some degree, depending upon the specific type of SAS, by the presence of clay particles, SOC and some other soil properties.

It has been suggested that the large background of SOC that is already present in the soil limits the opportunity to identify management-induced changes over short periods (Gregorich et al., 1994, Haynes, 2000), in turn, limiting how to test which agronomic practices have a positive effect on SOC increase. Thus, the use of different soil C fractions with an earlier response to changes in management compared to total SOC has been suggested as an efficient tool to identify optimized agricultural practices that increase the stock and quality of soil C. Different labile SOC pools, such as dissolved organic carbon (DOC), microbial biomass carbon and permanganate-oxidizable carbon, have recently received attention due to their sensitivity to agricultural management practices (Culman et al., 2012; Lucas and Weil, 2012). Several techniques have been suggested to separate soil samples into fractions with different physical and chemical properties affiliated to different soil functions and stabilizing mechanisms (Zimmermann et al., 2007). Generally, these techniques are used to examine the content of OC in various soil fractions to calculate turnover times and to determine the relationships between the distributions of SOC among the various fractions and land use or soil management (Hassink, 1997; Six et al., 2002; John et al., 2005; Sohi et al., 2010). According to Six et al. (2001), many of the suggested procedures involved isolation of the light particulate organic matter fraction and dispersion of aggregates. A possible explanation for particulate OM (POM) representing a relatively stable fraction is that its decomposition is reduced due to inhibited microbial activity. In line with this, incubation and field studies have reported that the microbial decomposition of SOM is reduced at elevated salinity (Rietz and Haynes, 2003; Rath and Rousk, 2015). However, POM is highly labile and can respond rapidly to changes in land management (Gregorich et al., 2006; Gregorich and Beare, 2008; Baldock et al., 2018). Another OC fraction is the OC bound to silt+clay (s+c). Several studies (Balesdent, 1996; Six et al., 2002; Feng et al., 2003) have shown that an essential mechanism of SOC stabilization is the formation of organo-mineral complexes, typically defined as SOC bound to the fine fractions of silt and clay. The other fraction that is reportedly believed to last in soils longer than other fractions is the chemically resistant carbon fraction (rSOC) or recalcitrant OC. This OC fraction is considered a stable form of OC that comprises a much greater proportion of the total soil carbon pool than those that are classified as labile (Davidson and Janssens, 2006).

Most recent studies on different aspects of soil science in SASs have been undertaken in arid, semi-arid, medium temperate arid and temperate semi-arid climates, where there is a very low annual rainfall (10–600 mm/yr) with a mean temperature range of 8.8–47°C (Masoud and Koike, 2006; Yuan et al., 2007; Rezapour et al., 2017; Manickam et al., 2021). Furthermore, most studies involving soil C fractions, in relation to salinity, Na and other soil properties associated with soil aggregates have been carried out in SASs formed in semi-arid and arid areas (Mavi et al., 2012; Emran et al., 2020; Garcia-Franco et al., 2021; Yu et al., 2022); however, there have been none reporting on SASs in the lowland areas of northeast Thailand. Therefore, the current study was undertaken to investigate the relationship between soil salinity, sodium, fractionated organic carbon and aggregates in humid tropical lowland SASs. The outcome of this study should provide a better understanding of how to reclaim these SASs to improve the performance of the jasmine rice that is extensively grown in these soils in northeast Thailand.

Materials and Methods

Study area and soils

Two transects of SASs were selected in Nakhon Ratchasima province, the Khorat basin, northeast Thailand for the study, with four soils located in the Lalerng Phimarn area (LP1–LP4) and the other four soils situated in the Non Thai area (NT1–NT4) with a distance between soil samples of 200 m, as shown in Fig. 1A and 1B, respectively. The study sites where SAS samples were studied and collected were at: LP1 = 47P 805351.76^E, 1671695.19^N, LP2 = 47P 805320.85^E, $1671364.72.19^N$, LP3 = 47P 805289.00^E, 1676440.00^N and LP4 = 47P 805282.75^E, 1676557.09^N for the Lalerng Phimarn area and NT1 = 48P 183975.99^E, 1682819.45^N, NT2 = 48P 183976.00^E, 1682692.19^N, NT3 = 48P 183955.43^E, 1682578.28^N and NT4 = 48P 183950.78^E and 1682448.76^N for the Non Thai area.

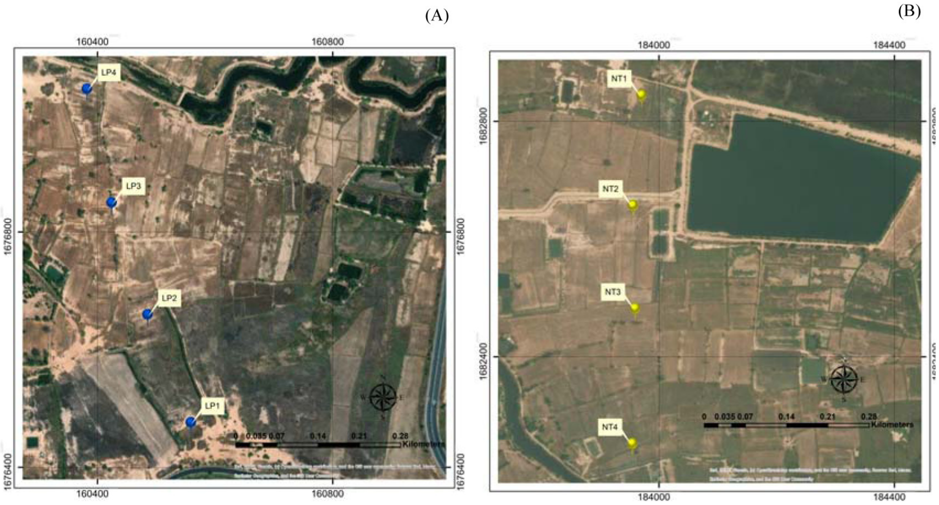


Fig. 1 Sampling locations of salt-affected soils in: (A) Lalerng Phimarn (LP) transect; (B) Non Thai (NT) transect

They were formed under a tropical savanna climate with average annual rainfall and temperature ranges of 1,054–1,204 mm/yr and 27.5–28.0°C, respectively. The elevation range for the soil transects in LP1–LP4 was 194–197 m and for NT1–NT4 was169–175 m. All soils in both areas had been used to grow jasmine rice (KDML 105 variety). Pedon analysis of soil pits in both transects was done according to standard field study methods, including a detailed soil profile description and soil sampling from genetic horizons (Soil Survey Division Staff, 1993).

The soils in these two transects were selected to compare fractionated organic carbon in relation to soil aggregates and other soil properties of SASs that had different textural classes, because the Lalerng Phimarn transect (LP1-LP4) had a finer texture, whereas the Non Thai transect (NT1-NT4) had a coarser texture.

General soil information

All soils chosen from both transects were salt-affected and had a similar genetic horizon sequence of Apng-Btng. All soils were deep with the topsoil thickness in the range 18–25 cm. They were located on nearly flat-to-undulating terrains with a surface slope in the range 1–3%. Apart from the LP1 soil that was formed on a depression landform, the other soils (LP2–LP4 and NT1 –NT4) were on low terraces. The parent material of these SASs was transported materials called old alluvium, except for LP1 whose parent material was a local alluvium overlying residuum (Table 1).

These SASs were lowland soils used for paddy rice (KDML105 variety) cultivation. The presence of groundwater at a very shallow depth with regular annual flooding during the rainy season has led to the soils having different mottled colors

Table 1 General setting and information of soils chosen

Soil	Thickness (cm)		Profile development	Slope (%)	Topography	Physiographic position	Parent material
	Topsoil	Profile					
Lalerng Phimarn transect							
LP1	20	140+	Apng-Btng	1	Nearly flat	Depression	Local alluvium over residuum
LP2	25	200+	Apng-Btng	3	Undulating	Low terrace	Old alluvium
LP3	20	200+	Apng-Btng	1	Nearly flat	Low terrace	Old alluvium
LP4	18	200+	Apng-Btng	1	Nearly flat	Low terrace	Old alluvium
Non Thai transect							
NT1	23	200+	Apng-Btng	2	Slightly undulating	Low terrace	Old alluvium
NT2	22	200+	Apng-Btng	1	Nearly flat	Low terrace	Old alluvium
NT3	22	200+	Apng-Btng	2	Slightly undulating	Low terrace	Old alluvium
NT4	21	200+	Apng-Btng	1	Nearly flat	Low terrace	Old alluvium

LP = Lalerng Phimarn; NT = Non Thai

throughout the soil profile, with low chroma matrix colors, as indicated by the ‘g’ suffix in Apng and Btng, in all genetic horizons (Fig. 2). In addition, the presence of clay particles in all soils increased with increasing depth within the soil profile, leading to these soils having a ‘t’ suffix in all subsoil horizons in Btng. As expected, these SASs contained high sodium levels; thus, all genetic horizons were composed of the ‘n’ suffix in Apng and Btng.

It was clear that SAS from both transects were inherently formed from different parent materials. The SASs of Lalerng Phimarn had finer texture, indicating that transported materials in this area came from siltstone-related rocks while at the other site, Non Thai, the soils had developed from mixed sediments with sandstone dominant. The variability of soil within each transect was not distinct, physically or chemically; however, morphologically they varied slightly, especially in soil color (Fig. 2), due mainly to the impact of the duration of ground water fluctuation annually. This was similar to several studies carried out in some lowland salt-affected soils developed across different landforms in the region (Miura et al., 1991; Wongpokhom et al., 2008; Kaewmano et al., 2009; Islam et al., 2014; Kantrikrom et al., 2020).

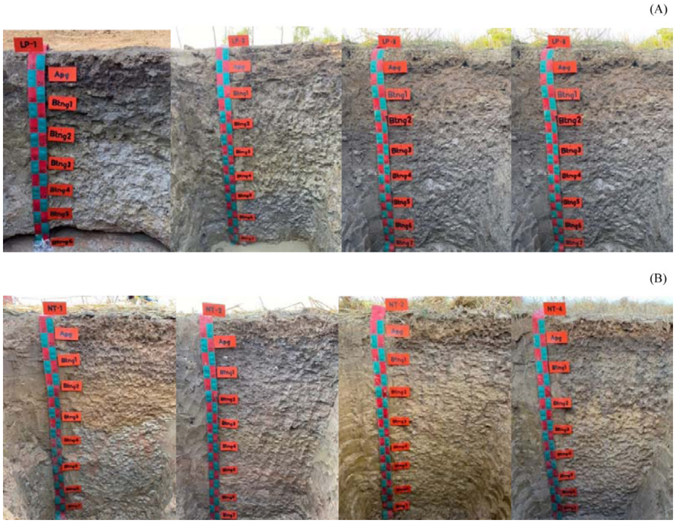


Fig. 2 Profiles of salt-affected soils in: (A) Lalerng Phimarn (LP) transect; (B) Non Thai (NT) transect

In terms of soil taxonomic units, all SASs in both transects were classified as Typic Natraqualfs (Soil Survey Staff, 1999). This soil is characterized by the presence of an argillic horizon in subsoils. Another diagnostic horizon of the soil is the natric horizon, a special kind of argillic horizon but with an ESP of 15% or more (or a SAR of 13 or more) in one or more horizons within 40 cm of its upper boundary. Typically, ground water in this type of soil perches above the natric horizon during one period and saturates the soils during another period. Based on Soil Survey Staff (1999), there are small areas of Typic Natraqualfs in the USA; however, they are also quite extensive in northeast Thailand, as shown in many studies there (Wongpokhom et al., 2008; Kaewmano et al., 2009; Kaewduang et al., 2013; Islam et al., 2014; Inboonchuay et al., 2016; Kantrikrom et al., 2020).

Physico-chemical properties of soils

Table 2 presents some physical and chemical properties of the soils in this study. Data of the subsoil are average values of each genetic horizon. All soils from the Lalerng Phimarn transect were dominated by silt and clay particles in rather similar proportions, whereas sand particles were clearly dominant in the SASs of the Non Thai transect. As a result, the textural class of the former group was clay with clay loam and loam textures in the topsoil of LP3 and LP4, respectively, while sandy clay loam texture was dominant in the latter group.

The soil pH in the topsoil was lower than that in the subsoil layers in almost all soils with the ranges 5.32–7.15 and 5.54–8.67 for the topsoil and subsoils, respectively. Organic matter varied among soils in both transects, with the amount being higher in the topsoil than in the subsoils; however, the amounts were still very low-to-low. The available P content was also low-to-very low in both the topsoil and subsoils (0.7–5.6 mg/kg) except in the topsoils of LP4 and NT2 that were moderately low (6.3 mg/kg and 9.0 mg/kg, respectively). In contrast to the OM and available P contents, available K tended to be higher in the subsoils in almost all soils. It was clear that the SAS soils in the Lalerng-Phimarn transect had a greater content of this nutrient than did those in the Non Thai transect. Notably, the amounts throughout the profiles of LP1 and LP2 were very high, while the K availability in the soils of the Non Thai transect was rather low-to-medium in the topsoil. The CEC varied among the soils and those in the Lalerng Phimarn transect generally had greater values in both the topsoil and subsoils than those in the Non Thai transect. In general, the values were rated moderately low-to-very high, ranging from 6.1 cmol_c/kg in the topsoil of NT1 to 32.3 cmol_c/kg in the subsoils of LP2. These SASs were composed of high bases, having base saturation of greater than 35% (moderate to high) in all horizons of all soils. The electrical conductivity of the soils in the Lalerng-Phimarn transect was far greater than in the Non Thai transect, with greater values being observed in the subsoils of most soils. Notably, apart from the topsoil of NT2, all soils had SARs greater than 13 in both the topsoil and subsoils.

Due to a similarity in the soil taxonomic units of all soils chosen in this study and despite these SASs characteristically having some differences to some degree (especially some chemical properties), it would be better to distinguish these soils from each other by using their electrical conductivity of the saturated extract (ECe) and the sodium adsorption ratio (SAR) (Richard 1954; Bohn et al., 2001; Rengasamy, 2010; Weil and Brady, 2016). Based on the data presented in Table 2, both the topsoils and subsoils of the LP1, LP2 and LP4 soils were classified as saline-sodic soils, characterized by ECe values greater than 4 dS/m and SAR values higher than 13 throughout their soil profiles. The topsoil and subsoils of NT1 were classified as sodic soils as the ECe values of all layers were lower than 4 dS/m and the SAR was higher than 13 throughout its soil profile. LP3, NT2, NT3 and NT4 had ECe values lower than 4 dS/m in their topsoils and greater than 4 dS/m in their subsoils; however, the SAR was greater than 13 throughout their profiles; thus, these SASs were sodic-topsoil and saline-sodic-subsoils. Thus, the LP1, LP2 and LP4 soils would pose more serious problems than the other soils due to the topsoil and subsoils having high levels of sodium ions that could induce clay dispersion and subsequent soil compaction coupled with highly soluble salts that could increase the soil osmotic potential to make it difficult for jasmine rice (commonly grown in these soils) to take up nutrient.

Table 2 Physico-chemical properties of soils chosen (average values of each genetic horizon)

Horizon	Depth	Particle size distribution[1/]			pH[2/]	OM[3/]	Available		CEC[6/]	BS[7/]	ECe[8/]	SAR[9/]
		Sand	Silt	Clay	(H_2O)	(g/kg)	P[4/]	K[5/]	(cmol$_c$/kg)	(%)	(dS/m)	
		(--------g/kg--------)					(--mg/kg--)					
LP1: SS-topsoil and subsoils												
Apng	0-20	312	288	400	6.77	9.65	4.1	131.6	16.5	68.3	15.5	32.5
Btng	20-140	381	210	409	8.12	2.87	0.8	165.7	20.2	82.6	15.2	40.5
LP2: SS-topsoil and subsoils												
Apng	0-25	399	332	269	6.56	8.69	5.6	139.7	13.0	78.9	26.1	63.9
Btng	25-200	140	371	489	7.44	2.69	0.7	320.7	32.3	83.0	14.5	50.4
LP3: SOD-topsoil and SS-subsoils												
Apng	0-20	206	430	364	5.97	17.12	2.5	90.9	20.4	64.9	3.2	25.2
Btng	20-200	174	393	433	5.54	5.44	1.3	66.1	23.8	67.3	6.9	46.4
LP4: SS-topsoil and subsoils												
Apng	0-18	455	327	218	5.95	9.86	6.3	63.3	9.6	56.4	4.2	29.6
Btng	18-200	130	398	472	6.29	5.76	1.1	118.2	29.1	70.1	13.4	55.6
NT1: SOD-topsoil and subsoils												
Apng	0-23	706	197	97	5.32	5.90	3.4	26.9	6.1	42.4	1.4	15.3
Btng	23-200	486	213	301	8.69	1.72	1.4	124.5	19.5	68.4	3.1	38.0
NT2: SOD-topsoil and SS-subsoils												
Apng	0-22	506	297	197	6.04	7.78	9.0	58.4	12.4	47.1	0.8	10.1
Btng	22-200	597	203	200	8.67	2.63	6.8	74.7	12.1	66.1	5.7	53.6
NT13: SOD-topsoil and SS-subsoils												
Apng	0-22	638	168	194	7.15	8.14	2.7	43.0	7.8	47.0	1.4	16.1
Btng	22-200	317	344	339	8.40	1.98	1.0	101.8	18.0	77.7	4.1	48.9
NT4: SOD-topsoil and SS-subsoils												
Apng	0-21	568	255	177	7.13	5.98	2.7	37.1	8.5	51.6	3.8	29.7
Btng	21-200	563	221	216	8.19	2.17	1.1	45.8	10.5	73.4	5.6	51.1

[1/] Pipette method (Gee and Bauder, 1986); [2/] 1:1 soil/solution ratio in H_2O (National Soil Survey Center, 2004); [3/] Walkley and Black titration (Walkley and Black, 1934; Nelson and Sommers, 1996) and the value was converted to soil organic matter content by multiplying the percentage of carbon by 1.724; [4/] Bray II extraction (Bray and Kurtz, 1945); [5/] 1 M NH_4OAc at pH 7.0 extraction (Pratt, 1965); [6/] Cation exchange capacity, saturating the exchange site and displacing by 1 M NH4OAc at pH 7.0 (Chapman, 1965); [7/] Calculated from extractable bases and extractable acidity; [8/] saturation extract (Richard, 1954); [9/] Calculated from proportion of extractable Ca, Mg and Na which were extracted with neutral 1 M NH4OAc (Thomas, 1996) and measured using atomic absorption spectrophotometry.

OM = organic matter; CEC = cation exchange capacity; BS = base saturation; ECe = electrical conductivity; SAR = sodium adsorption ratio; SS = saline sodic soil; SOD = sodic soil; LP = Lalerng Phimarn; NT = Non Thai

Remediation of the SASs in this study could involve available soil management technologies but that still require to be tested in this type of soil under field conditions in northeast Thailand. The soluble salts could be leached out by the addition of good-quality water, but usually Na^+ becomes an even greater problem and the soil pH rises to > 8.5 and the soil can become dispersed (Richards, 1954). This is not the case for the humid, tropical lowland SASs in the northeast, where the areas usually lack irrigated water and thick, dense argillic horizons, albeit as an artificially puddled layer that is common in paddy fields and impedes the vertical movement of water. Furthermore, it has been reported that complete remediation of saline soils or maintaining salinity levels below the salinity tolerance threshold is not practical, due to a lack of proper drainage, poor quality irrigation water and the high cost of soil remediation materials involved in the leaching process of saline soils (Qadir et al., 2007; Ashraf et al., 2010). A more likely approach would be to use a Ca^{2+} source ($CaSO_4$ $2H_2O$ or $CaCl_2$) to exchange Na^+ from the soil as a soluble salt, Na_2SO_4. (Sparks, 2003); however, this would still require a substantial amount of water. Another option could be the addition of some organic materials to increase the SOM content. For example, biochar adsorbs toxic ions, minimizes oxidation stress, enhances seed germination and improves soil water retention which leads to reduced osmotic stress (Fouladidorhani et al., 2020). Some humic substances, such as humic acid, are a crucial element of SOM, with their presence in the soil acting as a bio-stimulant for plant growth by supplying the plant with high levels of nutrients and having antistress effects (El-Sarkassy et al., 2017). Some organic wastes, such as burnt rice husk, cassava starch waste and cassava tails and stalk, have also been proven to release quite substantial major plant nutrients that can support growing jasmine rice in some SASs in Thailand (Opachat et al., 2018). The structure of soil and other soil properties that deteriorate due to excess salt can be amended using compost, which essentially increases the nutrient and OC contents of the soil and increases the water infiltration rate and holding capacity of saline-sodic soils (Day et al., 2019). The combined effects of gypsum and farmyard manure have also been reported to be highly efficient in reducing the soil pH and decreasing exchangeable Na in SASs in the eastern lowlands of Ethiopia (Adane et al., 2019), as well as there having been a promising effect of organic matter treatment demonstrated by Cha-um and Kirdmanee (2011) in their study on the grain of glutinous rice grown in SASs in northeast Thailand.

Laboratory analysis

The soil samples were air-dried and crushed to pass through a 2 mm sieve; the resultant particles were used for laboratory analyses except for the OM content that used particles passing through a 0.5 mm sieve. The general physical and chemical properties of the soils were analyzed based on standard procedures: particle size distribution was determined using a pipette method (Gee and Bauder, 1986); a glass electrode pH meter was used to determine the pH (National Soil Survey Center, 2004) of aqueous suspensions (1:1 soil/solution ratio); soil OC was measured using the wet digestion method with Walkley and Black titration (Walkley and Black, 1934; Nelson and Sommers, 1996) and the value was converted to SOM content by multiplying the percentage of carbon by 1.724; available phosphorus was extracted using Bray II solution (Bray and Kurtz, 1945) and determined colorimetrically using the molybdic blue method with spectrophotometry; available potassium was analyzed using 1 M NH4OAc at pH 7.0 extraction (Pratt, 1965) and measured using atomic absorption spectrophotometry; cation exchange capacity determination followed the procedure of Chapman (1965), with the removal of exchangeable bases using 1 M NH4OAc at pH 7 and subsequent replacement of exchangeable NH_4^+ ions with 10% NaCl and distillation of NH_3 into 2% H_3BO_3 followed by titration with 0.01 M HCl using bromocresol green-methyl red indicator; base saturation percentage was calculated from extractable bases and extractable acidity; saturated paste electrical conductivity was determined using a saturation extract (Richard, 1954); and SAR was calculated from the proportion of extractable Ca, Mg and Na that were extracted with neutral 1 M NH4OAc (Thomas, 1996) and measured using atomic absorption spectrophotometry.

The soil samples collected from the topsoil (Ap) and from the subsoil (Btng1) directly underlying the topsoil were used in the aggregate stability study based on the wet-sieving method using a series of nested sieves (wet-wash sieves), as described by Elliott (1986). Samples (each 100 g) of uncrushed soil aggregates (< 8.0 mm) were wet-sieved using a nest of six sieves with aperture sizes of 2.0–<8.0 mm (WSA1), 1.0–<2.0 mm (WSA2), 0.5–<1.0 mm (WSA3), 0.25–<0.50 mm (WSA4), 0.10–<0.25 mm (WSA5), 0.053–<0.10 mm (WSA6) and less than 0.053 mm (WSA7). Wet-sieving was performed for 30 min at 40 rpm through a vertical distance of 40 mm; following wet-sieving, the aggregate retained on each sieve was separately collected, oven-dried and weighed. The aggregate stability of each complete soil sample was expressed as the mean weight diameter (MWD) as shown in Equation 1:

$$\mathrm{MWD} = \sum_{i=1}^{n} \mathrm{WiXi} \tag{1}$$

where Xi is the mean diameter of aggregate size fraction i (i = 1 mm), and Wi is the proportion of aggregate size fraction i to the total sample weight. Higher MWD values indicate a higher proportion of macroaggregate in the sample and, therefore, higher stability (Kemper and Rosenau, 1986).

The stability of each of the seven aggregate size fractions (2.0–<8.0 mm, 1.0–<2.0 mm, 0.5–<1.0 mm, 0.25–<0.50 mm, 0.10–<0.25 mm, 0.053–<0.10 mm and less than 0.053 mm) was determined based on wet-sieving 100 g of uncrushed aggregate using the wet-sieving method, as described earlier. Sand correction was performed in each aggregate-size class because sand particles were not considered in those aggregates (Elliott et al., 1991). Therefore, the stabilityof the individual aggregate size fraction was expressed as the percentage of WSA of size fraction i (ASi) using Equation 2:

$$\mathrm{ASi} = \frac{\mathrm{(Wai\text{-}Yi)\text{-}Si}}{\mathrm{Wai\text{-}Si}} \times 100 \tag{2}$$

where Si is the correctional weight for sand particles larger than sieve size i.

For OC fractionation, both the topsoil (Apng) and subsoil (Btng1) samples were fractionated based on physical and chemical procedures. Samples (each 30 g) of the soil (<2 mm) were added to 150 mL water and dispersed using a calibrated ultrasonic probe-type (Bandelin; Berlin, Germany) with an output-energy of 22 J/mL as the application of a greater amount of energy may have disrupted any coarse, sand-sized SOM (Amelung and Zech, 1999). Then, this dispersed suspension was wet-sieved using a 0.053 mm aperture sieve until the rinsing water was clear. The fraction >0.053 mm, containing the sand fraction (S, which was separated from POM) and POM (S + POM), was dried at 40°C and weighed. The suspension <0.053 mm was filtered through a 0.45-mm aperture nylon mesh and the material >0.45 mm was dried at 40°C and weighed. An aliquot of the filtrate was frozen to measure the amount of DOC. The rSOC was extracted from the fraction <0.053 mm (s+c) using H_2O_2 oxidation with 10% H_2O_2 at 50°C, using a modified method of Helfrich (2007). The oxidation residue was centrifuged at 2,500×*g* for 15 min, decanted, washed with deionized water and then centrifuged again. This oxidation step was repeated twice. The apparent content of organic carbon bound with silt and clay (s+c) was derived from the total s+c minus rSOC. The C and N contents of the solid fractions were measured using a dry combustion C and N analyzer (LECO Tru-Spec CHN analyzer; Geleen, the Netherlands) and a Skalar-Primacs analyzer (Breda, the Netherlands, as described by Matejovic (1997) and Wright and Bailey (2001), respectively.

Data analysis

The values of soil aggregates and other soil properties measured were expressed as Pearson correlations (r) and the statistical significance of the correlation was examined using a two-tailed t test. The coefficient of variation was used to analyze the data (SAS Institute, 2004).

Results

Distribution of soil aggregates

The soil aggregate distribution only in the Apng and Btng1 layers is presented in Table 3. The results showed that the aggregates in the sizes 2.0–<1.0 mm (WSA1–WSA3) of all SASs were not detected or, in other words, soil aggregates with a size of 0.50 mm or larger were not formed in these soils. In addition, the Btng1 horizon of LP2, LP3 and NT3 did not contain any aggregates of 0.25–<0.50 mm (WSA4) and 0.10–<0.25 mm (WSA5) sizes, which meant that these horizons only had soil aggregates of 1 mm or smaller. This was also the case for the Apng layer of LP4 where soil aggregates were only of size 0.25 mm or smaller. Clearly, the Apng and Btng1 layers of all SASs in both transects were dominated by aggregates of less than 0.053 mm (WSA7) size, with the smallest aggregates accounting for almost 100% of the total aggregates. There were no clear differences between the soils in the Lalerng Phimarn and Non Thai transects for the aggregates in sizes of less than 0.25 mm (WSA4–WSA7) in the Apng and Btng1 horizons. However, the Apng layer contained more of the slightly bigger aggregate sizes than the Btng1 layer in the SASs of both transects, leading to the MWD of the topsoil being greater than that of the directly underlying subsoil.

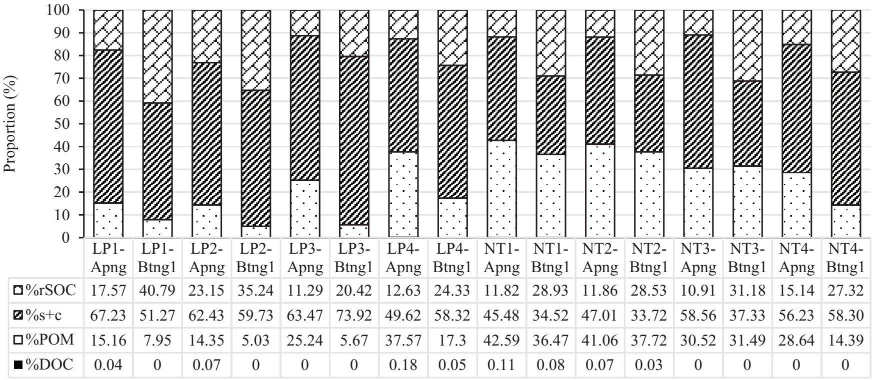
Organic carbon fractions in soils

The proportions of the OC fractions in the Apng and Btng1 horizons revealed hardly any DOC. The small amounts found in some layers were in the range 0.04%–0.78% (Fig. 3).

Table 3 Aggregate size distribution of topsoil (Apng) and directly underlying subsoil (Btng1) of soils chosen

Horizon	WSA4 (0.25–<0.50 mm)	WSA5 (0.10–<0.25 mm)	WSA6 (0.053–<0.10 mm)	WSA7 (<0.053 mm)	MWD (mm)
	(------------------------	----------------g/100 g	----------------	------------------------)	
LP1: SS-topsoil and subsoil					
Apng	0.73	1.34	3.74	94.19	0.098
Btng1	0.06	0.17	1.35	98.42	0.022
LP2: SS-topsoil and subsoil					
Apng	0.15	0.36	0.50	98.98	0.018
Btng1	0	0	0.53	99.46	0.007
LP3: SOD-topsoil and SS-subsoil					
Apng	0.15	0.36	0.50	98.98	0.018
Btng1	0	0	0.53	99.46	0.007
LP4: SS-topsoil and subsoil					
Apng	0	0.63	7.76	91.61	0.069
Btng1	0.45	0.30	1.76	97.50	0.040
NT1: SOD-topsoil and subsoil					
Apng	0.37	0.86	4.43	94.34	0.035
Btng1	0.04	0.08	2.64	97.24	0.016
NT2: SOD-topsoil and SS-subsoil					
Apng	2.49	1.74	7.00	88.77	0.126
Btng1	0.08	0.11	1.18	98.63	0.015
NT3: SOD-topsoil and SS-subsoil					
Apg	1.60	2.29	4.46	91.66	0.099
Btng1	0	0	1.86	98.14	0.013
NT4: SOD-topsoil and SS-subsoil					
Apng	0.16	0.38	2.73	96.73	0.027
Btng1	0.11	0.09	0.41	99.39	0.009

WSA = water stable aggregate; LP = Lalerng Phimarn; NT = Non Thai; WSA1–WSA3 sizes not detected



	LP1-Apng	LP1-Btng1	LP2-Apng	LP2-Btng1	LP3-Apng	LP3-Btng1	LP4-Apng	LP4-Btng1	NT1-Apng	NT1-Btng1	NT2-Apng	NT2-Btng1	NT3-Apng	NT3-Btng1	NT4-Apng	NT4-Btng1
☐%rSOC	17.57	40.79	23.15	35.24	11.29	20.42	12.63	24.33	11.82	28.93	11.86	28.53	10.91	31.18	15.14	27.32
▨%s+c	67.23	51.27	62.43	59.73	63.47	73.92	49.62	58.32	45.48	34.52	47.01	33.72	58.56	37.33	56.23	58.30
☐%POM	15.16	7.95	14.35	5.03	25.24	5.67	37.57	17.3	42.59	36.47	41.06	37.72	30.52	31.49	28.64	14.39
■%DOC	0.04	0	0.07	0	0	0	0.18	0.05	0.11	0.08	0.07	0.03	0	0	0	0

Fig. 3 Proportions of organic carbon fractions in topsoil (Apng) and directly underlying subsoil (Btng1) of soils chosen in both transects, where LP = Lalerng Phimarn, NT = Non Thai, %rSOC = %resistant soil organic carbon, %s+c = %organic carbon bound to silt and clay particles, %POM = %particulate organic matter, %DOC = %dissolved organic carbon

Among all OC fractions, s+c was in the highest proportion in all soils of the Lalerng Phimarn transect and in almost all soils in the Non Thai transect, while the amount of POM and rSOC varied among soils in both areas. The Apng layer tended to have a higher proportion of POM and s+c than the Btng1 horizon in all soils, resulting in the opposite trend for the rSOC quantity compared between these two layers. Clearly, the soils in the Lalerng Phimarn transect were composed of a greater s+c proportion than in the Non Thai transect which was in contrast to POM of which, there more in the latter group of soils. However, the rSOC amounts in the soils of both transects were not comparable as the proportion varied somewhat among horizons and soils. The highest POM, s+c and rSOC proportions of 42.59%, 67.23% and 40.79%, respectively, were observed in the Apng layer of NT1, the Apng layer of LP1 and the Btng1 horizon of LP1, respectively (Fig. 3).

Relationship between organic carbon fraction and soil properties

Considering the OC fractions in relation to soil physical properties, the %DOC was positively correlated with hydraulic conductivity (Ksat; r = 0.552, $p < 0.005$; Fig. 4). The correlation between the %POM and sand content was highly significantly positive (r = 0.783, $p < 0.01$; Fig. 4), contrasting to the clay content that was highly significantly negatively correlated with the %POM (r = -0.812, $p < 0.01$; Fig. 4). There was a significantly positive correlation between %s+c and the aggregate size 0.10–<0.25 mm (WSA5; r = 0.52, $p < 0.05$; Fig. 5) and the MWD (r = 0.525, $p < 0.05$; Fig. 5) but the %s+c was significantly negatively correlated with sand content (r = -0.524, $p < 0.05$; Fig.5). The relationship between the rSOC and soil physical properties illustrated that the aggregate sizes 0.25–<0.50 mm (WSA4) and 0.053–<0.10 mm (WSA6) had a significantly negative correlation with this OC fraction (r = -0.613, $p < 0.05$; Fig. 6 and r = -0.734, p <v0.01; Fig. 6, respectively). In contrast, this %rSOC was significantly positively correlated with the aggregates smaller than 0.053 mm (WSA7; r = 0.686, $p < 0.01$; Fig. 6) and clay content (r = 0.581, $p < 0.05$; Fig. 6).

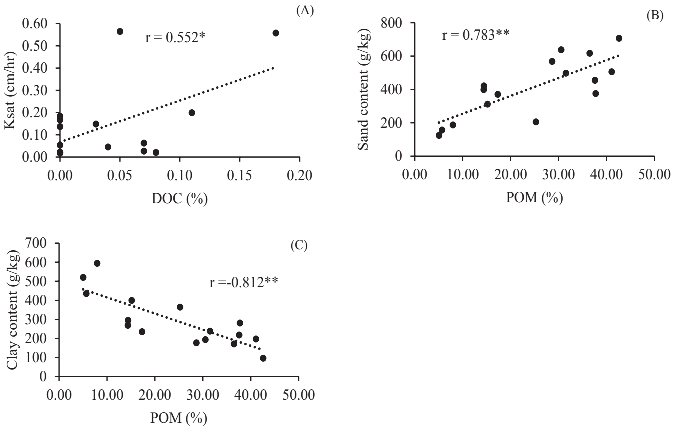


Fig. 4 Linear relationships for soils chosen (n = 16) between: (A) Ksat and %DOC; (B) sand content and %POM; (C) clay content and %POM, where Ksat = hydraulic conductivity measured using variable-head method (Klute, 1965), %DOC = dissolved organic carbon, POM = particulate organic matter, r = Pearson correlation coefficient, * = significant ($p < 0.05$) and ** = highly ($p < 0.01$) significant

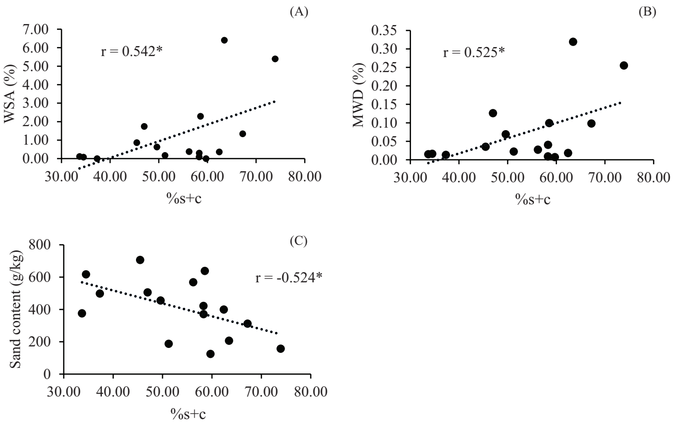


Fig. 5 Linear relationship of soils chosen (n = 16) between: (A) WSA5 and %s+c; (B) MWD and %s+c; (C) sand content and %s+c, where WSA5 = water-stable aggregate 0.10–<0.25 mm, WSA6 = water-stable aggregate 0.053–<0.10 mm, MWD = mean weight diameter of aggregates, s+c = organic carbon bound to clay and silt particles, r = Pearson correlation coefficient and * = significant ($p < 0.05$)

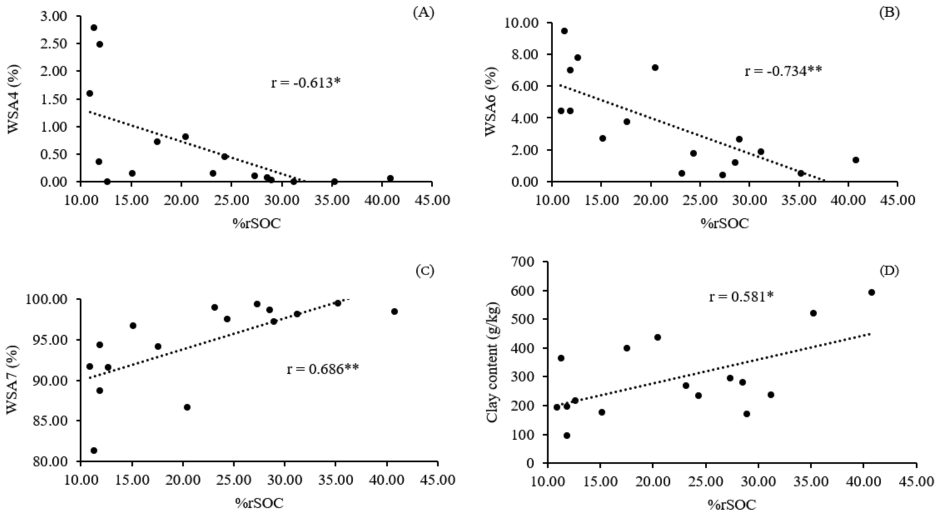


Fig. 6 Linear relationship of soils chosen (n = 16) between: (A) WSA4 and %rSOC; (B) WSA6 and %rSOC; (C) WSA7 and %rSOC; (D) clay content and %rSOC, where WSA4 = water-stable aggregate 0.25–<0.50 mm, WSA6 = water-stable aggregate 0.053–<0.10 mm, WSA7 = water-stable aggregate <0.053 mm, rSOC = chemically resistant organic carbon, r = Pearson correlation coefficient, * = significant ($p < 0.05$) and ** = highly ($p < 0.01$) significant

Considering the soil chemical properties in relation to OC fractions, the %DOC was not correlated with any of the soil chemical properties measured. There were numerous chemical properties that significantly and highly significantly had negative correlations with the %POM such as ECe (r = -0.706, $p < 0.01$), SAR (r = -0.741, $p < 0.01$), available K (r = -0.612, $p < 0.05$), extractable Ca (r = -0.717, $p < 0.01$), extractable Mg (r = -0.723, $p < 0.01$), extractable Na (r = -0.797, $p < 0.01$), sum bases (r = -0.791, $p < 0.01$), extractable acidity (r = -0.675, $p < 0.01$), base saturation percentage (r = -0.637, $p < 0.01$), CEC (r = -0.663, $p < 0.01$) and %ESP (r = -0.612, $p < 0.05$), with the exception of available P, which for this OC fraction had a significantly positive correlation (r = 0.581, $p < 0.05$), all of which are shown in Fig. 7. Several correlations between %s+c and soil chemical properties were observed. This OC fraction was significantly negatively correlated with pH_{water} 1:1 (r = -0.661, $p < 0.01$; Fig. 8) and pH_{KCl} 1:1 (r = -0.511, $p < 0.05$) but was significantly and highly significantly positively correlation with OM (r = 0.650, $p < 0.01$; Fig. 8), total N (r = 0.544, $p < 0.05$; Fig. 8), extractable Ca (r = 0.526, $p < 0.05$; Fig. 8) and extractable acidity (r = 0.780, $p < 0.01$; Fig. 8). In addition, the %rSOC was significantly negatively correlated with OM (r = -0.603, $p < 0.05$; Fig. 9), while this OC fraction was significantly positively correlated with available K (r = 0.529, $p < 0.05$; Fig. 9), extractable Mg (r = 0.588, $p < 0.05$; Fig. 9), extractable Na (r = 0.546, $p < 0.05$; Fig. 9), sum bases (r = 0.546, $p < 0.05$; Fig. 9) and %BS (r = 0.742, $p < 0.01$; Fig. 9).

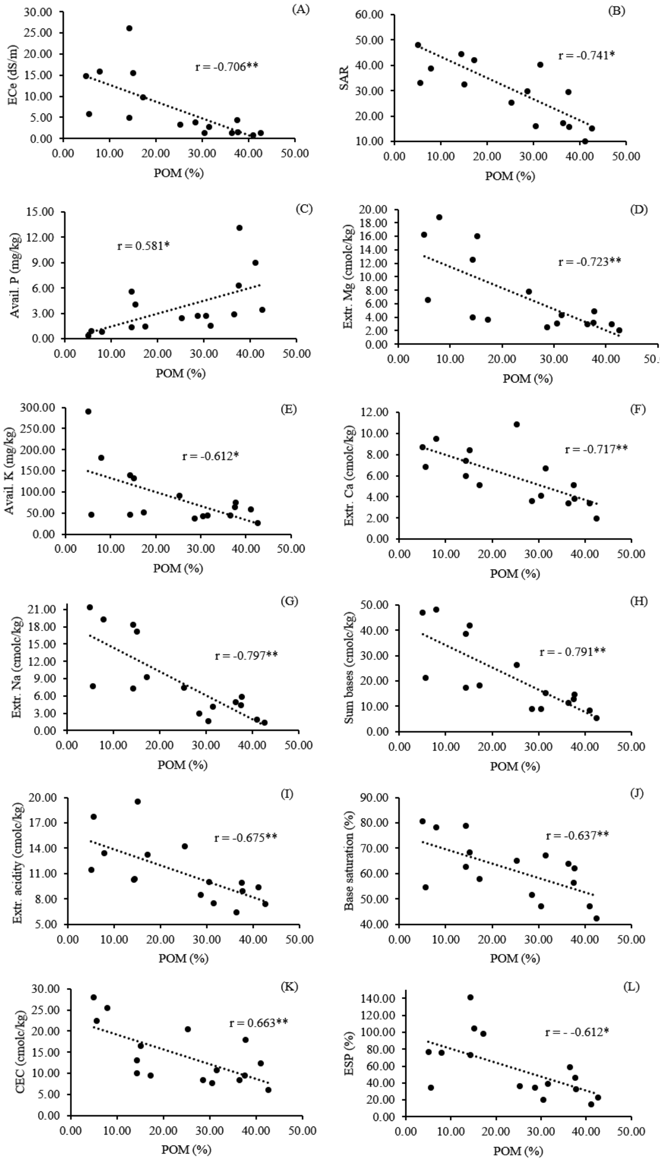


Fig. 7 Linear relationship of soils chosen ($n = 16$) between: (A) %POM and Ece; (B) %POM and SAR; (C) %POM and available (Avail.) P; (D) %POM and Avail. K; (E) %POM and extractable (Extr.) Ca; (F) %POM and Extr. Mg; (G) %POM and Extr. Na; (H) %POM and sum bases; (I) %POM and Extr. acidity; (J) %POM and base saturation; (K) %POM and CEC; (L) %POM and ESP, where ECe = electrical conductivity, SAR = sodium adsorption ratio, CEC = cation exchange capacity, ESP = exchangeable sodium percentage, POM = particulate organic matter, r = Pearson correlation coefficient, * = significant ($p < 0.05$) and ** = highly ($p < 0.01$) significant

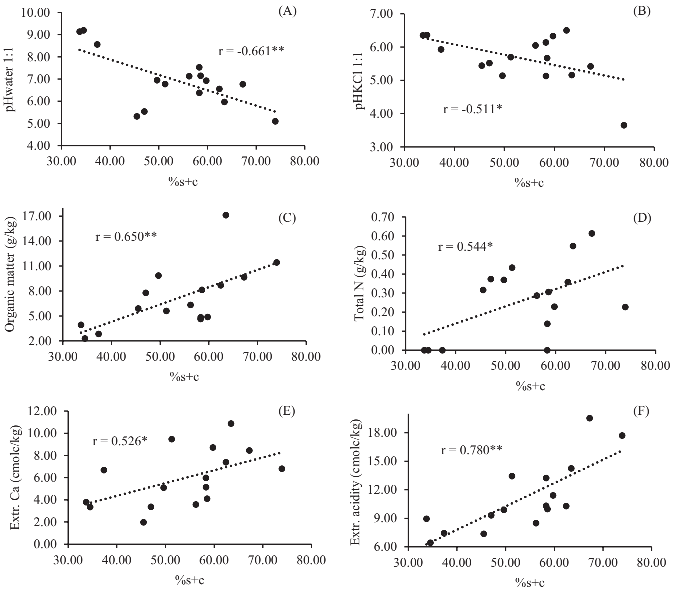


Fig. 8 Linear relationship of soils chosen ($n = 16$) between: (A) %s+c and pH_{water}; (B) %s+c and pH_{KCl}; (C) %s+c and organic matter; (D) %s+c and total N; (E) %s+c and extractable (Extr.) Ca; (F) %s+c and Extr. acidity, where s+c = organic carbon bound to clay and silt particles, r = Pearson correlation coefficient, * = significant ($p < 0.05$) and ** = highly ($p < 0.01$) significant

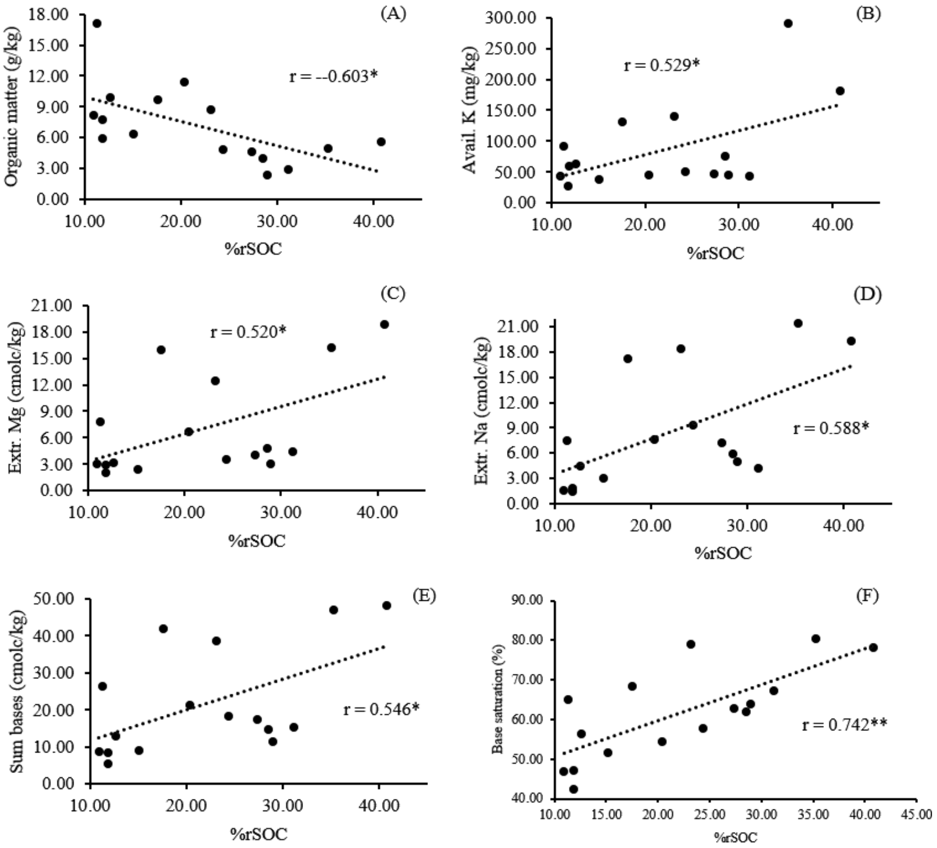


Fig. 9 Linear relationship of soils chosen ($n = 16$) between: (A) %rSOC and organic matter; (B) %rSOC and available (Avail.) K; (C) %rSOC and extractable (Extr.) Mg; (D) %rSOC and Extr. Na; (E) %rSOC and sum bases; (F) %rSOC and base saturation, where rSOC = chemically resistant organic carbon, r = Pearson correlation coefficient, * = significant ($p < 0.05$) and ** = highly ($p < 0.01$) significant

Discussion

Soil aggregate distribution

All SASs in this study had only WSAs smaller than 0.50 mm (Table 3), owing to these soils having high SARs (greater than 13), with the exception of NT2-Apng. An increase in Na, a dispersing agent, diminishes the stability of soil aggregate (Moghimi et al., 2012). In addition, highly soluble salts, especially Na salts, would prevent colloidal flocculation and macroaggregate formation (Levy et al., 1995). A plethora of Na (as indicated by the SAR values) in all the soils in this study overcame the role of OM that is normally deemed to be a cementing agent of soil aggregates; thus, there was a subsequent break down of large soil aggregates, leaving these soils with only small aggregates. However, the topsoil (Apng) of all soils still clearly had a greater aggregate size, as shown by their MWD values (Table 3), than their directly underlying subsoil (Btng1), due to the former having a higher organic matter content and also plant roots that could bind soil aggregates, contributing to a greater soil aggregate size (Vrdoljak and Sposito, 2002). Nonetheless, this finding contrasted to those of Kaewmano et al. (2009) and Kantrikrom et al. (2020), where the high Na contents in those lowland soils collected from northeast Thailand did not show any adverse impacts on large aggregate break down. This was possible, as Halliwell et al. (2001) mentioned, because soils may have identical sodicities and ionic strengths but may not always exhibit similar clay dispersion and permeability characteristics, for a variety of reasons, including soil texture and mineralogy, bulk density, pH, aggregate binding agents (iron and aluminum oxides and organic matter) and mechanical stresses (Balks et al., 1998).

Proportion of fractionated organic carbons and their relationship with other soil properties

Dissolved organic carbon barely had any correlation with the soil physical and chemical properties measured in this study and it was almost undetectable in almost all SASs in this study. This was because sodicity increases dissolved OM solubility, but DOC sorption is low due to the high sodium saturation of the exchange complex (Mavi et al., 2012), resulting in the loss of this OC fraction. The proportion of POM in the topsoil was higher than in the underlying subsoil in almost all SASs in this study because POM is largely made up of lightweight fragments that are relatively undecomposed, such as straw and root residues in the topsoil. This OC fraction was proportionally higher in the SASs from the Non Thai transect that had more sand particles than in the Lalerng Phimarn transect that had more clay particles and coincidently where the %POM was negatively correlated with the clay content and positively correlated with the sand content (Fig. 4). This result was due to POM being defined as a fraction associated with sand-sized particles and had been separated from the soil by sieving, so that generally, it consists mainly of fine root fragments and other organic debris (Cambardella and Elliot, 1992). Furthermore, the SASs from the former site generally had much lower ECe and SAR levels, which should contribute to better performance of jasmine rice and a subsequent greater crop biomass. This was also reaffirmed by the negative correlation for %POM with ECe and with SAR (Fig. 7). In addition, the %POM had a positive correlation with available P, demonstrating that POM can be a pool of P available to jasmine rice because the phosphate ions released by mineralization of P could contribute to the supply of plant-available P (Sharpley, 1985; Stewart and Sharpley, 1987), in humid tropical lowland SASs. However, this finding was in contrast to the results from Curtin et al. (2003), who investigated a non-salt-affected soil (stony silt loam Udic Ustrocrept) that in the majority (about 70%) of the P in the light fraction OC or POM was allocated to the stable, mineral-associated fraction.

Several studies (Balesdent, 1996; Six et al., 2002; Feng et al., 2003) have shown that an essential mechanism of SOC stabilization is the formation of organo-mineral complexes, typically defined as SOC bound to the fine fractions of silt and clay (s+c). The SASs from the Lalerng Phimarn transect had greater silt and clay contents than those from the Non Thai transect; hence, this OC fraction was higher (Fig. 3). In addition, the %s+c in this study was positively correlated with WSA5 and MWD, indicating that this OC fraction was stored more in this size of microaggregates (Fig. 5). However, based on the concept proposed by Tisdall and Oades (1982) and Hassink (1997) that OM addition to soils results first in the formation of SOM associations with clay and silt particles and with microaggregates (<250 μm) and that macroaggregate (>250 μm) formation starts if the SOM binding capacity of the clay and silt fraction is saturated, no macroaggregates were found in the studied SASs, meaning that the SOM content in these soils was not sufficient to form macroaggregates or this process might have been overcome by the presence of considerable amounts of Na, as mentioned before. Increasing OM in these soils is necessary to increase s+c as it also had a positive correlation with OM (Fig. 8). The positive correlation of %s+c with extractable Ca and total N (Fig. 8) suggested that the use of Ca-base material, such as gypsum, as earlier suggested for SAS reclamation, as well as N fertilization, could also contribute to the buildup of s+c. The latter was reaffirmed by the meta-analysis on fine silt and clay content as the main factor defining maximal C and N accumulations in soils (Matus, 2021). It could be that the positive correlation between %s+c and extractable acidity implied that during OM decomposition, acid radicals are broken down, resulting in some hydrogen ions being released to the soil, which would allow dissolved OC to bond with silt and clay particles.

A chemically resistant carbon fraction (recalcitrant OC) is considered a stable OC that comprises a much greater proportion of the total soil carbon pool than those that are classified as labile (Davidson and Janssens, 2006). All SASs in both transects contained higher sSOC levels in Btng1 than in Apng (Fig. 3) because in the subsoil conditions, overall microbial activity was less due to the low aeration and high salt contents in combination with other unfavorable factors. As a result, there were fairly stable and most probably highly recalcitrant forms of SOC to biodegradation in subsoils (Batjes, 1996; Kögel-Knabner, 2000; Nierop and Verstraten, 2003). Increasing the clay content in the subsoil also played a part in increasing the rSOC proportion, as shown by the positive correlation between clay content and this OC fraction (Fig. 6). This rSOC was also positively correlated with the aggregates smaller than 0.053 mm (WSA7) and not with any other larger sizes, such as 0.25–<0.50 mm (WSA4) and 0.053–<0.10 mm (WSA6), as shown in Fig.6. This was likely because these SASs had a greater amount of Na that greatly influenced the dispersion of small soil particles, causing the breakdown of soil aggregates (Ghasemi et al., 1995; Kaewmano et al., 2009). With respect to the findings in this study, this chemically resistant OC fraction increased with an increase in all the basic cations, with the exception of Ca, as shown by the positive correlations of %rSOC with available K, extractable Mg and Na, sum bases and base saturation percentage (Fig. 8).

Conclusions

All the studied SASs were deep soils with mottled and low chroma matrix colors, classified as Typic Natraqualfs. The soils in the Lalern Phimarn transect were dominated by clay and silt particles whereas sand particles were dominant in the Non Thai transect. All the SASs had only WSA components smaller than 0.50 mm in the Apng and Btng1 layers. Dissolved OC was barely found in these SASs. The SASs from the Lalerns Phimarn transect contained less POM and more s+c than those from the Non Thai transect. The POM was higher in Apng than in Btng1 but rSOC showed the opposite trend. Across all the SASs, the POM had a positive relationship with sand content but was negatively related to clay content. The ECe, SAR, ESP and most of the soil properties were negatively correlated with this OC fraction, with only available P having a positive correlation. The s+c was found mainly in the 0.10–<0.25 mm (WSA5) aggregate size, as was reaffirmed by the positive correlation with the MWD; however, the proportion decreased with increasing sand content. There was also a positive correlation with the amount of OM, total N, extractable Ca and acidity. The rSOC was clearly higher in the aggregates smaller than 0.053 mm (WSA7) and was tentatively augmented with the increase in the clay content. Most basic cations had a tendency to induce the formation of this chemically resistant OC fraction; however, the OM content was rather negatively correlated with this OC fraction. In terms of managing jasmine rice cultivation in these SASs, the addition of organic material and organic fertilizer should be prioritized to improve the stability of the soil structure because it is adversely affected by a plethora of Na ions in these SASs. Controlling the amount of standing water on the topsoil surface during almost all growth stages of this rice is important, because the considerable amounts of soluble salts found in these soils can pose harmful water stress to the rice plant.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

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