



Research article

Water stable aggregate distribution of lowland, humid, tropical, salt-affected soils

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Abstract

Ten areas of salt-affected soils in northeast Thailand were selected for studying soil properties and water-stable aggregates and their relationship. There were six saline sodic and four sodic soils with different salinity levels ranging from non-saline to very strongly saline (0.14–30.0 dS/m) and sodium adsorption ratios in the range of 4.52–94.54. There was a similar distribution trend in all 10 salt-affected soils of water-stable aggregates in all six size classes: 2–8 mm (WSA1), 1–<2 mm (WSA2), 0.5–<1 mm (WSA3), 0.25–<0.5 mm (WSA4), 0.1–<0.25 mm (WSA5) and <0.1 mm (WSA6). WSA6 was distributed in the highest amount (7.98–81.01 g/100 g soil) and varied greatly within the soil profile compared to the other sizes. The different-sized aggregates in the saline sodic soils varied more than in the sodic soils. The sodic soils had a higher WSA6 content than the saline sodic soils (19.25–78.59 compared to 13.01–75.01 g/100 g soil) but the structure of the sodic soils was more stable than the saline sodic soils, particularly in the topsoil where there was a higher amount of WSA1 (0.06–69.35 compared to 0.40–20.06 g/100 g soil) and greater mean weight diameter (MWD; 0.23–0.58 compared to 0.07–0.30 mm). Organic matter contributed to the formation of WSA1 and a larger MWD, with correlation coefficients of 0.33 ($p < 0.01$) and 0.37 ($p < 0.01$), respectively, while soil electrical conductivity ($r = -0.28$, $p < 0.01$) and sodium adsorption ratio ($r = -0.28$, $p < 0.01$) decreased the stability of WSA1. The clay content and extractable calcium and magnesium contributed to the stability of WSA2–WSA6 and in WSA6 this increased with an increasing sodium adsorption ratio ($r = 0.46$, $p < 0.01$). The available potassium in the soils was positively correlated with WSA1 and WSA2 ($r = 0.22$, $p > 0.01$ and 0.33 , $p < 0.01$, respectively). In addition, the cation exchange capacity had a positive correlation with WSA 3 ($r = 0.32$, $p < 0.01$) and a negative correlation with WSA5 ($r = -0.45$, $p < 0.01$).

Introduction

The size and stability of soil aggregates are indices of soil quality; large stable aggregates promote good soil physical properties,

such as strong soil structure, loosened nature with high resilience against soil compaction, and high moisture and nutrient retainability, suitable for plant growth (Tisdall and Oades, 1982; Pulleman and Marinissen, 2004; Six et al., 2004). In addition, they also decrease soil loss against water erosion (Barthes and Roose, 2002; Ramos et al., 2003; Pinheiro et al., 2004), and the formation of surface crust (Li et al., 2005). Soil aggregation and aggregate stability are a result

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of cementing agents in soils such as organic substances from activities of living organisms, including organic matter that adheres soil particles together, resulting in larger aggregates and greater stability (Tisdall, 1996; Nimmo, 2005). However, the stability of soil aggregates lowers as the size increases, particularly in soils with low organic matter content (Caravaca et al., 2004). Silicate clay, iron and aluminium oxides, and cations such as calcium are the cementing agents in small aggregates (Amezketta, 1999; Igwe and Stahr, 2004; Bronick and Lal, 2005) along with the soil pH, sodium content and sodium adsorption ratio (Kaewmano et al., 2009; Moghimi et al., 2012). In contrast, intensive cultivation and tillage tend to decrease soil organic matter content and adversely affect soil aggregate stability (Zheng et al., 2018).

Salt-affected soils in Thailand cover 2.302 million ha, of which inland saline soils make up 1.904 million ha and the rest are in coastal areas. Inland soils that are slightly to moderately salt affected are generally used for rice cultivation or other cash crops (Arunin and Pongwichian, 2015). Salt-affected soils can be saline, sodic or saline sodic soils. Saline soils are soils that contain soluble salts expressed in terms of the electrical conductivity (ECe) of the saturated soil extract having a value higher than 2 dS/m at 25°C and sodic soils have a sodium adsorption ratio (SAR) of higher than 13 (Abrol et al., 1988) while saline sodic soil has both unfavourable properties (Weil and Brady, 2016). Soil salinity lowered the ability of a plant to take up water efficiently, particularly jasmine rice that is broadly planted (Clermont-Dauphin et al., 2010) and also this plant has been poisoned by various ions such as sodium and chlorine that are dissolved in substantial amounts (Dobermann and Fairhurst, 2000; Cha-um et al., 2010). Sodium plays a part as a dispersing agent of clay, leading to the soil structure becoming unstable and compacted with restriction of root elongation in the growing plant (Ghassemi et al., 1995; Munns, 2002). Poor soil structural properties and a low soil organic matter content are common in sodic soils because sodium acts as a highly dispersive agent that directly breaks up aggregates and indirectly affects aggregation; furthermore, exchangeable Na⁺ in the soil solution and at exchange sites contributes to repulsive charges that disperse clay particles (Bronick and Lal, 2005). This can result in low soil hydraulic conductivity, leading to a risk of soil erosion on slopes (Warrence et al., 2002). Kaewmano et al. (2009) in Thailand reported that the content of water-stable aggregates in salt-affected soils decreased with depth within the soil profile as did the clay and organic matter contents. However, some horizons in the lower part of the soil profile in some areas contained very low amounts of water-stable aggregates due to the influence of sodium that increased with depth. This result agreed with Moghimi et al. (2012) in Iran who found that the stability of soil aggregates had a negative correlation with the sodium content, SAR and soil pH, whereas the contents of organic matter, nitrogen, phosphorus, potassium, calcium, clay and the cation exchange capacity (CEC) were properties that promoted the increase of soil water-stable aggregates. A literature review showed that studies were scarce on the relationship between water-stable aggregates and properties of salt-affected soils, particularly humid, tropical, inland,

saline soils in Thailand. To gather more useful information and knowledge, this study was undertaken to investigate the relationship between soil properties and water-stable aggregate distribution as affected by soil salinity in humid, lowland, tropical soils in northeast Thailand.

Materials and Methods

Study area

The study areas were located in the Korat basin, northeast Thailand with an elevation range of 125–203 m above mean sea level and a tropical savanna climate where the average annual rainfall and temperature ranges were 1,054–1,204 mm/yr and 27.5–28.0°C, respectively. Ten representative soils were sampled from different areas of Nakhon Ratchasima and Roi Et provinces (Fig. 1). All soils were used for growing the jasmine rice variety KDML 105. Pedon analysis of soil pits at each site was done according to standard field study methods, including a detailed soil profile description and soil sampling from the genetic horizons (Soil Survey Division Staff, 1993).

Laboratory analysis

Soil samples were air-dried and crushed to pass through a 2 mm sieve; the resultant particles were used for laboratory analyses. The general physical and chemical properties of the soils were analyzed based on standard procedures. The salinity level ranged from non to very strongly saline (0.14–30.0 dS/m) and the sodium adsorption ratio (SAR) was in the range of 4.52–94.54, while six soils were categorized as saline sodic soils (SS1, SS2, SS3, SS4, SS5, SS6) and the other four soils were sodic soils (Sod1, Sod2, Sod3, Sod4). All soils were classified as Typic Natraqualfs.

Aggregate stability was determined according to the wet-sieving method using a series of nested 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, 1.0–<2.0 mm, 0.5–<1.0 mm, 0.25–<0.50 mm, 0.10–<0.25 mm and less than 0.10 mm. 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:

$$\text{MWD} = \sum_{i=1}^n W_i X_i \quad (1)$$

where X_i is the mean diameter of aggregate size fraction i ($i = 1$ tonne), and W_i 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).

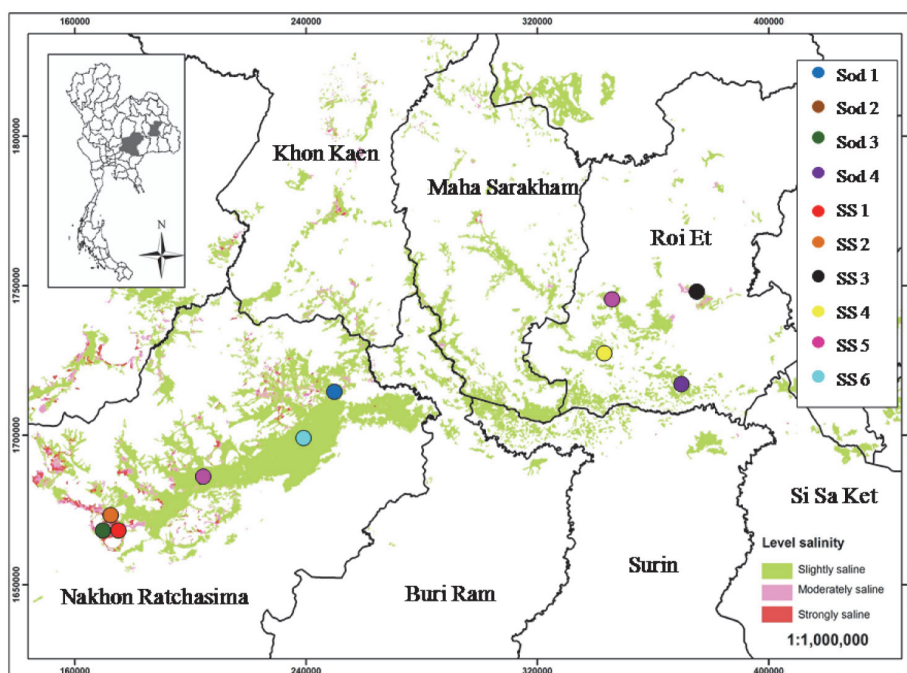


Fig. 1 Soil sampling locations in northeast Thailand

The stability of each of the six aggregate size fractions (2.0–<8.0, 1.0–<2.0, 0.5–<1.0, 0.25–<0.50, 0.10–<0.25, <0.10 mm) was determined by 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 this particle was not considered in those aggregates (Elliott et al., 1991). Therefore, the stability of the individual aggregate size fraction was expressed as the percentage of water-stable aggregates of size fraction i (AS $_i$) using Equation 2:

$$AS_i(\%) = \frac{(W_{ai} - Y_i) - S_i}{W_{ai} - S_i} \times 100 \quad (2)$$

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

Data analyses

The values of soil properties measured were subjected to linear correlation analyses with soil water stability indices using the STATISTICA Ver. 6.0 software package.

Results and Discussion

Soil property

All soils were deep, having poor drainage, and had an increase in sodium with increasing depth which coincided with the bridge grain structure and halite crystals in the soils. Most soils were dominated by sand particles rather than clay particles, having soil textural classes of sandy to clayey. Their properties varied considerably being very

strongly acidic to very strongly alkaline regarding soil pH (4.5–10.6). Their fertility varied from low to high with the soils having organic matter in the range of 0.69–14.45 g/kg, available phosphorus and potassium in the ranges of 1.21–19.65 and 1.22–129.79 mg/kg, respectively, and cation exchange capacity (CEC) in the range of 1.88–37.38 cmol_c/kg (Table 1).

Water stable aggregate and mean weight diameter

Stable aggregates in the soils studied were mostly smaller than 0.1 mm (WAS6) and in the range of 7.98–81.01 g/100 g soil (Figs. 2 and 3). This indicated that these soil aggregates had low stability due to the high sodium content in the soils, resulting in the structure of these soils being destroyed quite easily (Moghimi et al., 2012). The SS1 soil had the lowest aggregate stability because it comprised the highest amount (48.65–80.48 g/100 g soil) of <0.1 mm aggregate (WAS6). However, this quantity was nearly the same as that of the SS4 and SS5 soils. The SS2, SS6 and Sod3 soils also had similarly vulnerable structures whereas the Sod1 soil had the strongest structure which coincided with the soil having the greatest content of 2–8 mm aggregate size, especially in the topsoil layer (Figs. 2 and 3). The average mean of water-stable aggregate sizes varied in the range of 0.03–0.85 mm and the size decreased with increasing depth within the soil profile with the exception of the SS3 soil (Figs. 2 and 3). On average, the Sod4 and SS3 soils had the smallest sizes of water-stable aggregate (0.04–0.07 and 0.04–0.011 mm, respectively). The topsoil layer clearly had a greater aggregate size due to the layer consisting of more organic matter content and also plant roots that can bind soil aggregates, contributing to the greater soil aggregate size (Vrdoljak and Sposito, 2002).

Table 1 Physico-chemical properties of salt affected soils (average values of each genetic horizon)

Horizon	Depth	pH ^{1/}	OM ^{2/}	Available		CEC ^{3/}	BS ^{6/}	ECe ^{7/}	SAR ^{8/}	Particle size distribution ^{9/}		
				P ^{3/}	K ^{4/}					Sand	Silt	Clay
	(cm)	(H ₂ O)	(g/kg)	(mg/kg)		(cmol/kg)	(%)	(dS/m)			(g/kg)	
Sod1: Typic Natraqualf												
Apg	0–38	5.8	8.95	2.00	49	16.5	43	2.35	12	322	295	384
Btng	38–200	7.3	3.53	1.73	84	15.3	57	2.77	39	351	226	423
Sod 2: Typic Natraqualf												
Apg	0–25	5.8	14.50	6.60	23	10.1	45	3.00	23	650	170	180
Btng	25–200	7.1	3.36	1.83	52	17.2	63	1.93	14	334	288	378
Sod 3: Typic Natraqualf												
Apg	0–20	8.6	3.40	2.80	3	4.9	40	2.40	27	747	145	108
Btng	20–200	9.6	1.99	2.05	7	9.1	57	1.05	30	686	129	185
Sod 4: Typic Natraqualf												
Apg	0–20	4.9	14.10	13.30	15	5.1	11	0.90	8	511	385	104
Btng	20–200	6.6	2.29	2.03	21	15.4	55	0.25	12	366	235	399
SS 1: Typic Natraqualf												
Apg	0–25	7.5	3.80	1.90	4	14.4	38	4.00	35	655	253	92
Btng	25–200	9.6	2.03	1.76	6	8.0	49	5.11	67	606	225	169
SS 2: Typic Natraqualf												
Apg	0–20	10.6	2.40	6.40	12	6.4	67	7.40	89	764	132	104
Btng	20–200	10.2	1.60	2.09	13	8.8	68	2.64	54	717	113	170
SS 3: Typic Natraqualf												
Apg	0–14	4.7	4.50	3.90	8	2.0	16	8.60	47	875	61	64
Btng	14–71	4.6	2.33	2.10	9	3.2	21	6.17	56	819	89	92
Bvng	71–160	4.8	1.90	1.73	14	5.2	41	5.10	71	705	68	228
SS 4: Typic Natraqualf												
Apg	0–15	5.5	6.50	7.20	8	4.1	37	16.60	31	716	168	116
Btng	15–52	6.2	2.25	2.35	37	6.3	54	9.15	36	626	142	232
Btcng	52–98	6.4	1.90	1.70	43	6.8	50	11.40	43	706	79	216
Btng	98–170	6.4	1.23	1.63	27	4.0	45	11.07	44	712	72	216
Bvng	170–200	6.2	2.10	1.20	42	3.9	61	17.30	42	687	109	204
SS 5: Typic Natraqualf												
Apg	0–48	6.1	3.45	11.40	11	6.7	41	19.80	46	763	114	124
Btng	25–48	6.8	2.10	3.20	13	9.9	45	9.10	57	663	149	188
Bvng	48–119	7.5	2.75	2.25	20	17.4	63	5.80	80	544	177	280
BCrtng	119–200	7.4	2.43	2.08	38	28.6	72	7.83	63	307	293	400
SS 6: Typic Natraquert												
Apng	0–27	8.2	6.90	17.60	66	27.4	76	3.90	95	232	364	404
Bssng	27–200	7.8	3.61	8.79	65	28.9	74	11.29	58	187	373	439

OM = organic matter; CEC = cation exchange capacity; BS = base saturation percentage; ECe = electrical conductivity; SAR = sodium adsorption ratio.

^{1/}1:1 soil/solution ratio in H₂O (National Soil Survey Center, 2004); ^{2/}Wet digestion and Walkley-Black titration (Walkley and Black, 1934); ^{3/}Bray II extraction (Bray and Kurtz, 1945); ^{4/}1 M NH₄OAc at pH 7.0 extraction (Pratt, 1965); ^{5/}Cation exchange capacity, Saturating the exchange site and displacing by 1 M NH₄OAc at pH 7.0 (Chapman, 1965); ^{7/}^{8/}saturation extract (Richard, 1954); ^{9/}Pipette method (Gee and Bauder, 1986)

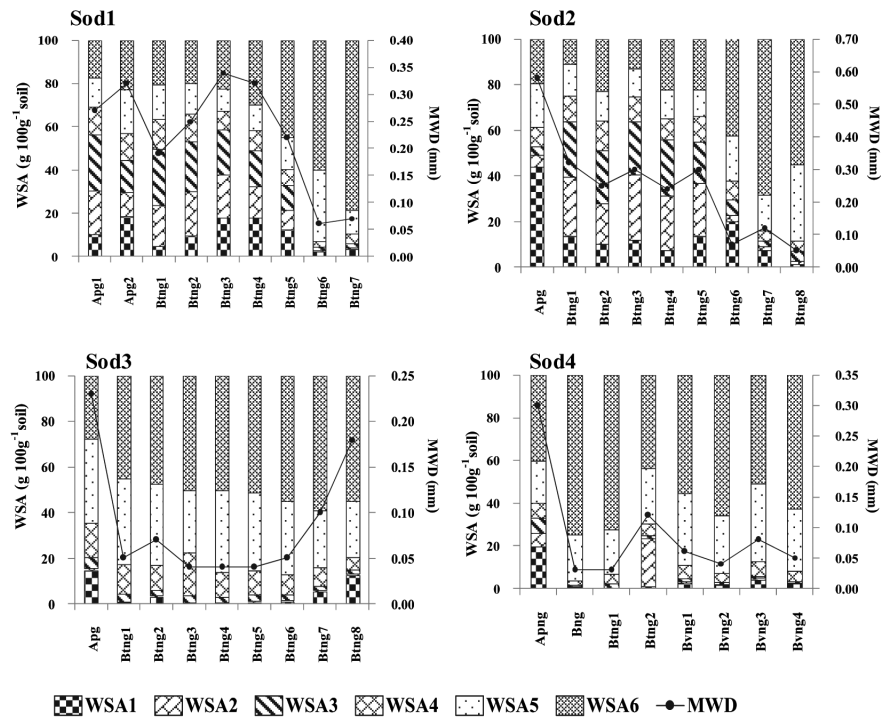


Fig. 2 Trend of aggregate size distribution and mean weight diameter (MWD) with depth of sodic soils (Sod1–Sod4), where WSA = water-stable aggregate

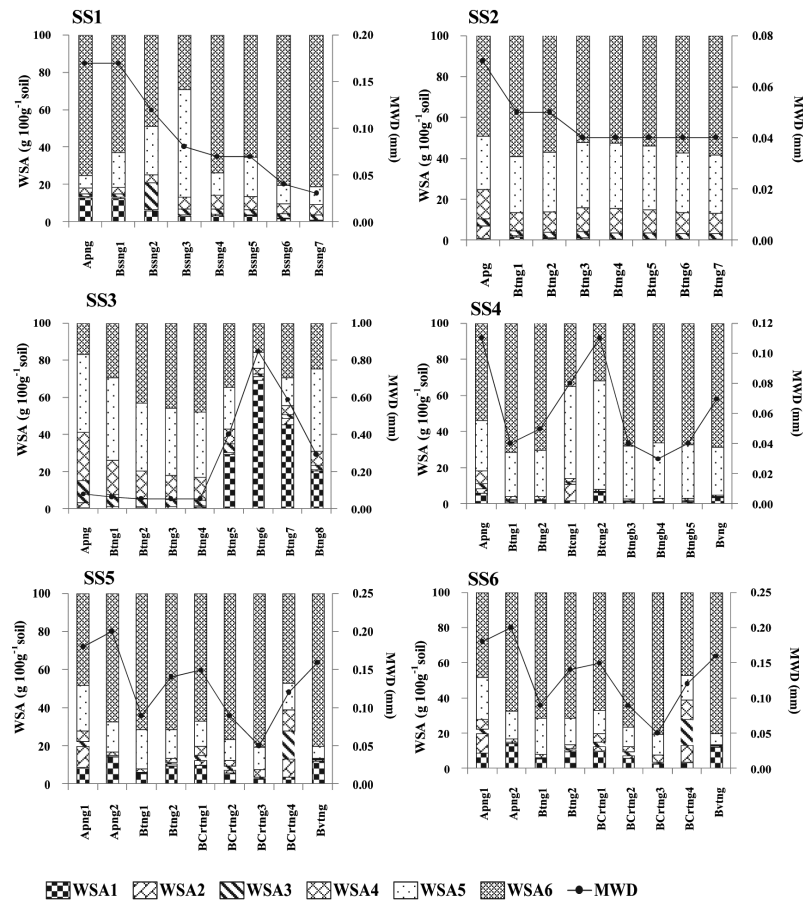


Fig. 3 Trend of aggregate size distribution and mean weight diameter (MWD) with depth of saline sodic soils (SS1–SS6), where WSA = water-stable aggregate

Aggregate size distribution in saline sodic and sodic soils

A comparison of the average content of different sizes of water-stable aggregate in the topsoil (Apg/Apng) between saline sodic and sodic soils is presented in Fig. 4. The stability of aggregates in the saline sodic soils was poorer because they were composed of lower quantities of 2–8 mm water-stable aggregate (WSA1), owing to their greater sodium content, as the stability of soil aggregate diminished with increasing sodium (Moghimi et al., 2012). Sodium played a role in breaking down large aggregates into smaller aggregates; thus, these sodic soils contained mainly <2 mm aggregate size, particularly the 1–2 mm and <0.1 mm sizes. In addition, most of the sodic soils contained a greater content of organic matter that has been deemed to be a cementing agent of soil aggregates (Zhang et al., 1996), than the saline sodic soils. In addition, carbon also can bind small size aggregates (0.1–0.25 mm) to form larger aggregates (Bronick and Lal, 2005; Six et al., 1999) indicating that the sodium found in substantial amounts in these soils, especially the sodic soils, was not sufficient

to entirely break down large aggregates into smaller aggregates. As a result, these soils were still composed of large aggregates to some degree which was indicative of the soils still having good structure and the influence of these large soil water-stable aggregates meant that these soils had rather good physical properties suitable for plant growth (Tisdall and Oades, 1982; Pulleman and Marinissen, 2004; Six et al., 2004) even though they were affected by sodium. The soils selected in the current study are particularly used for growing jasmine rice and in some dry years, there is insufficient water for growing rice and salinity becomes a more severe problem. However, the considerable amount of large-sized aggregates contributes to a good soil structure and also increases their ability to retain soil moisture slightly longer and in a greater quantity which in turn reduces the adverse effect of salts in the soils. Additionally, good structure assists the distribution of rice roots, so the plant can tolerate droughtiness slightly longer. The current results clearly indicate that the problem posed by sodic soils is lower than by saline sodic soils in the context of jasmine rice cultivation.

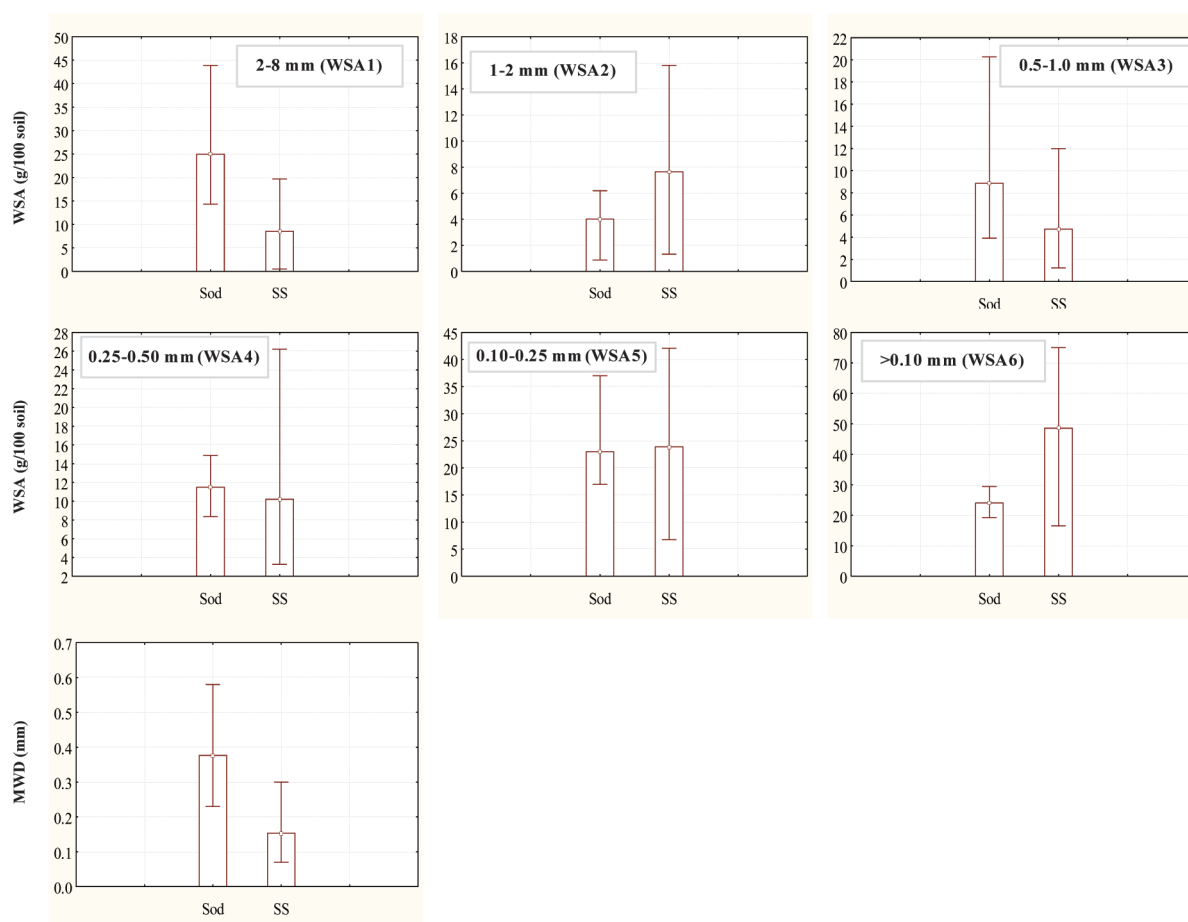


Fig. 4 Average value of water-stable aggregate (WSA) and mean weight diameter (MWD) of topsoil horizon (Apg/Apng) of sodic soils (Sod, n= 4) and saline sodic soils (SS, n= 6), where vertical error bars indicate $\pm$ SD

Soil properties in relation to water-stable aggregate

All six sizes of soil water-stable aggregates had both positive and negative linear correlations with most soil properties (Table 2). Large soil water-stable aggregates (2–8 mm; WSA1) positively correlated with organic matter content ($r = 0.33$, $p < 0.01$) as shown in Table 2 and Fig. 5. This result was consistent with Emami et al. (2014), Igwe and Stahr (2004), Mamedov et al. (2007) and Ogunwale (2008) and was due to organic carbon binding small aggregates together to form larger aggregates, resulting in more water-stable aggregates of this size. Furthermore, soil microorganisms synthesized exudates to cement soil particles during which organic matter was decomposed, customizing larger and more stable aggregate formation (Zhang et al., 1996). Nitrogen also had a positive correlation ($r = 0.33$, $p < 0.01$) with 2–8 mm aggregates (Table 2) because soil nitrogen was derived from the decomposition of organic matter and plant residues (Kalembasa, 2008; Weil and Brady, 2016), which are important food sources for soil microbes and the microbes subsequently produce exudates to bind soil particles together (Six et al., 2002). Fungal hyphae also play a part in binding soil particles together (Tisdall, 1996; Nimmo, 2002).

In contrast, 2–8 mm soil water-stable aggregates (WSA1) were negatively correlated with SAR ($r = -0.25$, $p < 0.01$; Table 2, Fig. 5), in agreement with the results of Moghimi et al. (2012). In the current study, <0.1 water-stable aggregates (WSA6) had a positive correlation with extractable sodium ($r = 0.39$, $p < 0.01$), electrical conductivity ($r = 0.42$, $p < 0.01$) and SAR ($r = 0.46$, $p < 0.01$) and a negative correlation with silt ($r = -0.25$, $p < 0.05$) and organic matter content

($r = -0.23$, $p < 0.05$). For SAR, the soils had a greater amount of sodium versus calcium and magnesium; hence sodium, a dispersing agent, greatly influenced the dispersion of small soil particles causing the breakdown of soil aggregates (Ghassemi et al., 1995; Kaewmano et al., 2009). Therefore, the greater the sodium content in the soil, the lower the stability of soil aggregates was observed, resulting in low amounts of large sized, water-stable aggregates. However, organic matter played less crucial part in small aggregates because it had a role in binding these small aggregates together to form medium and large aggregates (Nwadialo and Mbagwu, 1991; Amezketa, 1999; Bronick and Lal, 2005; Molina et al., 2010).

Soil water aggregates, 1–<2 mm size (WSA2) had a positive correlation with clay content ($r = 0.43$, $p < 0.01$), available potassium ($r = 0.22$, $p < 0.05$) and extractable calcium ($r = 0.26$, $p < 0.05$; Table 2) due to calcium and magnesium acting as a cementing agent to bridge organic matter and clay particles to become soil aggregates (Wuddivira and Camps-Roach, 2006; Martinez-Trinidad et al., 2012). This cementing agent was found to adhere to small soil aggregates (Mbagwu and Bazzoffi, 1988; Mbagwu, 1989; Tisdall and Oades, 1982). However, these cementing agents had a lesser role than the organic matter, especially in coarse-textured soils (Boix-Fayos et al., 2000; Six et al., 2004) which was consistent with Mbagwu and Bazzoffi (1988) who found that the role of organic carbon as a soil cementing agent lessened when there were greater amounts of other cementing agents such as silicate clay, iron and aluminum oxides and cations, such as calcium; therefore, the latter had more power in binding soil particles. This aggregate size (WSA2) was negatively

Table 2 Correlation coefficients (r) for linear relationship between soil property and water-stable aggregate

Soil property	WSA1	WSA 2	WSA3	WSA4	WSA5	WSA6	MWD
Sand (g/kg)	-0.13	-0.37**	-0.59**	-0.05	0.57**	0.18	-0.23
Silt (g/kg)	0.11	0.21	0.36**	0.06	-0.48**	-0.05	0.15
Clay (g/kg)	0.12	0.43**	0.65**	0.04	-0.54**	-0.25*	0.25*
BD (Mg/m ³)	-0.19	-0.18	-0.34**	-0.07	0.34**	0.18	-0.22*
Ksat (cm/hr)	0.04	-0.02	-0.09	-0.11	-0.01	0.05	0.03
FC (% by vol.)	0.23*	0.10	0.22*	0.12	-0.29**	-0.13	0.23*
PWP (% by vol.)	0.20	0.10	0.23**	0.12	-0.30	-0.11	0.20
AWC (% by vol.)	0.25*	0.00	-0.16	0.02	0.13	-0.15	0.23*
pH (H ₂ O)	-0.02	-0.28**	-0.08	0.43**	0.23*	-0.08	-0.06
pH (KCl)	-0.04	-0.31**	-0.11	0.44**	0.26*	-0.06	-0.09
OM (g/kg)	0.33**	0.16	0.22	0.07*	-0.26*	-0.23*	0.37**
Total N (g/kg)	0.33**	0.09	0.10	0.10	-0.19	-0.21	0.34**
Avai. K (Mg/kg)	0.03	0.22*	0.33**	-0.19	-0.36**	0.00	0.08
Extr. Ca (cmol _e /kg)	0.06	0.26*	0.43**	-0.06	-0.51**	-0.04	0.12
Extr. Mg (cmol _e /kg)	0.05	0.36	0.46**	-0.14	-0.50**	-0.05	0.14
Extr. Na (cmol _e /kg)	-0.10	-0.36**	0.22*	-0.18	0.01	0.39**	-0.20
Extr. K (cmol _e /kg)	0.03	0.22*	0.12	-0.19	-0.36**	0.00	0.08
CEC (cmol _e /kg)	0.07	0.12	0.32**	-0.03	-0.45**	0.02	0.10
ECe (dS m ⁻¹)	-0.28**	-0.15	-0.36**	-0.39**	0.13	0.42**	-0.33**
SAR	-0.28**	-0.40**	-0.47**	-0.13	0.17	0.46**	-0.37**

BD = bulk density; Ksat = hydraulic conductivity; FC = field capacity; PWP = permanent wilting point; AWC = available water holding capacity; OM = organic matter; Avai. = available; Extr. = extractable; CEC = cation exchange capacity; ECe = electrical conductivity; SAR = sodium adsorption ratio; MWD = mean water-stable aggregate diameter (mm).

n=87, * significant at 95% level of confidence, ** significant at 99% level of confidence.

WSA1 = water-stable aggregate 2–8 mm; WSA2 = water-stable aggregate 1–<2 mm; WSA3 = water-stable aggregate 0.5–<1 mm; WSA4 = water-stable aggregate 0.25–<0.5 mm; WSA5 water-stable aggregate 0.1–<0.25 mm; WSA6 = water-stable aggregate <0.1 mm; (mm)

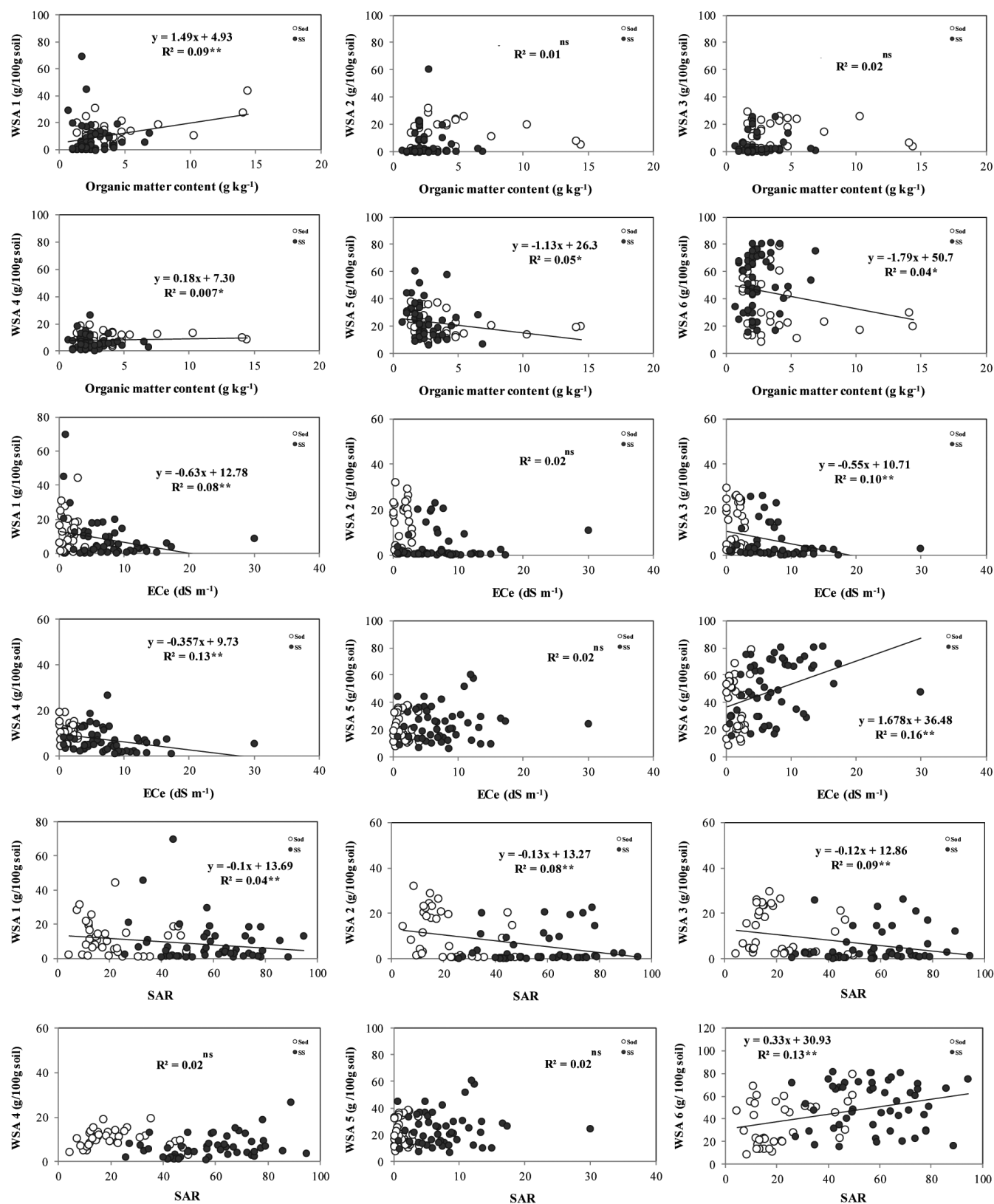


Fig. 5 Linear relationship between water-stable aggregate (WSA) and organic matter (OM), salinity level (ECe) and sodium adsorption ratio (SAR) of salt affected soils (n=87), where ns = non-significant ($p > 0.05$); * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).

WSA1 = water-stable aggregate 2–8 mm; WSA2 = water-stable aggregate 1–<2 mm; WSA3 = water-stable aggregate 0.5–<1 mm; WSA4 = water-stable aggregate 0.25–<0.5 mm; WSA5 water-stable aggregate 0.1–<0.25 mm and WSA6 = water-stable aggregate <0.1 mm; R^2 = coefficient of determination

correlated with the soil pH measured in water ($r = -0.27$, $p < 0.01$) and in KCl ($r = -0.31$, $p < 0.01$), extractable sodium ($r = -0.36$, $p < 0.01$) and SAR ($r = -0.40$, $p < 0.01$) (Table 2), agreeing with studies conducted by Kaewmano et al. (2009) and Moghimi et al. (2012) that reported the soil pH, sodium content and SAR influenced a decreased stability of soil aggregates and consequently, large aggregates were broken down into smaller aggregates.

Soil water-stable aggregates, 0.5–<1 mm (WSA3) had a positive correlation with available potassium ($r = 0.33$, $p < 0.01$) and soil moisture content at permanent wilting point ($r = 0.23$, $p < 0.01$; Table 2), illustrating that most soil potassium possibly accumulated in this aggregate size while the water stored in these aggregates (which contained mainly micropores) would be held too tightly with a high matrix potential; thus, this water might not be available to plants. Soil water-stable aggregates, 0.25–0.55 mm (WAS4) were positively correlated with the soil pH measured in water ($r = 0.43$, $p < 0.01$) and in KCl ($r = 0.44$, $p < 0.01$) and with the organic matter content ($r = 0.07$, $p < 0.05$; Table 2), demonstrating that this aggregate size can be a sink of carbon as also reported by Zhang et al. (1996) and Adesodun et al. (2005) who concluded any soil aggregates with a size smaller than 0.25 mm had the highest amounts of organic carbon and nitrogen compared to other sizes.

The soil properties studied as affected by salinity differed quite variably but the soil water-stable aggregates found in all soils were mainly smaller than 0.1 mm (WSA6). The distribution of soil water-stable aggregates in various sizes in sodic soils varied more than in the saline sodic soils. The structure of the sodic soils was more stable than that of the saline sodic soils which was consistent with the greater amount of 2–8 mm (WSA1) soil water-stable aggregates and the larger mean diameter of soil water-stable aggregates (MWD) in the former soils than in the latter soils.

Organic matter was the major factor that induced the formation of large aggregate (WSA1) in these salt-affected soils. Clay and extractable bases such as calcium, magnesium and potassium influenced water-stable aggregates formation in other sizes (WSA2–WSA5) whereas sodium and the salinity level diminished the stability of soil aggregates except for sizes smaller than 0.1 mm (WAS6). This would adversely increase soil salinity to a level harmful for growing plants, in addition to soil compaction that could impede root elongation. Therefore, soil improvement must be addressed by the incorporation of rice husk, crop residues, or locally available agricultural wastes in order to increase the amount of larger soil water-stable aggregates, and subsequently solve the problem for jasmine rice cultivation commonly grown in the study area.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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