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Relationship between Carbon Sequestration and Physico-chemical Properties of Soils in Salt-affected Areas, Northeast Thailand

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ABSTRACT

Variation of soil organic carbon as a result of differences in soil physico-chemical properties under natural and agricultural land use systems is of significance for understanding and determining soil organic carbon sequestration (SOC_{seq}). For the objectives of investigating C_{seq} and its relationship with different physical and chemical soil properties and high concentrations of Na^+ salts, this study was carried out in sandy-natured soil areas with salt-contaminated soil distributing in the lower areas of Ban Nong Suang in Kham Thale Sor district, Nakhon Ratchasima province, northeast Thailand. Soil samples were collected for laboratory analysis at four different depths of 0–15, 15–30, 30–45 and 45–60 cm. Three transects (tran-1, tran-2 and tran-3) were chosen, each comprising six mini soil pits located from the upper to the lower part of the transect. Most soils had loamy sand to sandy loam texture, being composed of very low amounts of organic carbon (OC), total N, available P and K in association with high bulk density, low pH and low cation exchange capacity. Some of the soils studied had sodic and saline sodic features with extremely high pH, electrical conductivity, sodium adsorption ratio, exchangeable sodium percentage and base saturation percentage. The percentage of silt+clay had a positive correlation with carbon sequestration (C_{seq}), whereas bulk density had a significant negative correlation. Total N and available P were highly significantly and significantly positively correlated, respectively, with C_{seq}, while pH and other exchange properties were negatively correlated. A high concentration of Na^+ caused a highly significant depletion of OC in soils, creating extremely hazardous conditions in crop production, especially in low-lying areas of this undulating terrain.

Keywords: carbon sequestration, soil physico-chemical properties, coarse-textured soils, salt- affected soil, northeast Thailand

INTRODUCTION

Carbon sequestration (C_{seq}) is an important global phenomenon that plays a significant role in maintaining a balanced global carbon cycle and sustainable crop production (Department of Energy, 1999). Agricultural production is directly or indirectly related to the quality of the soil (Srinivasarao *et al.*, 2013). An increasing rate of C_{seq} in the vegetation results in more organic matter being added to the soil which is essential for productivity and long-term sustainability of the ecosystem in degraded landscapes (Lal, 2011, Janzen, 2005). Global soils of agro-ecosystems have the potential to sequester about 1.2–3.1 billion tonnes of carbon per annum ($t. C.yr^{-1}$) and

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an increase of 1 t $C.ha^{-1}.yr^{-1}$in the organic carbon (OC) pool in soils can contribute an additional amount of 24–32 million t of food grains and 6–10 million t of roots and tubers in developing countries (Lal, 2011). Carbon sequestration is a natural process of humification (Department of Energy, 1999) that occurs through putting carbon into the surface layer of soil, while erosion, nutrient mining, acidification, mineralization, leaching, structural degradation and contamination cause depletion in the soil organic carbon pool (Lal, 2008). C_{seq} begins with photosynthesis by plants trapping CO_2 from the atmosphere and converting it into plant biomass (Jimenez and Lal, 2006, Schoroder and Pesch, 2011), part of which is further processed into soil organic carbon (SOC) through the process of humification, aggregation and illuviation (Lal and Follett, 2009). Physical, chemical and biological processes occurring in the soil help to protect the SOC sequestered and, as a whole, soil type plays a significant role and acts as the greatest determining factor in soil carbon dynamics (Hagedorn *et al.,* 2001). Differences in the physical and chemical properties of soils result in variability in the distribution and concentration of SOC on a sloping landscape in undulating terrain (Johnson *et al.,* 2011). The potential for agricultural land to sequester carbon is determined by a number of factors including climate (Jobbágy and Jackson, 2000, Ise and Moorcroft, 2006), land topography (Yimer *et al.*, 2006, Segnini *et al.*, 2011), depth in the soil profile (Sheikh *et al.*, 2009, Johnson *et al.,* 2011), soil type (Hagedorn *et al*., 2001, Wong *et al*., 2008) and vegetation (Natthaphol *et al*., 2006, Berhangoray *et al*., 2013). According to Swift (2001), the C_{seq} ability of a soil depends on plants grown therein, the mineralogy of the soil, depth in the soil profile, the drainage condition, aeration and availability of water, the temperature and above all the type and nature of organic matter, which ultimately determine how easily it decomposes or shows resistance to microbial decomposition.

In a study carried out in different land use areas of Wang Nam Kaew district, Nakhon Ratchasima province, northeast Thailand, Natthaphol *et al.* (2006) observed that most soils had a sandy texture with strongly acidic pH and bulk density values between 1.46 and 2.04 $Mg.m^{-1}$. The highest amounts of OC and total nitrogen were found in forest soil followed by reforestation areas, while corn fields had the lowest. Organic carbon and total nitrogen decreased gradually with increasing soil depth in all areas but no correlation between OC and soil properties was found. A study of sandy loam to clay loam soils under different forest types on the Sakaerat Environmental Research Station, Nakhon Ratchasima province, Thailand (Suwanprapa *et al.*, 2012) revealed that the organic matter content influenced the stability of macroaggregates, which were the most abundant aggregate size class found in these soils. In addition, a high amount of Na^+ in the soil generally has an adverse effect on plant growth and subsequent carbon stock, with a study in Australia revealing that soil carbon stocks to 0.30 m were much lower in the scalded and scalded-eroded soils that had been affected by salinity and sodicity (Wong *et al*., 2008).

Studying soil properties in relation to SOC_{seq} (where the amount is calculated using the area multiplied by a specified depth of soil) is important for the development of ecologically viable, sustainable development plans. It is essential to formulate strategies on the basis of changing courses as well as nature and on the extent of land degradation, deforestation, depletion of soil organic carbon pool and emissions of greenhouse gases from the terrestrial biosphere resulting from the location of specific, sustainable agricultural development. This study was undertaken: 1) to examine selected physical and chemical properties of soils and relate them to C_{seq}; 2) to observe the variability of soil organic carbon, total N, available P and available K under different land uses; and 3) to investigate the impact of a high concentration of Na^+ on carbon storage in coarse to medium-textured soils in the study area.

MATERIALS AND METHOD

Study site and soil sample collection

This study was carried out in Ban Nong Suang in Kham Thale Sor district, Nakhon Ratchasima province, Thailand in an area situated between latitude 0810270 and 0811887. The average annual temperature and rainfall at the site were 28 °C and 1,200 mm, respectively (Thai Meteorological Department, 2012). The area was characterized by low to medium terraces with gentle slopes having a wide range of light-textured soils of non-saline and heavily salt affected areas. Land uses in the area where soil samples were collected included: native forest, tree plantation, cassava, maize and paddy rice as well as bare land. Three transects were chosen to cover the different types of land use, objectively to investigate the relationship among soil properties and $\mathrm{SOC}_{\mathrm{seq}}$ along the toposequence. In tran-1, land uses were native forest, fruit tree plantation, eucalypt plantation and paddy rice. Tran-2 was composed of eucalypt plantation, cassava, corn and paddy rice, whereas in tran-3, paddy rice was the only crop grown (although no crop was in the ground at the time of sampling) with bare land located in the lower part. In each transect, six sampling spots were marked with respect to different land uses along the toposequence (Figure 1). Three small soil pits were dug at each spot. Disturbed and undisturbed soil samples were collected at four different depths, 0–5, 15–30, 30–45 and 45–60 cm. The disturbed soil samples obtained from the same location were mixed together as a composite sample. The undisturbed soil samples were collected using a soil core for the analysis of soil bulk density (BD) at the same depth as the disturbed samples.

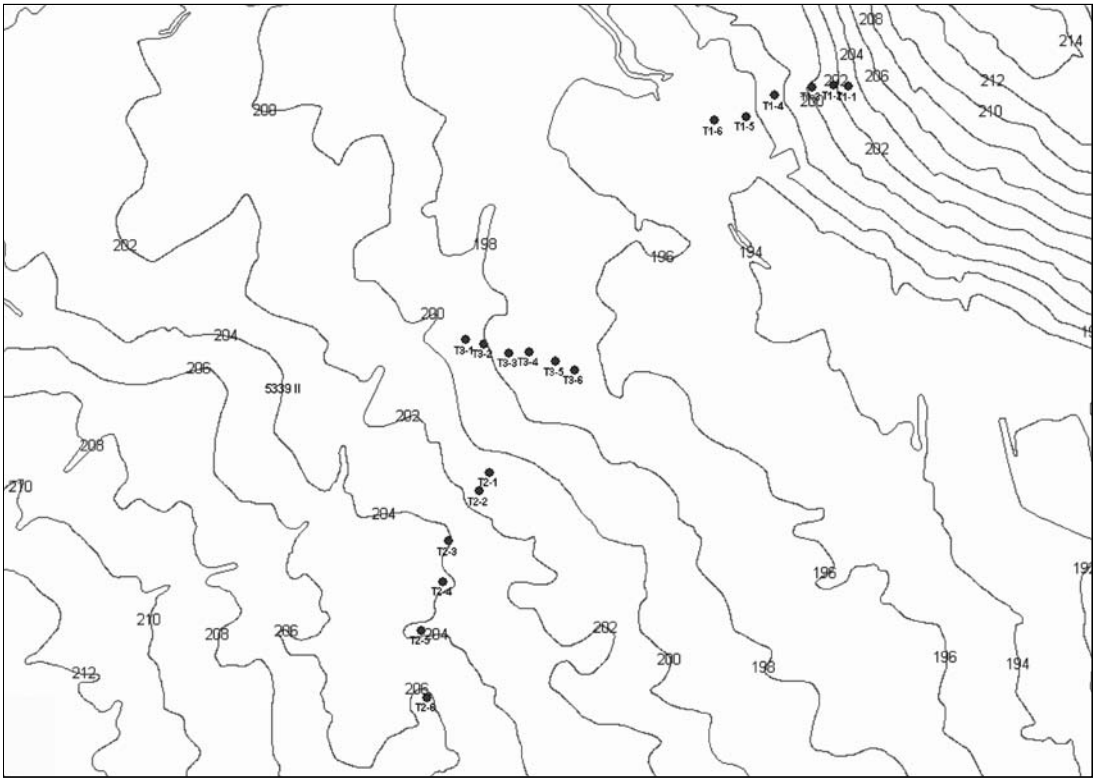

Figure 1 Sampling points of each transect and contour lines in the area studied. 5339 II = Topographic sheet number of Amphoe Dan Khun Thot, T1-1–T1-6 = Sampling points of tran-1, T2-1–T2-6 = Sampling points of tran-2, T3-1–T3-6 = Sampling points of tran-3.

Preparation of soil samples and methods of soil analyses

The composite soil samples collected were air dried, crushed and sieved passing through a 2 mm sieve for soil physical and chemical analyses while those ground and passed through a 0.5 mm sieve were used for the analysis of SOC. Core samples were oven dried at 105 °C until their weights were constant before measuring the BD (Blake and Hartge, 1986).

Prepared bulk soil samples were used for a determination of particle size distribution using the pipette method after removing the organic matter with H_2O_2 (Gee and Bauder, 1986). Soil pH was determined by a 1:1 ratio of soil to solution in H_2O with a pH meter (National Soil Survey Center, 1996). Organic carbon was determined according to the Walkley and Black wet oxidation procedure (Walkley and Black, 1934; Nelson and Sommers, 1996). Total N was measured basing on the semi-micro Kjeldahl digestion procedure (National Soil Survey Center, 1996). Soil was extracted by the Bray II method and subsequently the available phosphorus content was determined by the molybdate blue method (Bray and Kurtz, 1945). Extractable Na, K, Ca and Mg were leached from soil with NH_4OAc pH 7.0 and element concentrations measured by atomic absorption spectrometry (AAS) (Thomas, 1996). The cation exchange capacity (CEC) of soils was measured by saturating the exchange site in the soil sample and displacing with 1M NH_4OAC at pH 7, washing with alcohol and again displacing with 10% NaCl followed by titration (Chapman, 1965). Electrical conductivity (EC_e) was determined from the soil extract obtained at the saturated stage and measured using an EC meter (National Soil Survey Centre, 1996) and the same soil extract was used to determine the sodium adsorption ratio (SAR) in AAS (U.S. Salinity Laboratory Staff, 1954; National Soil Survey Centre, 1996). The exchangeable sodium percentage (ESP) was calculated from dividing the exchangeable [Na^+] by the sum of the exchangeable bases multiplied by 100 (Thomas, 1996).

Statistical analysis

Analytical data were statistically analyzed using the SPSS analytical software package (version 16.0; SPSS Inc; Chicago, IL, USA) and Microsoft Excel 2010 software (Microsoft; Redmond, WA, USA) for correlation, regression, SD and coefficient of variation (CV) among soil properties. The relationship between different soil properties and C_{seq} was expressed using Pearson’s correlation coefficient.

RESULTS AND DISCUSSION

Light texture with low fertility and salinity and sodicity of different levels are common characteristics of soils in northeast Thailand (Ragland and Boonpuckdee, 1987; Kheoruenromne *et al.*, 1998), with no exception in the case of the soils in the study area. Variation in the physical and chemical properties of the soils studied as indicated by their mean, median, SD and CV are presented in Tables 1–6. The relationship among soil characteristics was also shown using a correlation matrix (Tables 4 and 6), all of which are described below.

Physical properties of soil and their relationship to carbon sequestration

Soil particle size distribution

Soils in the areas selected were dominated by coarse particles, having a sandy to sandy clay loam texture. Among the 72 samples, there were 22 loamy sands and 48 sandy loams. It was found that silt particles had the widest range (2.77–22.46%) with a mean value of 10.41, SD of 5.24 and CV of 50% (Figure 2 (b) and Table 1), whereas the sand content in these soil samples was rather constant with a CV of only 6%. Most soils of tran-1 were loamy sands, whereas soils of tran-2 and tran-3 had slightly heavier textures (sandy loam) together with a gradual decrease of the percentage sand (%sand) values from the upper part of tran-1 to the

Table 1 Mean, median, minimum, maximum, range, SD and coefficient of variation (CV) of soil physical properties at the surface (0–15 cm).

Property	BD (Mg.m^{-3})	%sand	%silt	%clay	%silt+clay
Mean	1.60	79.23	10.41	10.36	20.05
Median	1.49	78.41	10.62	10.97	21.59
Minimum	1.48	64.46	2.77	6.33	11.30
Maximum	1.78	88.70	22.46	18.57	35.54
Range	0.30	24.24	19.69	12.24	24.24
SD	0.09	7.24	5.24	3.44	7.24
CV	0.06	0.09	0.50	0.33	0.36

BD = Bulk density.

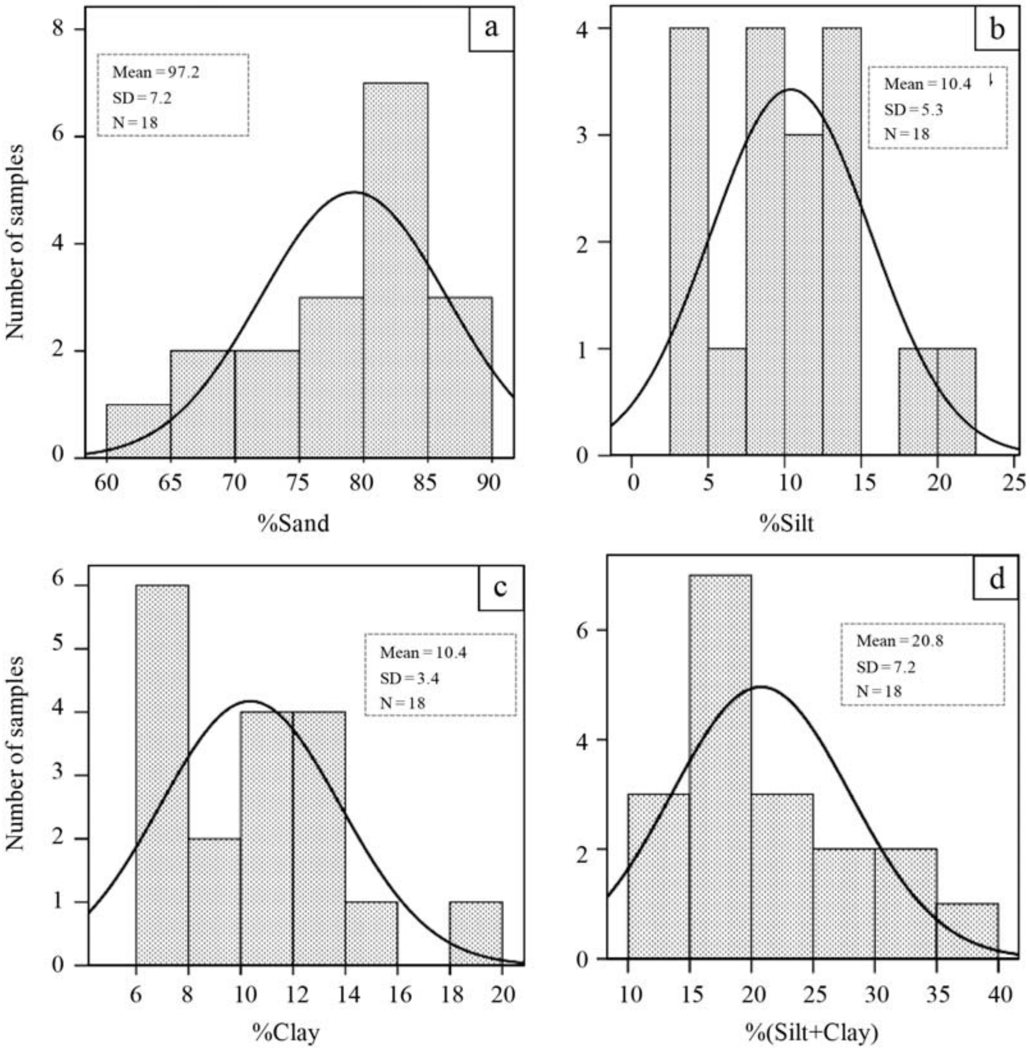

Figure 2 Variability of particle size distribution: (a) %sand; (b) %silt; (c) %clay; and (d) %silt+clay in surface soils (0–15 cm).

lower part of tran-3, indicating that finer particles from the upper part were removed by the erosion process to be deposited in the lower part of the landscape.

The pattern of particle size distribution with depth was rather similar among the soils studied. The amount of finer soil particles (%silt+clay) was lower in the soil surface (0–15 cm) and steadily increased with increasing depth to the highest content at a depth between 45 and 60 cm (Figure 3). This trend was a clear indication of eluviation of finer particles through leaching from the top soil to the subsoil making the surface soils sandier in nature (Buol *et al.*, 2011).

The distribution of individual soil particles did not show any significant relationship with C_{seq} (Table 6). However, the result was consistent with the finding of Hassink (1994) who pointed out that the relationship of texture with OC is unclear, and organic matter in a sandy soil makes this relationship confusing with soil texture. As differences of individual soil particles did not create much variation in the soil textural classes, the particle size distribution might fail to produce a significant relationship with SOC_{seq}. This finding suggests that soil management and an addition of organic carbon through crop residues or manures are rather more important than soil texture in the case of sequestering more carbon in the soil. The %silt+clay together showed a positive correlation with SOC_{seq} except for on tran-1. This revealed that SOC_{seq} increased or decreased with the same trend of increasing or decreasing %silt+clay. It can be stressed that the %silt+clay fraction of a soil type is a better predictor of SOC_{seq} in the soil, as previously reported (Parton *et al.*, 1987)

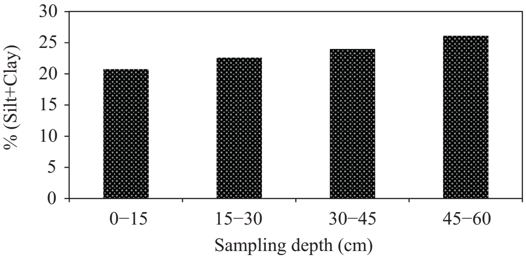

Figure 3 Amount of finer soil particles (%silt+clay) at different depths.

Bulk density

Little variation (CV only 6%) in the BD was observed among the soils having low to high status with values ranging from 1.20 to 1.97 $Mg.m^{-3}$, and a mean value of 1.67 $Mg.m^{-3}$ and an SD of 0.09 (Table 1). The average values of BD in each transect were similar with almost identical values of 1.68, 1.64 and 1.68 $Mg.m^{-3}$ for tran-1, tran-2 and tran-3, respectively. Surface soils had slightly lower BD than did subsoils and the trend showed that the value increased to a depth between 30 and 45 cm and then decreased slightly in the underlying layer (45–60 cm). For all samples, the average values of BD were 1.60, 1.70, 1.69 and 1.68 $Mg.m^{-3}$ for soil samples collected from 0–15, 15–30, 30–45 and 45–60 cm depths, respectively (Table 2). However, these results were inconsistent with the findings of Laopoolkit (2011) which might be due to a difference in the types of land use leading to different soil management, especially in the areas used for growing paddy rice. This is in addition to the presence of Na that is common in the areas studied.

A negative correlation ($r = -0.26^*$, where * indicates the correlation is significant at the 0.05 probability level) was observed between the BD and $SOC_{seq,}$ (Table 6), which was corroborated by the report of Berhangoray *et al.* (2013) where a highly negative correlation was found between the BD and SOC. A different result was observed by Steller *et al.* (2008), who reported a weak, positive relationship between BD and SOC in cropland soil and it was pointed out that BD is very specific to location and land use and it is unwise to consider BD as a single factor affecting storage of SOC because it is related to several soil properties such as particle size distribution, soil aggregate, hydraulic conductivity. In this study, a reduction in the porosity as indicated by an increase in the BD is an unfavorable condition for plant root distribution, thus resulting in a limitation of SOC accumulation in the soil. In this study, positive and negative correlations of some other soil properties with BD were also observed. For example, the CEC, base saturation percentage (%BS), ESP and %clay were found to be positively correlated with BD ($r = 0.26^{*}$, 0.31^{**}, 0.28^{*} and 0.23^{*}, respectively, where ** indicates the correlation is significant at the 0.01 probability level) as shown in Table 6. In contrast, %sand had a negative correlation with BD ($r = -0.28^{*}$).

Chemical properties of soil and their relationship with carbon sequestration

Soil pH

The pH values of the soils (saturated extract of soil:H_2O, 1:1) varied from extremely acid to very strongly alkaline (pH 3.81–10.23). The pH values of soils in tran-1 and tran-2 were acidic, whereas the soils in tran-3 had an alkaline condition. The mean values of soil pH in each transect were 5.88, 5.10 and 8.91 for tran-1, tran-2 and tran-3, respectively (Table 5). The pH values for soils with respect to depth were 6.45, 6.77, 6.67 and 6.65 at 0–15, 15–30, 30–45 and 45–60 cm, respectively, (Table 5), indicating a lower pH in the surface soil and a slightly higher pH in the subsoil.

Table 2 Average values of bulk density, particle size distribution and carbon sequestration (C_{seq}) in soil samples collected from different depths in different transects (tran-1, tran-2 and tran-3).

Transect	Depth (cm)	BD ($Mg.m^{-3}$)	Sand	Silt	Clay	C_{seq} ($Mg\ C.ha^{-1}$)
				%		
Tran-1	0–5	1.61	82.50	9.41	8.21	10.56
Tran-2		1.57	76.20	10.40	13.30	7.74
Tran-3		1.62	79.00	11.40	9.60	4.82
Average		1.60	79.20	10.40	10.40	7.71
Tran-1	15–30	1.69	80.50	9.75	9.77	5.31
Tran-2		1.64	77.00	9.83	13.20	5.50
Tran-3		1.76	74.70	12.90	12.40	2.75
Average		1.69	77.40	10.80	11.80	4.52
Tran-1	30–45	1.72	79.90	9.98	10.10	3.60
Tran-2		1.70	75.10	10.40	14.50	4.42
Tran-3		1.68	71.50	14.70	12.20	1.97
Average		1.70	76.00	11.80	12.30	3.33
Tran-1	45–60	1.70	79.00	9.88	11.10	3.21
Tran-2		1.66	71.60	12.70	15.70	4.89
Tran-3		1.68	71.00	15.10	13.90	1.82
Average		1.68	73.90	12.60	13.60	3.30
Transect Average	Tran-1	1.68	80.50	9.78	9.79	5.67
	Tran-2	1.64	75.00	10.80	14.20	5.63
	Tran-3	1.68	74.10	13.50	12.00	2.84
Overall Average	0-60	1.66	76.60	11.40	12.00	4.71

The pH value showed a negative correlation with carbon sequestration (r = -0.60$^{**)}$ which agreed well with the findings of Berhangoray *et al.* (2013). This property also had a positive correlation with BD, EC_e, CEC, SAR, ESP and available K with r values of 0.27*, 0.47**, 0.67**, 0.52**, 0.78** and 0.27*, respectively (Table 6). The highly positive correlation of pH with SAR indicated that Na^+ plays a critical role in determining the pH of these soils. However, this ion has a negative impact on plant growth, as in its presence, a high amount of SOC_{seq} is rarely found.

Total nitrogen

The amount of nitrogen was very low in all soils studied, ranging from 0.05 to 0.95 g.kg^{-1} with an average value of 0.02 g.kg^{-1}, SD of 0.015 and CV of 69% (Table 3). There was a slight variation among transects with average values of 0.22, 0.25 and 0.18 g.kg^{-1} for tran-1, tran-2 and tran-3, respectively (Table 4). A decreasing trend of total N content with an increase in depth from the soil surface was observed throughout the study area with the average content in soils from all transects being 0.34, 0.20, 0.18 and 0.16 g.kg^{-1} at depths of 0–5, 15–30, 30–45 and 45–60 cm, respectively. This indicates the impact of short rooted plants grown in the area that contribute N stored in their biomass in association with the poor fertility status of the soils that rarely contributes to a substantial amount of OM in the area.

Total N showed a highly positive correlation (r = 0.58**) with C_{seq} (Table 6), which was similar to the study of Wong *et al.* (2008). A positive correlation was also found with available P (r = 0.24*) and K (r = 0.31**). However, the pH, BD and SAR (r = -0.31*, -0.39** and -0.31*, respectively) each had a negative correlation with this major plant nutrient.

Organic carbon

The soils studied were very infertile, resulting in very low amount of organic carbon content in these soils. The contents ranged between 0.10 and 8.60 g.kg^{-1} with a mean value of 3.26 g.kg^{-1} (Table 4). Soils of tran-1 and tran-2 had higher contents of SOC (2.34 and 2.31 g.kg^{-1}, respectively) than did tran-3 (1.14 g.kg^{-1}) as shown in Table 5. The low input of plant material in the soils of tran-3 and the adverse soil conditions were the main causes the low concentration of SOC in this case (Wong *et al.*, 2008). The average amount of SOC decreased gradually to a depth of 30–5 cm (3.26, 1.82, 1.32 and 1.32 for depths of 0–15, 15–30, 30–45 and 45–60 cm, respectively). This was a clear indication of the SOC accumulation in the surface soil, which is a normal phenomenon in tropical soils (Buol *et al.*, 2011).

It was not surprising that there was a highly positive correlation between SOC_{seq} and SOC ($R^2 = 0.99^{**}$) as shown in Figure 4. However, the slope of this correlation was not that steep, indicating that the BD values of these soils were

Table 3 Mean, median, minimum, maximum, range, SD and coefficient of variation (CV) of chemical properties of surface soils (0–15 cm).

Properties	OC	Total N	Avail. P	Avail. K	pH	EC_e	SAR	CEC	ESP	SOC_{seq}
	(----g.kg^{-1}----)		(----mg.kg^{-1}-----)			(dS.m^{-1})		(cmol$_c$.kg^{-1})	(%)	(Mg C.ha^{-1})
Mean	3.26	0.34	7.19	37.40	6.50	14.79	1319	4.86	84.05	7.82
Median	2.85	0.30	21.60	79.60	5.50	1.17	5.49	5.00	6.46	6.32
Minimum	0.80	0.05	1.14	6.20	4.30	0.16	1.64	2.25	3.34	2.06
Maximum	8.60	0.95	26.20	120.00	10.00	110.60	11313	7.50	447.70	19.60
Range	7.80	0.90	25.00	114.00	5.90	110.44	11311	5.25	444.30	17.54
STD	1.81	0.23	7.14	32.30	1.90	31.59	3609	1.52	131.70	4.15
CV	0.56	0.69	0.99	0.86	0.30	2.14	2.76	0.31	1.57	0.53

mostly high, as mentioned earlier, resulting in a higher weight of soil particles in the samples. According to Laopoolkit (2011), soils in that study area had a lower BD, resulting in the correlation between the total C and SOC showing a steeper slope (y = 0.92x+1.26).

Available phosphorous and potassium

The available P content in the soils studied varied from very low to high with the values ranging from 0.51 to 26.17 mg.kg^{-1}. In nearly 75% of the samples (54 out of 72), the amount of this nutrient ranged between 0 and 5.0 mg.kg^{-1} (Figure 5a). The average value of the available P content for all 72 samples was 4.88 mg.kg^{-1} with an SD of 6.244, whereas the average value in the surface soil (0–5 cm) was 7.19 mg.kg^{-1} with an SD of 7.135 (Figure 5c).

The range in the available K content in the soils was also broad, being from very low to very high (4.4–20.19 mg.kg^{-1}). The average value for all samples was 30.93 mg.kg^{-1} with an SD of 34.933 (Figure 5b). This nutrient was stored more in the surface layer (0–5 cm) being 37.43 mg.kg^{-1} with an SD of 32.281 (Figure 5d). Apparently, the average value rarely explained the current status of available K in these soils because there were only four samples that had an available K content in the range 80–200 mg.kg^{-1} and these values influenced

Table 4 Average value of soil chemical properties in each transect.

Transect	Depth (cm)	OC	TN	Avail. P	Avail. K	pH	EC$_e$ dS.m^{-1}	CEC cmol$_c$.kg^{-1}	ESP	SOC$_{seq}$ (MgC.ha^{-1})
		(----g.kg^{-1}----)		(-----mg.kg^{-1}-----)						
Tran-1	0–15	4.44	0.40	7.59	47.9	5.81	11.5	4.46	70.4	10.56
Tran-2		3.31	0.31	11.9	42.1	5.30	0.72	5.29	6.90	7.74
Tran-3		2.03	0.31	2.10	22.3	8.24	32.2	4.83	175	4.82
Average		3.26	0.34	7.19	37.4	6.45	14.8	4.86	84.1	7.71
Tran-1	15–30	2.17	0.21	5.34	26.7	5.89	3.37	4.00	42.4	5.31
Tran-2		2.24	0.24	8.70	27.3	5.21	0.45	4.92	6.41	5.50
Tran-3		1.06	0.15	1.40	22.8	9.21	12.2	7.54	117	2.75
Average		1.82	0.20	5.14	25.6	6.77	5.34	5.48	55.3	4.52
Tran-1	30–45	1.45	0.13	4.40	23.8	5.90	2.59	4.50	37.5	3.60
Tran-2		1.75	0.24	6.14	20.3	5.02	0.40	4.96	7.17	4.42
Tran-3		0.77	0.17	1.01	53.1	9.10	9.41	7.54	116	1.97
Average		1.32	0.18	3.85	32.4	6.67	4.13	5.66	53.6	3.33
Tran-1	45–60	1.32	0.16	3.38	19.2	5.95	2.08	5.54	33.1	3.21
Tran-2		1.95	0.22	5.60	19.7	4.90	0.52	5.63	9.21	4.89
Tran-3		0.70	0.10	1.02	45.9	9.12	8.65	8.00	106	1.82
Average		1.32	0.16	3.33	28.3	6.65	3.75	6.39	49.4	3.30
Transect average	Tran-1	2.34	0.22	5.17	29.4	5.88	4.88	4.62	45.9	5.67
	Tran-2	2.31	0.25	8.08	27.4	5.10	0.52	5.20	7.42	5.63
	Tran-3	1.14	0.18	1.38	36.0	8.91	15.6	6.97	129	2.84
Overall average	0–60	1.93	0.22	4.87	30.9	6.63	9.34	5.59	60.6	4.71

the mean value, whereas more than 50% of the samples had an available K content in the range 0–20.0 mg.kg^{-1}.

The average amounts of available P and K in the soils of each transect were rather the same. These two plant nutrients were available in the soils of tran-3 (1.38 and 36.0 mg.kg^{-1}, for P and K, respectively) seemed to be slightly higher than in the soils of tran-1 and tran-2 (Table 4). The variation of available P within the same transect, that is in different positions in the landscape, and among transects indicated a clear effect of land use which, in turn, reflected different fertilizer management. Fruit trees and eucalypt plantations that dominated the land use in tran-1 showed higher amounts of available P due to the high input of litter and root exudates, whereas a residual effect of fertilization in the soils of tran-2 that were used

Table 5 Correlation between organic carbon (OC) and extractable cations.

Properties	OC	Na^+	K^+	Ca^{2+}	Mg^{2+}
OC	1.00				
Na^+	-.481**	1.00			
K^+	-.001	-.036	1.00		
Ca^{2+}	.068	.128	.081	1.00	
Mg^{2+}	.217	-.135	.049	.846**	1.00

** = Correlation is significant at 0.01 probability level.

Table 6 Correlation matrix of soil physico-chemical properties with soil organic carbon sequestration.

Property	TN	pH	BD	EC^e	CEC	SAR	ESP	% Sand	% Silt	% Clay	Avail. P	Avail. K	SOC_{seq}
TN	1.00												
pH	-.31**	1.00											
BD	-.39**	.27*	1.00										
EC_e	-.12	.47**	.22	1.00									
CEC	-.17	.67**	.26*	.21	1.00								
SAR	-.31**	.52**	.16	.87**	.25*	1.00							
ESP	-.22	.78**	.27*	.89**	.39**	.81**	1.00						
% Sand	-.04	-.23	-.28*	-.11	-.68**	-.04	-.13	1.00					
% Silt	-.07	.20	.21	.31**	.53**	.26*	.25*	-.84**	1.00				
% Clay	-.03	.15	.23*	-.21	.53**	-.28*	-.10	-.70**	.19	1.00			
Avail. P	.24*	-.20	-.05	-.07	-.10	-.15	-.22	-.02	-.02	-.02	1.00		
Avail. K	.31**	.27*	-.16	.05	.22	-.08	.13	-.07	.02	.10	.39**	1.00	
SOC_{seq}	.58**	-.6**	-.26*	-.17	-.38**	-.29*	-.41**	.12	.00	-.22	.27*	.05	1.00

TN = Total nitrogen, BD = Bulk density, EC_e = Electrical conductivity, CEC = Cation exchange capacity, SAR = Sodium adsorption ratio, ESP = Exchangeable sodium percentage, Avail. P = Available phosphorous, Avail. K = Available potassium, SOC_{seq} = Carbon sequestration.

*. = Correlation is significant at 0.05 probability level, **. = Correlation is significant at 0.01 probability level for growing cassava, corn and tree plantation also contributed to the higher levels of available P. In contrast, the lowest content was found in tran-3 where bare land and paddy fields were dominant. A high concentration of Na$^+$ is likely to be the cause of retardation in the accumulation of P.

Variation was also observed in both the available P and available K with respect to soil depth. The average value of available P decreased with increasing depth from the soil surface, whereas the average content of available K distribution had an irregular pattern within soil depth. The availability of both plant nutrients in the soils studied was unsurprisingly higher in the top 0–5 cm of these soils (Figure 6).

The available P had a positive correlation ($r = 0.27^*$) with SOC$_{seq}$ as corroborated by the study of Hou *et al.* (2014), whereas available K showed no relationship (Table 6). In addition, the availability of both plant nutrients showed a highly positive correlation with each other ($r = 0.39^{**}$) as shown in Table 6.

In the context of major plant nutrients, and of total nitrogen and available phosphorus in particular, although they had a highly positive and positive correlation with SOC$_{seq}$, respectively, the impact of these two nutrients on the accumulation of SOC in these soils was small because their amounts were mainly in the range of low to very low. Low amounts of SOC, total nitrogen and available phosphorus are quite common as shown by Anusontpornperm *et al.* (2005 and 2009) in the cassava-growing soils of northeast Thailand.

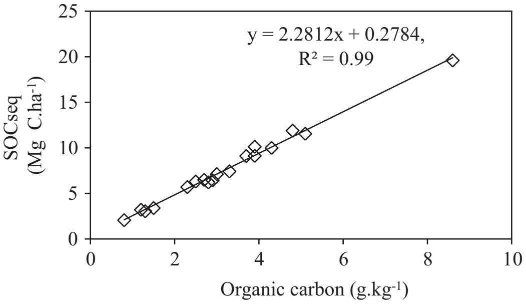

Figure 4 Correlation and regression coefficient (R^2) between carbon sequestration (SOC$_{seq}$) and organic carbon.

Cation exchange capacity

The CEC of the soils studied was very low to moderately low with the values ranging from 2.25 to 9.0 cmol$_c$.kg^{-1}. The mean value of the CEC for all the 72 samples was 5.60 cmol$_c$.kg^{-1} with an SD of 2.02 (Figure 7a), whereas for the topsoil (0–5 cm) the mean and SD were 4.86 and 1.52 cmol$_c$.kg^{-1}, respectively (Figure 7b). The sandy nature of the soils with low clay and organic matter contents was responsible for the soils in all areas having a low CEC.

The CEC values of the soils of the three transects showed little variation both within the same transect and between transects, although the soils of tran-3 comprised slightly greater CEC values than did the other two transects (Table 4). With increasing depth, the CEC values increased with the exception of values obtained from soils at a depth of 15–0 cm in tran-1, where the values decreased slightly (Figure 8). This trend is indicative of the relationship between the CEC and clay content in the study area as has also been reported elsewhere (Laopoolkit, 2011).

In this study, the CEC had a highly negative correlation ($r = -0.38^{**}$) with SOC$_{seq}$ which was inconsistent with the findings of Laopoolkit (2011) where a positive correlation between CEC and C$_{seq}$ was reported. There might be differences in the clay content and type of clay mineral in both studies. The CEC of soils in this study had a positive correlation with SAR ($r = 0.25^*$) and a highly positive correlation with %BS, ESP, %silt and %clay ($r = 0.71^{**}$, 0.39^{**}, 0.53^{**} and 0.53^{**}, respectively). A highly negative correlation was found when CEC was paired with %sand, having an r value of -0.68^{**} (Table 6), which was not surprising because the high sand content in the soils generally possessed a low CEC due to the particles having no charge. However, there could be other factors, such as a high salt content and limited rainfall that result in a high CEC but a low SOC$_{seq}$.

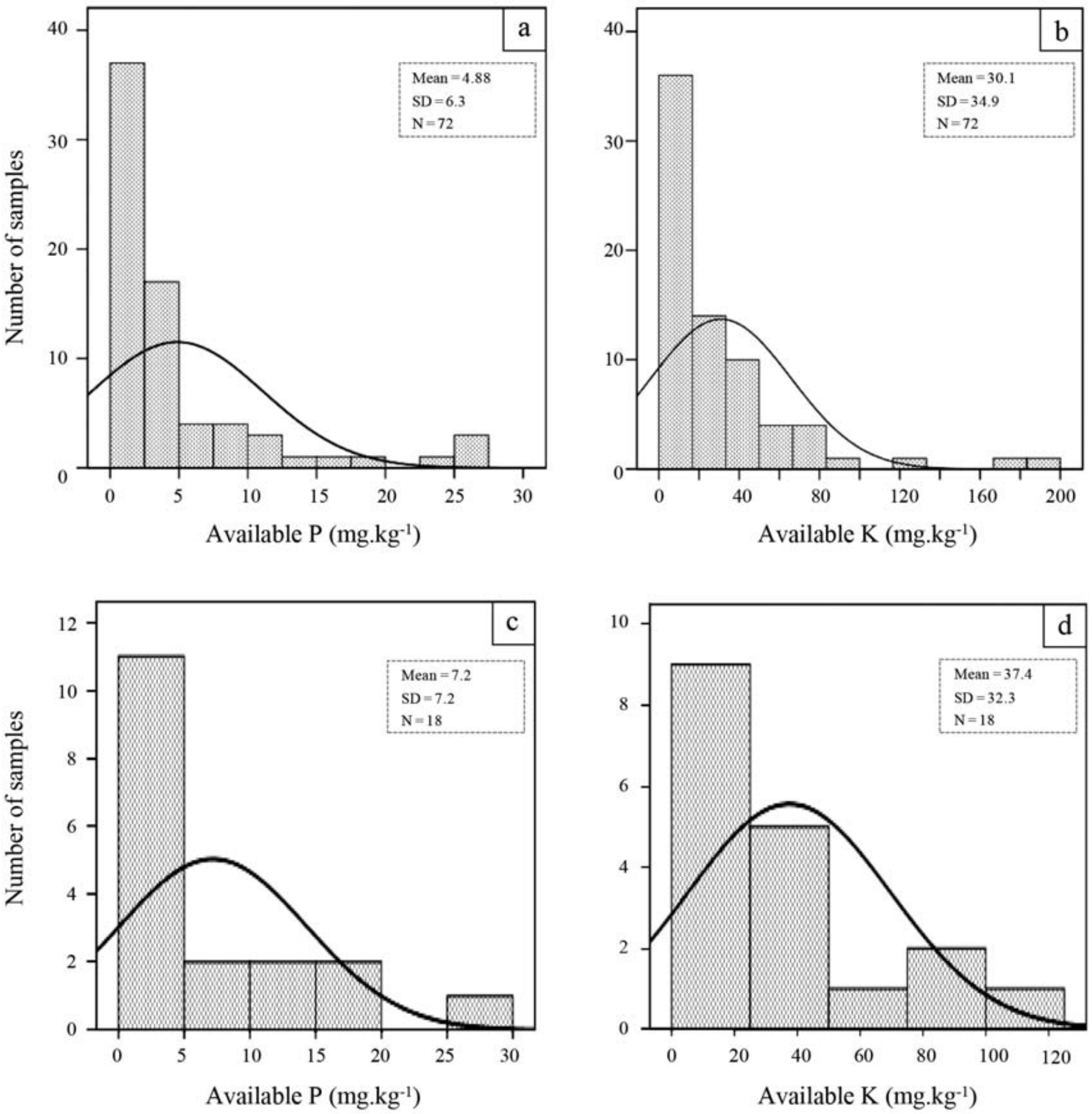

Figure 5 Variability of available P and K of: (a and b) whole soils; and (c and d) topsoil (0–5 cm).

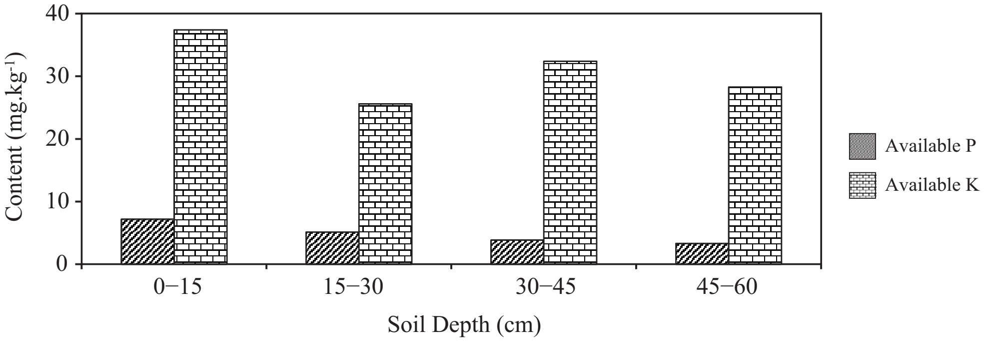

Figure 6 Average content of available P and K in the soils studied.

Electrical conductivity

A wide range of EC_e values (0.07–10.6 $dS.m^{-1}$) was observed with an average value of 7.0 $dS.m^{-1}$ in the soils of the study area, where surface soils had a higher mean value of 14.78 $dS.m^{-1}$ (Table 3). The range and average values of EC_e barely explained the general condition of EC_e in the soils because the range was too wide and the average value was too high due mainly to more than 85% of the soil samples having EC_e values in the range 0–10.0 $dS.m^{-1}$, while nearly 78% of samples collected were below 1.0 $dS.m^{-1}$(Figure 9a). In addition, there were only a few extreme EC_e values (10–12% of the total number) in between 10 and 110.6 $dS.m^{-1}$.

The average EC_e values in the soils of tran-1, tran-2 and tran-3 were 4.88, 0.52 and 15.6 $dS.m^{-1}$, respectively (Table 4). The soils of tran-2 were non-saline. There was only one sample collected from paddy field situated in the lowest position of tran-1 that had high salt accumulation in the surface layer (57.9 $dS.m^{-1}$). Substantial amounts of salt were found that had accumulated on the surface of bare land areas in tran-3 (110.6 and 72.01 $dS.m^{-1}$). The EC_e values of the soils studied tended to decrease with increasing depth. The average EC_e values of soils at respective depths of 0–5, 15–30, 30–45 and 45–60 cm were 14.8, 5.34, 4.13 and 3.75 $dS.m^{-1}$, respectively. The extremely dry conditions as a result of the very hot weather prevailing over the study area might have been the cause of capillary upward movement of salts to accumulate in the upper horizons, resulting in very high EC_e values in the topsoil.

The EC_e had no significant correlation with SOC_{seq} in this study, which agreed with the study carried out by Berhangoray *et al.* (2013), but an antagonistic relationship was observed between EC_e and SOC_{seq}. A strong negative, significant correlation between Na^+ and SOC (Table 5) clearly supported this relationship. However, this analytical data had a highly positive correlation with SAR, ESP and %silt (r = 0.87^{**}, 0.89^{**} and 0.31^{**}, respectively) as shown in Table 6. Apart from SAR and ESP that are in fact closely related to the EC value, %silt showed a surprisingly close relationship with EC_e.

Sodium adsorption ratio

A wide variation in the values of SAR was observed in the studied soil samples, having values

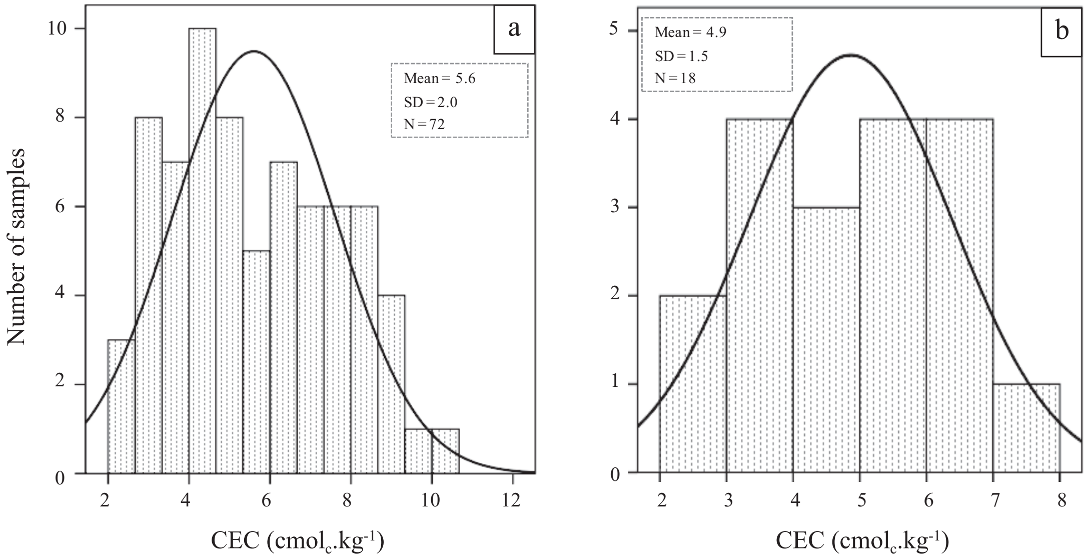

Figure 7 Variability of cation exchange capacity (CEC) of: (a) whole soil (0–60 cm); and (b) topsoil (0–15 cm).

ranging from 1.64 to 11,313.66; nonetheless, there were more than 50% of soil samples where the values were in the range 0–20.0 (Table 3). Extremely high values (847.96–1,313.66) of SAR were detected from the samples collected from the bare land located in the lowest position on the landscape where soluble salts had been removed from the upper parts and deposited on this area in addition to the capillary rise of the salty ground water table that results in soluble salt precipitating in the topsoil.

A great variation of SAR values was observed within and among transects (Table 4). The soils of tran-1 and tran-2 generally had lower SAR values than tran-3. The parent material with a predominant Na^+ content is likely to be responsible for the contribution of very high SAR values in the soils of this transect. The trend with depth also indicated that SAR values were highest in the surface soil and decreased gradually with an increasing depth.

SAR had a negative correlation with SOC_{seq} with an r value of -0.29* (Table 6). High sodium salt causes dispersion of soil aggregates and favors rapid loss of OM in soil. Additionally, excessive sodium salt limits crop growth and subsequently affects SOC_{seq}. The same correlation as for EC_e with %silt was also found for SAR. Furthermore, this study also found a negative correlation between SAR and % clay (r = -0.28*).

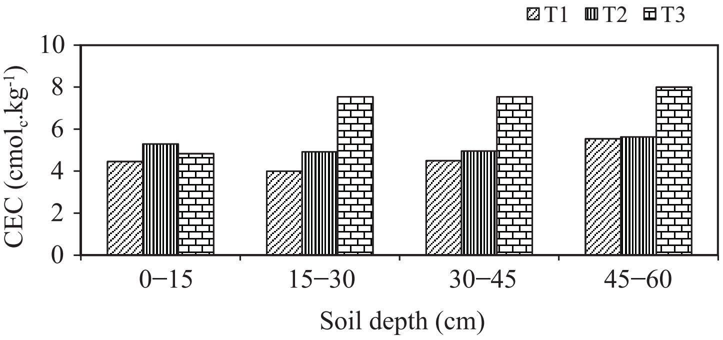

Figure 8 Cation exchange capacity (CEC) values at different depths among different transects (T1, T2 and T3).

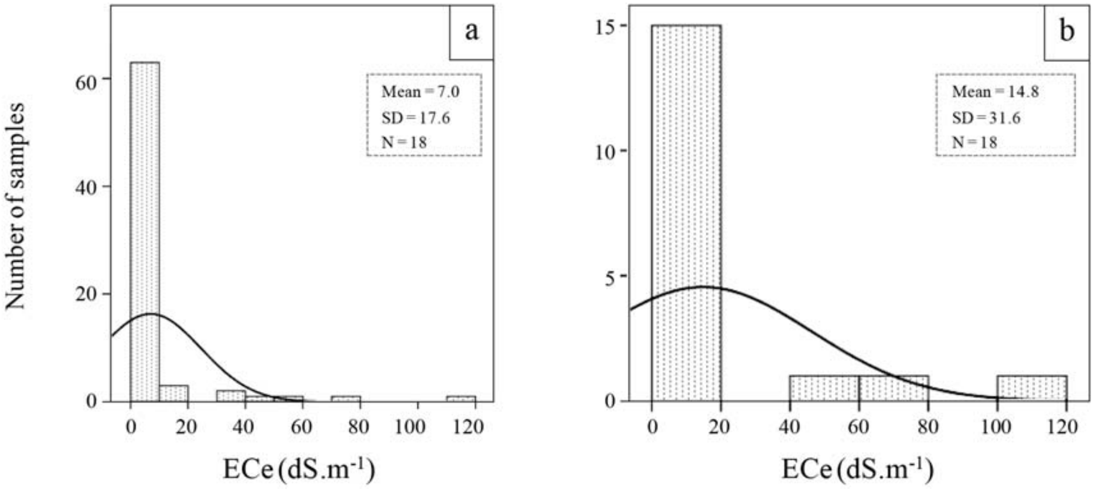

Figure 9 Variability of electrical conductivity (ECe) in: (a) all samples; and (b) topsoil (0–15 cm).

Exchangeable sodium percentage

The soils studied also had a very wide range of ESP, varying between 3.34 and 447.67 (Table 3). However, more than 50% of soil samples had ESP values in the range 0–10.0 with only 25% of the samples having values over 100.

The ESP values in the soils of tran-1 and tran-2 were very low with few exceptions but very high values were found in almost all the soil samples collected from tran-3 (Table 4). The average values were high (84.10) in the top 0–5 cm and those values of samples collected from other depths below were quite constant and lower (55.3, 53.5 and 49.4 at depths of 15–0, 30–45 and 45–60 cm, respectively).

ESP was highly negatively correlated ($r = -0.40^{**}$) with SOC_{seq}, as was also reported by Laura (1976), which could be explained by the excessive sodium salt dispersion and dissolution causing chemical hydrolysis of organic material leading to the storage of a very low amount of SOC in the soil. In a similar fashion to EC_e and SAR, ESP showed a positive correlation ($r = 0.25^{*}$) with %silt in the soils (Table 6).

CONCLUSION

The studied soils were sandy in nature, having textural classes of sandy loam and loamy sands with few exceptions throughout the study area, regardless of land use, topographical variation and depth in the soil profile. An increasing trend of finer particles (%silt+clay) was found with an increase in the soil depth. Variation was observed in the bulk density among the soils with a rating ranging from low to high and being slightly lower in the topsoils than in the subsoils.

A very low to low content of SOC and total N was observed with few exceptions. The available P and K contents were very low to high, although more than 50% of the samples contained low to very low contents of available P and K. Most soils were acidic to neutral, but salt affected soils had a very high soil pH. The amounts of SOC, total N, available P and K were high in topsoils and decreased with increasing depth. EC_e, SAR, and ESP also had the same trend, whereas, pH, BD, and CEC values increased with increasing depth in relation to the increase in finer soil particles.

Finer particles positively influenced SOC_{seq} in soils which were also observed in the total N, available P and K, while the pH and other exchange properties had a negative correlation. All negatively correlated soil variables, especially the high amount of sand particles and high concentration of Na^+ salt in the soils, prevailed in positively correlated variables owing to the latter being low in content in most soils. As a result, low OC_{seq} of soils in the study area was common.

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