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SOIL PHYSICAL AND CHEMICAL PROPERTIES UNDER FALLOW AND CROPPED AGRICULTURAL SYSTEMS IN OYAM DISTRICT, NORTHERN UGANDA

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ABSTRACT

Soil quality is an important component of agricultural systems, including those in Oyam District, northern Uganda. Yet, little is known about the soil properties in this region and how they may respond to different crop management practices. This study examined the physical and chemical properties of soils collected agricultural fields in Oyam District, northern Uganda that were subjected to fallow or cropping. Soils under fallow exhibited greater ammonium-N concentrations and clay content compared to cropped soil. Although not statistically significant, fallow soils tended to have greater exchangeable calcium, cation exchange capacity and % base saturation. The upper 15 cm of the soils exhibited higher total C, total N, exchangeable cations, cation exchange capacity and % base saturation than underlying soil. The fallow period used in this study was very short; we recommend a longer fallow period to discern whether this practice shows longer-term benefits as compared to continuously cropped soil.

Keywords: Agricultural system, soil productivity, sub-Saharan Africa

INTRODUCTION

Sub-Saharan Africa is characterized by food insecurity, poverty, widespread malnutrition, environmental degradation which, in part, is due to "nutrient mining of generally old and nutrient-poor soils" (Bekunda *et al*., 2004). Soil is a key resource for crop production (Troeh *et al*., 1999) and its fertility is dynamic, determined by the interactions among chemical, biological, physical and anthropogenic processes (Bekunda *et al*., 2004). In East Africa, nutrient mining is among the highest in Sub-Saharan Africa with an estimated annual depletion rate of 41 kg nitrogen (N), 4 kg phosphorous (P), and 31 kg potassium (K) per hectare (Bekunda *et al*., 2004); this nutrient loss is due to crop residue removals, leaching, gaseous losses, surface runoff and erosion amongst other factors (Bekunda *et al*., 2004).

In Uganda, soil degradation is widespread though it varies in scale from region to region depending on farming practices, population pressure, and vulnerability of soil to erosion (Barungi *et al*., 2013). Technologies, such as terraces, contours, trenches, agroforestry, and planting of grass along contours and terraces, have been promoted in Uganda to help farmers control land degradation (Turinawe *et al*., 2015). Despite these land conservation measures crop yields continue to decline (Bekunda *et al*., 2004), due to low adoption rates of the technologies by farmers (Turinawe *et al*., 2015; Fungo *et al*., 2011). Addition of inorganic fertilizers and soil amendments are not common and the traditional practice of incorporating long fallows in agricultural systems has largely been eliminated or replaced by short fallows. Natural fallows involve retiring cultivated soil for a period of time so that naturally growing vegetation (e.g., grasses and shrubs) can help restore soil physical properties and natural fertility of soil (Blanco and Lal, 2008).

In northern Uganda, anecdotal information suggests that when crops are established in farmers' fields, crop growth/yields often vary significantly despite similar climate and growing conditions. Differences in soil properties may account for some observed differences in crop growth/yield. Thus, knowing the properties of soils, including their limitations, is an important agricultural issue. Such knowledge is essential in crafting appropriate soil conservation measures which should include integration of biological and socioeconomic factors in the region.

Numerous studies on properties of soil and their effects on crop production have been undertaken in Sub-Saharan Africa (e.g., Lal, 1988; Mustegi *et al*., 2012; and Muntaqa *et al*., 2013). However, very few studies have been conducted in Uganda. Furthermore, almost no (except Ssali, 2000) scientific studies have been conducted in northern Uganda to determine whether or not variability in crop yield is due to limitations in soil properties. More research is needed to determine if different cropping management strategies influence soil properties.

This paper reports on the physical and chemical properties of soils collected from short-term fallow and cropped agricultural fields in Kamdini Parish in Oyam District, northern Uganda in 2011. The specific objective of the study was determine the differences in soil properties between short-term fallow and cropped agricultural systems. The authors hypothesized that short-term fallow would not produce significant differences in key soil quality parameters relative to those in cropped soils.

MATERIALS AND METHODS

Study area

The study area of Kamdini Parish is located slightly north of the equator (2^{o}14'45"N, 32^{o}19'55"E) and is part of Oyam District, Northern Uganda. The landscape is characterized by savannah grasslands with scattered trees. *Erythrina abyssinica* Lam, a nitrogen-fixing tree, *Albizzia gummifera*, and speargrass (*Heteropogon contortus* L) dominate the landscape. The average daily temperature ranges from 20-30 ^{o}C. The two rainy seasons are March-May and September-November, with the average annual rainfall of 1440 mm. The predominant soil type in the region is ferrosolic sandy clay (Ollier, 1959), which typically fall within the Oxisol or Ferralsol FAO Soil Groups (Eswaran *et al*., 1997). These red soils are characterized by high iron and aluminium sesquioxides with subsequent high phosphorous retention (i.e., low availability to plants), low available water holding capacity, and poor overall productivity. They are highly weathered and acidic soils.

Farmers in Kamdini Parish, depending on their household circumstances, clear their land and continuously cultivate for a period of 3 to 6 months then it is abandoned and allowed to remain fallow for the same period and then move on to another plot on the land and repeat the same farming practice. Weeds, dominated mainly by speargrass, occupy the abandoned land under fallow system. Common crops in the region include finger millet, beans, pigeonpea, cowpea, groundnut, sesame (sim-sim), sorghum, maize, cassava, and sweet potatoes (Nangoti *et al*., 2004; Nuwategeka and Nyeko, 2017). These crops are grown during the two rainy seasons; harvested and cured when they mature. Legumes are typically harvested, cured, with some spent parts burned and its ash collected and procured to produce ash filtrate for cooking beans (Bergeson *et al*., 2016). Residues from other crops are normally left in farmers' fields as organic matter. It is common to find maize intercropped with legumes during the growing seasons in the study sites.

Experimental design and sample collection

Four sites (i.e., four fields – each ~0.25 ha) were randomly selected from a total of 18 sites for soil sample collection and analysis: Buga, Dog Abam A, Dog Abam B, and Dog Abam C. All sites were uniform in farming practices. The study involved two treatments at each of the four sites: fallow and cropped soils.

At each site, three locations were randomly selected for soil sampling from both fallow and cropped sections of the field. Since the soils were relatively uniform within the upper 30 cm of the soil profiles (i.e., no clear horizon designation), soil samples were collected by depth (rather than from horizon type) from 0-15 cm (designated as depth A) and 15-30 cm (depth B) depths. Thus, a total of 48 soil samples (n = 48 soil samples) were collected. Soil samples were collected using a coring device and were placed in clean plastic bags; each bag had approximately 300g of the soil sample. Samples were air-dried at room temperature soon after sampling to avoid N-mineralization and subsequent nitrate build-up. Dried samples were then shipped to the University of Northern British Columbia in Prince George, Canada for analysis.

Soil analyses

Particle size analysis was conducted on <2 mm air-dried samples using the pipette method (Kalra and Maynard, 1991). Hydrogen peroxide pre-treatment was not used because the soil samples contained less than 5% organic matter (Kalra and Maynard, 1991). Clays were separated from sand and silt through successive dispersion and gravity sedimentation following the principles of Stoke's Law. The sand fraction was separated from the silt fraction by wet sieving on a 53 μm sieve.

Soil pH was determined in deionized water and 0.01M $CaCl_2$ using 1:2 soil to solution (1 g : 2 mL) ratios and an electronic pH meter (Thermo Orion 550A). Available nitrogen (NO_3^--N + NH_4^+-N) was determined using the 2.0 M KCl method described by Kalra and Maynard (1991). A 1:10 soil to extractant ratio was shaken for 30 minutes and filtered using Whatman filter paper #42. The extracts were analyzed for mineral nitrogen via colorimetry using a Bran+Luebbe Auto Sampler 3. Chemical elements were analyzed using inductively coupled plasma-mass spectroscopy (ICP-OES/MS). Available phosphorus was estimated using the Bray P1-method (Kalra and Maynard 1991). Total C and N were determined by combustion using a Costech 4010 CHNSO analyzer).

Statistical analysis

We used linear mixed effects models to analyze the influence of management (cropped or fallow) and soil depth (A or B) on the abundance of each of the measured soil elements. An interaction term between management and soil depth was also specified. In each model site location (Buga, Dog Abam A, Dog Abam B, or Dog Abam C) was included as a random factor. Statistical analyses were performed using the CRan R package nlme (Pinheiro and Bates, 2000).

ISSN: 2455-6939

Volume:04, Issue:03 "May-June 2018"

Each model was fit using log-likelihood maximization. Significance of all tests was assessed at a p-value of 0.05. Pearson's correlation coefficient was performed to examine potential relationships between total soil carbon versus total soil N and cation exchange capacity. Potential relationships were also examined between soil pH (both methods) versus exchangeable Ca (the dominant cation) and cation exchange capacity. Significance of all tests was assessed at a p-value of 0.05.

RESULTS

Land management type (fallow versus cropped) only had minimal effects on soil properties (Table 1 and 2). Ammonium-N concentrations were significantly greater in fallowed fields as compared to cropped ones (Figure 1, Table 1 and 2). In contrast, nitrate-N and total available-N (sum of ammonium-N and nitrate-N) did not show a land management effect. There was a tendency for exchangeable Ca (Figure 2), cation exchange capacity (Figure 3) and percent base saturation (Figure 4) to be greater in fallow, as compared to cropped systems, but the p-values slightly exceeded $\alpha = 0.05$ (Table 2). Clay content was significantly greater in fallow versus cropped soils (Table 1 and 2).

ISSN: 2455-6939

Volume:04, Issue:03 "May-June 2018"

Table 1: Mean (and 1 standard deviation) of selected physical and chemical properties of soils collected from farmers' plots in Oyam District, Northern Uganda. All sites of similar management have been combined.

Parameter	Fallow (n=12)	Cropped (n=12)	Average (n=24)
	Depth A (0-15 cm)		
Sand (%)	68.07 (14.67)	67.94 (5.90)	68.01
Silt (%)	27.20 (13.67)	28.19 (5.00)	27.70
Clay (%)	4.75 (2.89)	3.87 (1.12)	4.31
pH (1:2 soil:H_2O)	5.99 (0.44)	6.06 (0.44)	6.03
pH (1:2 soil:$CaCl_2$ sol.)	5.57 (0.57)	5.52 (0.57)	5.55
Total soil C (%)	2.11 (0.48)	1.98 (0.53)	2.05
Total soil N (%)	0.15 (0.03)	0.14 (0.04)	0.15
C:N ratio	14.3 (1.1)	13.8 (1.2)	14.0
NH_4^+ -N (mg kg^{-1})	11.23 (3.22)	10.36 (2.05)	10.80
NO_3^- -N (mg kg^{-1})	5.21 (5.47)	4.06 (4.97)	4.64
Available N (mg kg^{-1})	16.44 (6.18)	14.42 (5.07)	15.43
Bray P (mg kg^{-1})	1.39 (1.94)	1.02 (2.26)	1.21
Exch. Na (cmol kg^{-1})	0.23 (0.11)	0.22 (0.09)	0.23
Exch. Mg (cmol kg^{-1})	2.62 (0.85)	2.42 (0.69)	2.52
Exch. K (cmol kg^{-1})	0.45 (0.32)	0.60 (0.47)	0.53
Exch. Ca (cmol kg^{-1})	9.51 (2.50)	8.17 (3.22)	8.84
Effective CEC ($cmol_c$ kg^{-1})	12.96 (3.02)	11.56 (3.97)	12.26
Base saturation (%)	98.84 (0.55)	98.35 (1.08)	98.60
	Depth B (15-30 cm)		
Sand (%)	49.28 (16.21)	48.73 (8.50)	49.01
Silt (%)	43.38 (14.99)	45.38 (7.56)	44.38
Clay (%)	7.35 (1.78)	5.89 (2.08)	6.62
pH (1:2 soil:H_2O)	5.22 (0.48)	5.04 (0.47)	5.13
pH (1:2 soil:$CaCl_2$ sol.)	4.53 (0.42)	4.36 (0.39)	4.45
total soil C (%)	0.89 (0.10)	0.89 (0.14)	0.89
total soil N (%)	0.08 (0.01)	0.08 (0.01)	0.08
C:N ratio	11.3 (1.5)	11.2 (1.3)	11.3
NH_4^+ -N (mg kg^{-1})	10.14 (3.95)	7.62 (1.83)	8.88
NO_3^- -N (mg kg^{-1})	4.96 (7.35)	4.10 (6.36)	4.53
Available N (mg kg^{-1})	15.10 (8.80)	11.72 (6.09)	13.41
Bray P (mg kg^{-1})	0.27 (0.41)	0.13 (0.10)	0.22
Exch. Na (cmol kg^{-1})	0.21 (0.06)	0.20 (0.08)	0.21
Exch. Mg (cmol kg^{-1})	1.81 (0.50)	1.72 (0.79)	1.77
Exch. K (cmol kg^{-1})	0.14 (0.11)	0.14 (0.09)	0.14
Exch. Ca (cmol kg^{-1})	5.65 (2.07)	4.41 (1.67)	5.03

ISSN: 2455-6939

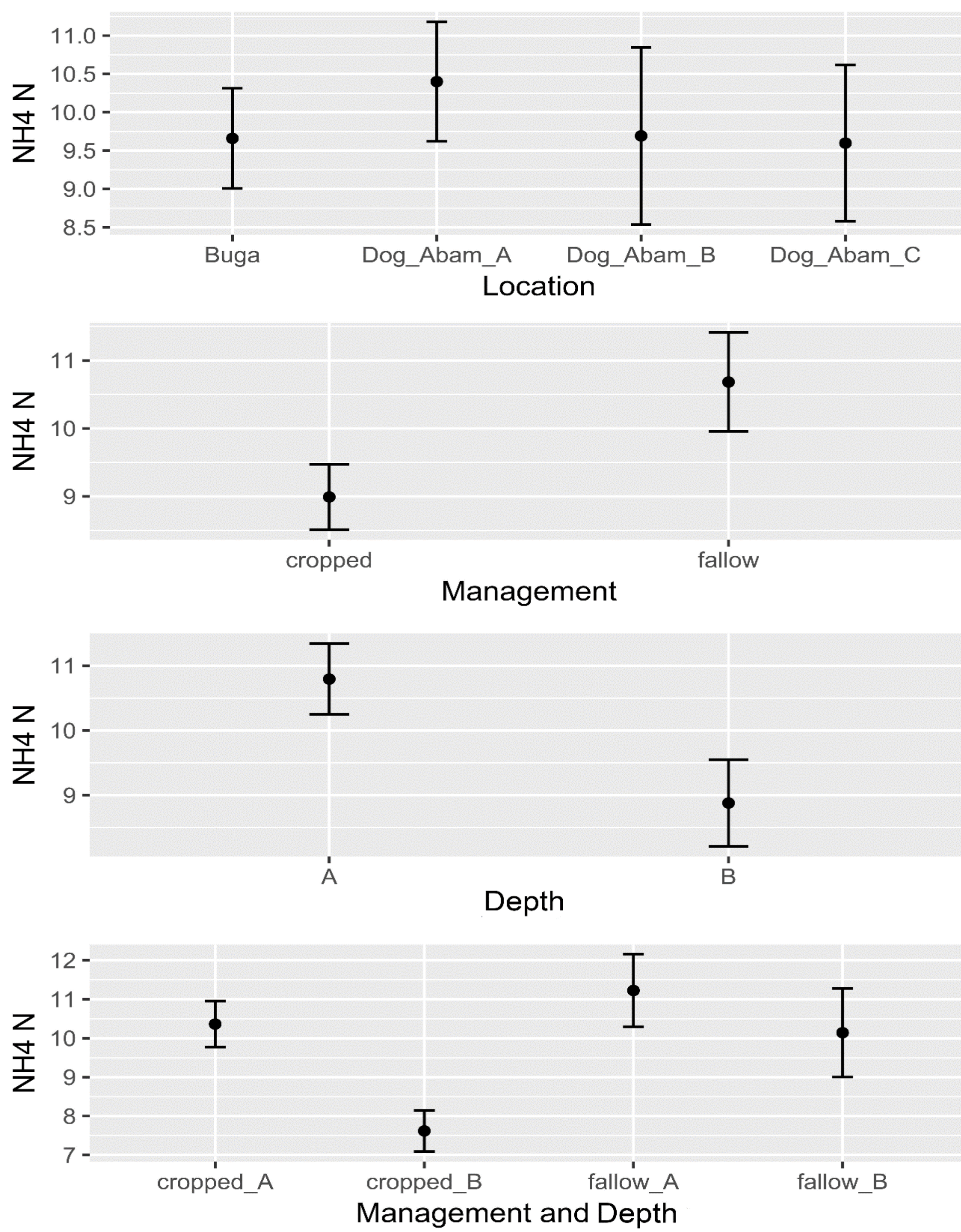
Volume:04, Issue:03 "May-June 2018"

Effective CEC (cmol$_c$ kg^{-1})	8.77 (2.06)	7.93 (2.16)	8.35
Base saturation (%)	88.73 (8.50)	80.76 (13.82)	84.75

Table 2: Results from linear mixed model analysis of land management (fallow, cropped), soil depth (A,B), and the interaction between management and soil depth. Significant effects ($p \leq 0.05$) are indicated in bold.

Variable	Management		Soil Depth		Management*Depth	
	F-value	p-value	F-value	p-value	F-value	p-value
Sand	0.02	0.9	51.42	**<0.001**	0.01	0.94
Silt	0.34	0.56	42.24	**<0.001**	0.04	0.84
Clay	6.23	**0.02**	24.29	**<0.001**	0.38	0.54
pH (H_2O)	0.24	0.62	61.83	**<0.001**	1.18	0.28
pH ($CaCl_2$)	0.74	0.39	70.77	**<0.001**	0.19	0.67
Total soil C	0.34	0.56	121.8	**<0.001**	0.34	0.56
Total soil N	0.03	0.86	86.6	**<0.001**	0.16	0.69
C:N ratio	0.72	0.4	61.06	**<0.001**	0.34	0.56
NH_4^+ -N	4.1	**0.05**	5.25	**0.03**	0.99	0.33
NO_3^- -N	0.35	0.56	<0.001	0.95	0.01	0.93
Avail. N	2.06	0.16	1.15	0.29	0.13	0.72
Bray P	0.15	0.7	6.12	**0.02**	<0.001	0.95
Exch. Na	0.13	0.72	0.49	0.49	0.03	0.87
Exch. Mg	0.88	0.35	22.2	**<0.001**	0.13	0.72
Exch. K	0.81	0.37	22.07	**<0.001**	0.93	0.34
Exch. Ca	3.82	0.06	33.29	**<0.001**	0.01	0.94
Effect. CEC	2.41	0.13	29.36	**<0.001**	0.16	0.7
Base Sat.	3.25	0.08	34.75	**<0.001**	2.53	0.12

Figure 1: Mean ammonium-N concentration in soil (mg NH_4^+ -N kg^{-1} soil); bars indicate +/- 1 standard deviation. Results are expressed on a dry weight basis.



International Journal of Agriculture and Environmental Research

ISSN: 2455-6939

Volume:04, Issue:03 "May-June 2018"

Figure 2: Mean exchangeable calcium (cmol kg^{-1} soil); bars indicate +/- 1 standard deviation. Results are expressed on a dry weight basis.

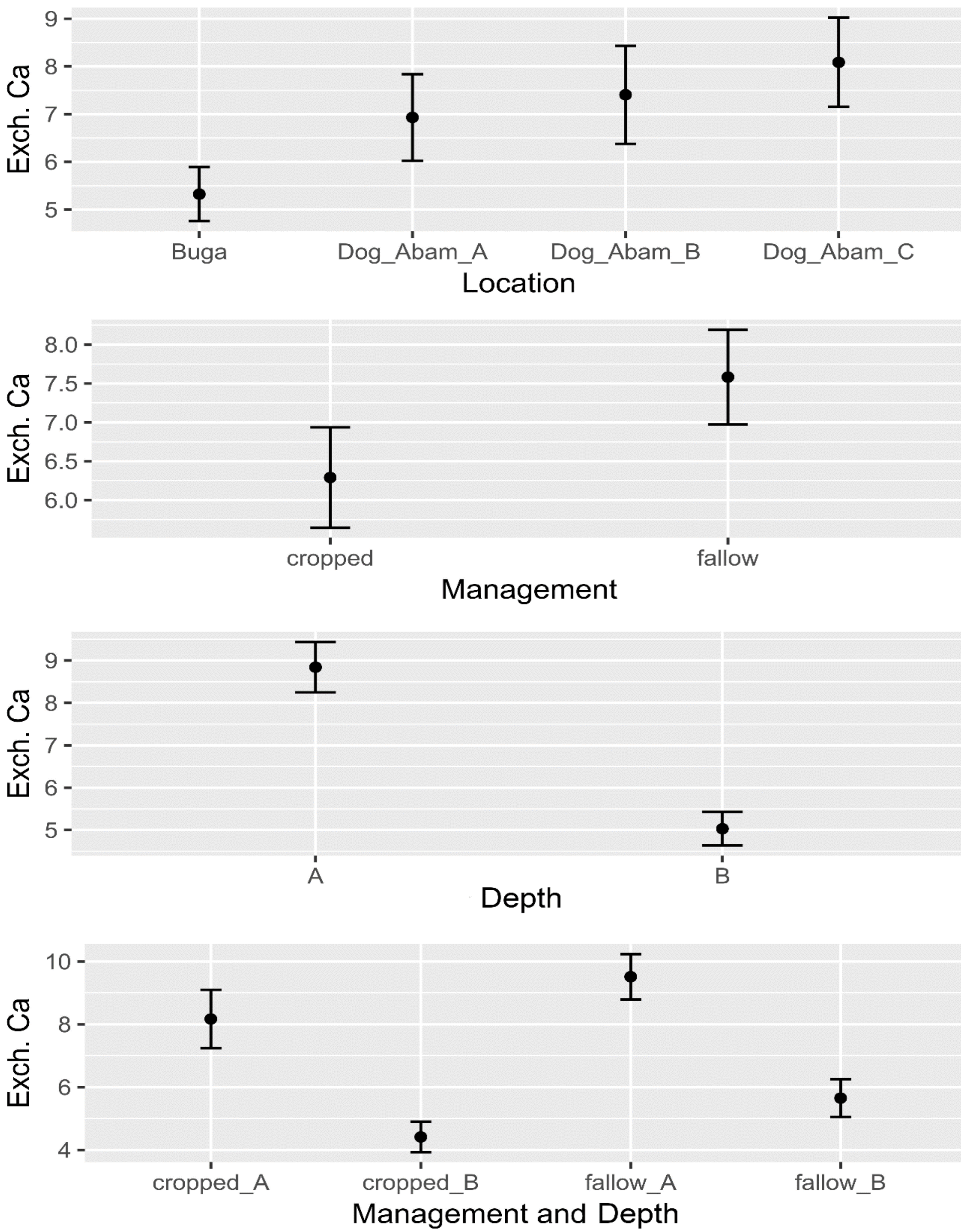


Figure 3: Mean effective cation exchange capacity (cmol (+) kg^{-1}); bars indicate +/- 1 standard deviation. Results are expressed on a dry weight basis.

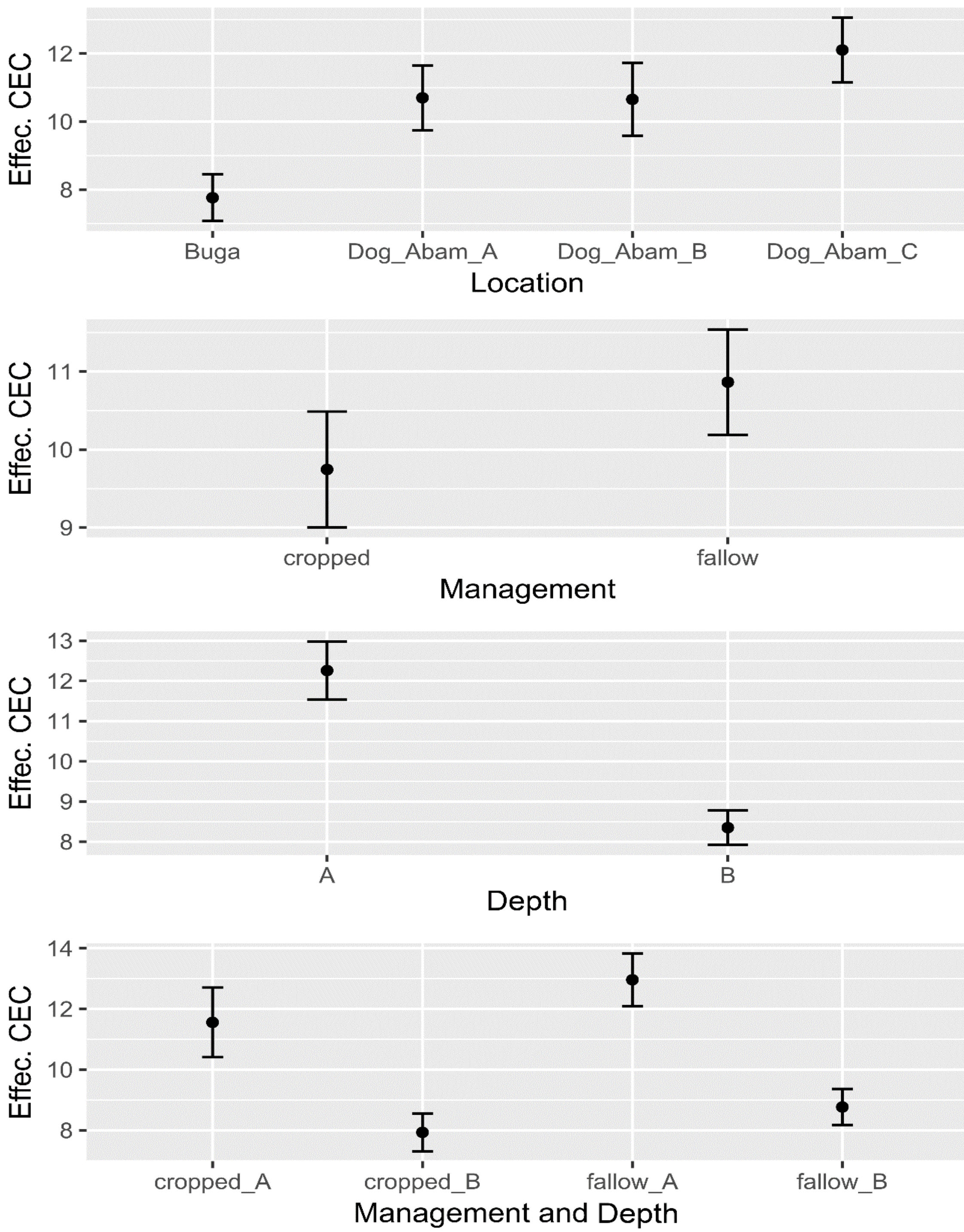
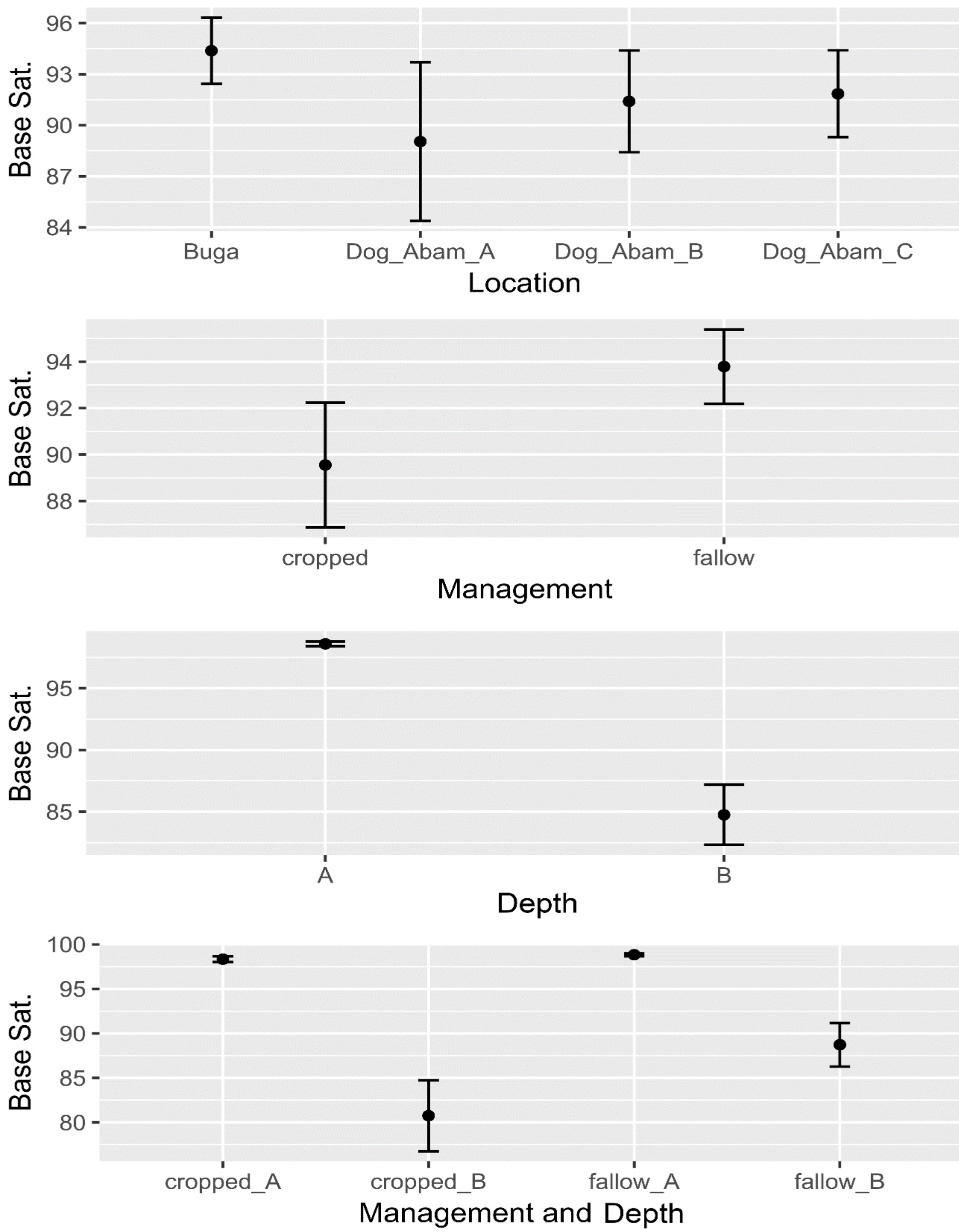


Figure 4: Mean percent base saturation of the cation exchange complex (%); bars indicate +/- 1 standard deviation.



ISSN: 2455-6939

Volume:04, Issue:03 "May-June 2018"

In contrast to land management type, soil depth had a large effect on soil properties. Overall, the 0-15 cm surface soils (depth A) in this study were generally coarser in texture (sand: 68.1%; silt: 27.7% and clay: 4.3%) than those collected from 15-30 cm (depth B) (sand: 49.0%, silt: 44.4% and clay: 6.6%), but both surface and subsurface soils still fell within the USDA sandy loam textural class (Table 1 and 2).

Concentrations of total soil C and N were both approximately 2-fold greater in surface soil (2.05%, 0.15%, respectively) than 15-30 cm subsoil (0.89%, 0.08%, respectively). Exchangeable cations, percent base saturation, cation exchange capacity, available (Bray) P and soil pH (both methods) were generally greater in the surface 0-15 cm soil than in 15-30 cm subsoil (Table 1 and 2). Of the remaining soil parameters measured in this study, all except for nitrate-N, available-N (sum of ammonium-N and nitrate-N) and exchangeable Na were significantly greater in the surface soil horizon (depth A) than the underlying one (depth B).

There were significant correlations between some of the soil properties. Total soil C was positively correlated with total soil N and cation exchange capacity (Table 3). Also, soil pH (both types) was positively correlated with % base saturation (Table 3).

Table 3: Correlation between total soil C and selected soil chemical parameters; and, correlation between base saturation and selected soil chemical parameters. Significant Pearson correlations ($p \leq 0.05$) are indicated in bold.

Variable 1	Variable 2	t-value	Df	p-value	Correlation Coefficient
Total soil C	Total soil N	25.48	46	**<0.0001**	0.966
Total soil C	Effect. CEC	7.27	46	**<0.0001**	0.731
Base Sat.	pH ($CaCl_2$)	7.69	46	**<0.0001**	0.750
Base Sat.	pH (H_2O)	7.92	46	**<0.0001**	0.759
Base Sat.	Exch. Ca	5.69	46	**<0.0001**	0.643

DISCUSSION

This study was conducted to determine if land management practice would have an impact on soil properties relevant to soil quality. In particular, do short-fallow systems result in more favorable soil properties than cropped systems? In Africa, it has been reported that the incorporation of fallow periods can enhance the yield of subsequent crops, as compared to continuous cropping systems (e.g., Musinguzi *et al.*, 2010; Norgrove and Hauser, 2016; Gaiser *et al.*, 2011; Maliki *et al.*, 2016; Kintché *et al.*, 2015; Bekunda *et al.*, 2004). Regeneration of native

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Volume:04, Issue:03 "May-June 2018"

vegetation may occur during the fallow period, increasing soil organic matter inputs and decreasing the nutrient demand that a continuous cropping system may impose on the soil (Blanco and Lal, 2008). Improvements to soil quality would include less acidic soil pH, higher total soil carbon and nitrogen (related to greater soil organic matter content) greater available N (e.g., ammonium and nitrate), greater available phosphorus and greater concentrations of exchangeable cations, leading to a greater % base saturation of the cation exchange complex. Soil available nutrient (N, P, and K) concentrations increase with fallows, with longer fallows of up to 7 years significantly increasing soil nutrients. These increases have been attributed to the decay of above-ground and root biomass of fallow vegetation and the presence of native leguminous species among the vegetation (Samaké *et al.*, 2005). Changes to land management practices tend to influence the topsoil to a greater extent than the subsoil because most soil inputs occur at (or near) the soil surface, and, soil management practices tend to manipulate the upper part of the soil profile (Blanco and Lal, 2008; Weil and Brady, 2016).

In general, this short-term study did not find many statistically significant land management effects on soil parameters commonly included in the assessment of soil quality. Ammonium-N concentrations were significantly greater in fallow soils, as compared to cropped ones. This was likely due to less plant uptake from the soil, but there may also have been greater net N mineralization in the fallow soil (Aguilera *et al*., 2013). In contrast to ammonium, nitrate is quite mobile and movement from the surface soil (0-15 cm) to the underlying subsurface soil (15-30 cm) or deeper was possible. The high variability in nitrate-N concentrations (e.g., relatively large standard deviations) may have in part be due to differential downward movement of nitrate through the soil profile.

There was a tendency for exchangeable Ca and percent base saturation to be greater in the fallow soil, again perhaps due to less plant uptake and removal from the fields not planted to agricultural crops. The fallow period in this study ranges between 3 to 6 months, depending on each household circumstance. The effect of sites on soil properties suggest that farming practices vary among study sites, hence influencing soil properties. Although not statistically significant, it is notable that almost all soil properties reported in Table 1 were equal to or greater under fallow as compared to those for cropped soils. It is not clear why there was a significantly greater clay content in fallow field soils; soil particle size distribution is considered to be stable and not subject to change through cropping, although it can be changed through soil erosion events (Blanco and Lal, 2008). But, the difference in clay content between the two management systems (in either depth A or B) is quite small and differs by less than 2%.

The fact that the surface soil had greater total soil carbon and nitrogen, available nitrogen, available P, (most) exchangeable cations and cation exchange capacity is consistent with the greater organic matter present in topsoils (Blanco and Lal, 2008; Weil and Brady, 2016). The positive correlation between total soil C and these other parameters supports this premise. Inorganic carbonate C would not be stable in the pH of these soils so it is safe to assume that almost all of the soil carbon is in the form of soil organic carbon (i.e., organic matter).

CONCLUSION

This study was about determining whether or not short- fallow systems result in more favourable soil properties than cropped systems. Although average concentrations of most measured chemical parameters were greater under fallow as compared to continuously cropped management, only ammonium-N concentrations (and clay content) were significantly ($\alpha = 0.05$) greater under fallow relative to cropped soils. This is still encouraging as it suggests that even very short fallows are moving these measures of soil quality in the right direction. It would be worthwhile to examine if slightly longer fallow periods (e.g., 2-3 years) would significantly enhance the quality of these Ugandan soils relative to continuously cropped soil. It would also be worthwhile to determine what factors have contributed to the loss of longer fallow periods on these Ugandan farms.

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