Linkages between plant nutrients, soil acidity and land use types on Ferralsols of Central Uganda

Abstract

A study to examine the linkages between plant nutrients, soil acidity and land use types on Ferralsols was carried out on smallholder farms in Central Uganda. The objective of this study was to assessed soil pH effects on plant nutrient availability under different land use types in Central Uganda. The study was carried out in five districts, namely Mpigi, Masaka, Wakiso, Mukono and Mubende. Soil samples were randomly collected from Coffee, Banana, annual crop, and virgin/undisturbed fields in the five districts and the pH and nutrient concentration analyzed accordingly. Results from the study showed that soil pH had no significant effect on the different land use types. Analysis of variance (ANOVA) also revealed significant difference ($p<0.01$) for soil nitrogen, Calcium ($p< 0.05$) and Magnesium ($p< 0.05$). Locations in the study showed no significant difference on potassium. However, when treatment was assessed, the study showed significant difference ($p< 0.01$) for potassium. Besides, the study also showed high concentrations of Manganese (Mn) and Iron (Fe) in addition to very high sand and low silt and clay contents. The land use types for coffee production in Masaka district recorded the lowest soil pH (4.4) followed by annual fields (pH 4.60) in Mpigi. The highest soil pH (5.7) was however recorded in banana land use types in Mubende. The study also recorded very low to low N, P and K. Generally, there was rapid soil fertility decline in smallholder farms in the region.

Key words: Soil pH, soil acidity, Ferralsols, nutrient availability and land use types

Introduction

Ferralsols are the most dominant soils constituting 25% of the soil type in Uganda (Bamutaze, 2015). The soils are weathered and leached with strong acidity containing toxic levels of Al^{3+}, Fe^{2+}, Mn^{2+}, low available phosphorus and has a pH (5.2) below the critical soil pH of 5.5 (Jaetzold *et al.,* 2012, Drake et al., 2017). The capacity of these soils to supply plant nutrients and retain cation exchange capacity (CEC) are both low. Additionally, soil pH is the most important factor in evaluating plant nutritional status due to its close association with nutrient availability (Beheiry et al., 2023). The chemical and physical Characterization of soils' properties are key in effectively managing acid soils on different land use types. In East Africa, research has indicated that N, P, Mg, Ca and soil acidity are the major constraints to crop production (Kyomuhendo et al., 2020). Besides, in central Uganda, years of continuous cropping, erosion and poor soil management have contributed to soil acidity limiting average farm sizes to about 0.8 to 1.2 hectares per household in many farming communities with subsistence farming being unavoidable (Bulyaba et al., 2020; FAO and ITPS, 2015).

Soil pH can be defined as the negative logarithm of the active hydrogen (H+) or hydroxyl ion concentration (OH−) or simply, pH = − log [H+]; pOH = − log [OH−] (Zhang et al., 2019). A pH scale ranging from 0 to 14 is used to describe soil acidity and alkalinity. pH values of less than 7 refer to acidic conditions, while those above 7 indicate an alkaline environment; however, a pH values of 7 is considered neutral (Jackson and Meetei, 2018). Soils found in tropical regions such as Uganda are commonly acidic due to heavy precipitation and leaching. Soil acidity can result into sequestration of certain nutrients like phosphorus (P), causing it to be insoluble through binding with cations (Sharma et al., 2013). The use of compost from organic agricultural wastes has been recognized generally as an effective means for buffering soil pH, improving soil fertility and enhancing the contribution of inorganic fertilizers to soil fertility maintenance (Iqbal et al., 2015).

Agricultural food production is constrained by reduced soil fertility that threatens the livelihoods of most farmers in Uganda (Muzira et al., 2018). Accelerated soil fertility reduction under different land use types contributes to many soil management problems, including soil acidity. Though there are currently a number of soil fertility strategies being promoted in Uganda, soil acidity management has not been given serious attention. Although the extent and distribution of soil acidity are not well documented, it seems to be wide spread in many smallholder farms in the country. Besides, limited or no research emphasis has been placed on the management of acid soils (mainly Acrisols and Ferralsols) to promote sustainable crop production in Uganda. The objective of this study was to assess soil pH effects on plant nutrient availability under different land use types in Central Uganda. The study hypothesized that addition of different quantities of liming materials ($CaCO_3$ and biochar) to Ferrasols improve soil acidity (soil pH). It is expected that the findings from this study will improve on the knowledge and practices of soil fertility management on smallholder farmers' fields in Central Uganda. More to that, this study will provide information that will help the Ugandan policy makers understand the threats soil acidity poses to agricultural production and productivity in the country. Results from this study will also assist in integrating soil acidity (soil pH) management science in current soil fertility and productivity assessment for sustainable agricultural land use planning and environmental conservation.

Materials and Methods

Study Location

The study was carried out in Central Uganda. Central Uganda has nineteen (19) districts, five (5) of which were randomly selected, namely Mpigi, Mubende, Wakiso, Mukono and Masaka. The Central part of Uganda is a plateau, surrounded by four main mountain ranges: Rwenzori, Elgon, Mufumbira, and Moroto; the tallest point is the peak of Mt. Rwenzori at 5,110 m. According to Drake et al. (2017), the soils in these areas are highly weathered, have strong acidity and low level of phosphorus.

Soil sampling and preparation

Five (5) districts i.e., Mpigi, Masaka, Mukono, Wakiso and Mubende in Central Uganda were randomly selected. Soil samples were collected at a depth of 0-20cm with the use of an auger and thoroughly mixed to form composite samples. The samples were put in plastic bags, tagged and transported at Les Rams Consultant, Water Quality, Soil and Plant Analysis Laboratory situated in Kampala, Uganda, Apollo Kaggwa Road, Bwaise. The samples were later air dried and ground to pass through a 2 mm sieve for analysis of selected soil chemical and physical properties.

Soil physico-chemical analyses

Soil particle size distribution was analyzed using the Bouyoucos hydrometer method (Day, 1965). Soil pH was determined in 1:2.5 soil water ratio using a glass electrode attached to a digital pH meter as described by Okalebo et al. (2002) while soil organic carbon was determined by the dichromate oxidation method as described by Walkley and Black (1934). Total Nitrogen was determined by the micro-Kjedahl digestion method as described by Bremmer and Mulvaney (1982). Soil available phosphorus was determined based on the Mehlich 3 extraction procedure (Mehlich, 1984). Exchangeable potassium was determined by use of the ammonium acetate method (McLean and Watson, 1985). Exchangeable calcium was determined by the buffer method as described by Adams and Evans (1962). Copper was determined by the DTPA method as described by Lindsay and Norvell (1978). Zinc was determined by the zincon method as described by Miller (1979). Iron, Magnesium and Manganese were determined by the EDTA method as described by Schnug *et al.* (1996).

Data Analysis

All data collected were subjected to analysis of variance (ANOVA) using GENSTAT 16th edition and declared significant at $p < 0.05$ using the statistical model as described by Gomez and Gomez (1984). Mean separation was done using the Duncan's Multiple Range Test (DMRT) and conclusions made at $p < 0.01$, 0.05 and 0.1 levels of significance.

RESULTS AND DISCUSSION

Soil acidity in Central Uganda

Location and treatment had no significant effect on soil pH among the different land use types in the study area. Interaction effect of location and treatment also showed no significant difference (Table 1b). There was varying, but decreasing soil pH in the different land use types. In terms of location and treatment application, coffee fields in Masaka showed the lowest soil pH (4.4) for the different land use types, followed by annual fields in Mpigi (pH 4.6) and virgin/undisturbed fields in Wakiso District (pH 4.8), respectively. In addition to the lowest soil pH observed in the different land use types in Masaka, Mpigi and Wakiso Districts, the study recorded deteriorating soil pH in all study locations cultivating banana, coffee and annual crops (Table 1b). According to the rating by Horneck et al. (2011), the varying soil pH as recorded showed strongly to very strongly acidic soils, while a few soils are moderately acidic. In these acidic soil conditions, there is also a complex interaction of growth-limiting factors among which is declining plant available nutrients.

Plant growth may be restricted by one or more of the following: Al or Mn toxicity; Ca, Mg, P or Mo deficiency and reduced mineralization and nitrification (Dinkecha and Tsegaye, 2017). Acid soils constrain crop production and affect nutrient availability. Plants can better survive in soil with pH 5.5 to 6.5; unfortunately, most of the soils in the study area have pH far below this range. According to Karltun et al. (2014), pH less than 4.5 is classified as strongly acidic, 4.5-5.5 is highly acidic, 5.6-6.5 is moderately acidic, 6.6-7.3 is neutral to near neutral, 7.4-8.4 is moderately alkaline and >8.5 is strongly alkaline. Hence, soils of the study area are classified as moderately, strongly to very strongly acidic.

Effects of soil pH on nutrient availability in different land use types on Farmers' fields in Central Uganda

Location showed significant differences for Nitrogen ($p < 0.01$). According to Karltun et al. (2014), nitrogen is rated as very low (< 0.10%), low (0.1-0.15%) and optimum (0.15-0.30%). Based on these ratings, the study area had low nitrogen content. However, when %N content was assessed in the different land use types, it was observed that virgin/undisturbed fields located in Mubende recorded optimum N (0.18%), followed by annual (0.15 %N) and banana (0.15 %N). Coffee fields located in Masaka showed low N (0.14%), followed by Mubende (0.14% N). Low N levels were also recorded in Wakiso District (0.05%) (Table 1b). The low soil N observed in the study area may probably be attributed to the low soil pH. Wairegi et al. (2014) reported that coffee grows well in moderate acid soils (pH>5) and banana performs better at high pH (pH above 5.5). Both crops grow best in soils with total N above 0.15%.

There were significant differences for Calcium ($p<0.05$) and Magnesium ($p<0.05$) in the study area. According to the rating by Dan et al. (2011), Calcium and Magnesium are all low as observed in the different study locations (Table 1b). The low levels of soil pH could be contributing to the reduced calcium and magnesium observed, suggesting an unfriendly environment for sustaining crop production. Takala et al. (2020) observed highest growth performance on coffee seedling as well as plant height, stem girth, leaf number and area, tap and lateral root length, lateral root number, root volume, stem, leaf and root dry matter when 4 tons of $CaCO_3$ and 12.5 tons of coffee husk biochar were applied. Low soil pH affects the availability of nutrients, and particularly that of phosphorus and other macronutrients; therefore, correction of the low pH through liming is critical for sustainable management of acid soils for increased crop production (Tigist et al., 2019). Bossolani et al. (2021) observed that increased soil pH improves effective basic cations (Ca^{2+} and Mg^{2+}) and reduces acidic cations (Al^{3+} and Mn^{2+}) when lime was applied. Ameliorating low pH soils with liming materials such as calcium, magnesium and/or biochar reduces the toxicity effects of Al^{3+} and Mn^{2+} associated with low pH and at the same time helps create an enabling soil environment for sustainable crop production.

Location in the study had no significant effect on potassium levels (Table 1b). There were no significant differences for all the plant available nutrients when treatment was assessed, with the exception of potassium which showed significant difference ($p<0.01$). The interaction effect of treatment and location showed no significant effect for all the soil physiochemical properties in the different land use types. However, significant differences were noted on K^+ among the banana fields. According to the rating by Horneck et al. (2011), K^+ in this study area is low to high across farmers' fields, with banana fields located in Masaka having the highest K^+ concentration (1.69 meq/100 g soil), followed by Coffee fields in Mubende (1.69 meq/100 g soil) (Table 1b). The lowest K^+ concentration was recorded in virgin/undisturbed fields located in Mpigi District (0.12 meq/100 g soil). The low to high K^+ concentration recorded in the study could be attributed to the decomposition and addition of plant litters to the soils. Li et al. (2020) reported large amounts of K^+ concentration present in cereal crops such as maize and wheat. It has been well documented that both crop yield and soil K^+ availability can be improved by long-term straw return (Tan et al., 2017). In China, crop straw return is widely practiced in agricultural production (Huang et al., 2012; Zhu et al., 2015). Relying only on the internal circulation of the soil-plant system is not sufficient to relieve the soil K^+ deficiency (Li et al., 2020). Plant biomass should be combined with other soil amendments such as limestone so as to improve K^+ cycling.

Results in Table 1b show significant differences of different land uses on soil organic carbon ($p<0.01$) and organic matter ($p<0.01$) in the study area. According to Dan et al. (2011), organic carbon and organic matter is optimum, ranging from 1-4% (Table 1b). The changing soil pH in the different land use types suggests an influence on soil organic matter and organic carbon. Besides, the optimum range (1-4%) could be attributed to the recycling of crop residues, addition of cow manure, short fallow and biomass transfer in the different land use types in the study area. Farmers in the study area carry out these practices with the hope of replacing lost nutrients and reversing soil acidity. However, the observed soil pH suggests the introduction of Integrated Soil Fertility Management (ISFM) approaches, with use of liming materials that could alleviate the problem of soil degradation due to increasing soil acidity in the region. Hence, Soil organic matter and organic carbon measure the overall health of agricultural soils. Soil organic matter in particular is very important because of its influence on a number of soil chemical, physical and biological properties (Dan et al., 2011). Several authors (Filipe et al., 2015; Ghimire et al., 2017 and; Neina, 2019) have reported the negative impacts of low pH on Soil Organic Matter (SOM). Solly et al. (2019) found that SOM content was lower in soils with pH < 5.5. However, Aye et al. (2016) found higher OC of an experimental soil after application of lime integrated with N and P fertilizers at Haryana Agricultural University in India. The present study identifies soil pH as the most important variable affecting SOC and other soil parameters that are essential for sustainable crop production in the study area (Table 1b).

The study locations showed significant differences of land uses on %sand (p<0.01) and %Clay (p<0.05) and not on %silt (Table 1b). Percentage sand, silt and clay also showed no significant differences when the different treatments were assessed. However, %clay and sand were optimum, though high in some areas and low in others. The highest sand content (63%) was observed in annual fields in Mpigi, followed by banana fields (56.67%) in Mubende and Coffee fields (56%) in Masaka. Percentage clay (48%) was observed to be equally distributed in Coffee and banana farming systems in Masaka and Mubende, followed by annual fields in Mukono (45.33%) and annual fields in Masaka (43%). Percentage silt was observed to range from 10% in Coffee fields in Mpigi to 20% in virgin/undisturbed fields in Masaka (Table 1b). Zhang et al. (2017) also attributed macropores reduction and increase in water retention times and nitrogen supply for plant growth to the optimality of silt and clay particles. Furthermore, Chen et al. (2020) reported significant effects soil texture has on soil aeration, water-holding capacity, soil fertility, crop yield and the important role it plays in regulating the leaching of soil nitrogen.

Effects of soil pH on selected trace elements in smallholder farms in Central Uganda

Location showed significant effect on iron (p<0.05) and zinc (p<0.001) as observed in the study (Table 2b). For treatment application, different soil parameters showed no significant effects, with the exception of manganese (p<0.1). Interaction effect for treatment and location showed no significant differences on the different soil parameters as recorded in the study (Table 2b). The rating by Landon (1991) and Lindsay and Norvell (1978) showed very high iron and manganese concentration in different land use types. Manganese concentration in the study ranges from 121.1 ppm in the virgin/undisturbed fields in Masaka to

139.3 ppm in Coffee fields in Masaka District (Table 2b). Iron was also highest in the virgin/undisturbed fields in Mpigi (1271.4 ppm). The high Fe^{2+} and Mn^{2+} concentrations indicate a soil acidity problem in the area. These findings are in agreement with those of Zama et al. (2022) who reported an increase in soil acidity due to the toxicity effects of Al, Mn and Fe; they concluded that soil pH has a significant effect on plant growth and agricultural productivity. Low soil pH affects availability of plant nutrients, especially phosphorus and other macronutrients; hence, correction of soil pH through liming and/or application of organic materials is critical for sustainable soil management (Tigist et al., 2019).

Conclusion

Soil pH is fast declining in banana, coffee, annual crops (maize, soybean, cowpea etc.) and virgin/undisturbed fields, thereby affecting plant nutrient availability on smallholder farms in Central Uganda. Low soil pH (4.4) recorded in banana fields of Masaka, pH 4.7 recorded in coffee fields of Mpigi, pH 4.9 recorded in coffee fields of Mubende and pH 4.6 recorded in annual crop fields of Mpigi, coupled with the high Manganese (Mn) and Iron (Fe) contents in soils of these areas significantly influencing the low availability of plant nutrients as was observed in the different land use types. Soil acidity due to low soil pH is fast spreading across the different farming systems in Central Uganda. The extent of declination tends to affect crop production, and hence reduces soil productivity.

Recommendations

Stakeholders, policy makers, researchers and academics are required to do more to address the problem of soil acidity in the study area. Liming practices should be adopted in the different land use types of Central Uganda as a means of addressing the problem of soil degradation due to soil acidity.

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Table 1a: Source of Variation for Soil Nutrients by Location and Treatment

Source of Variation	P.H	N	P	K	Ca	Mg	OC	OM	Sand	Clay	Silt
Location	0.5325ns	0.012***	4367ns	0.9924ns	10.133**	2.8762**	1.5346***	4.562***	404.11***	250.76**	19.25ns
Treatment	0.8715ns	0.003ns	5828ns	1.2402*	3.555ns	0.6303ns	0.0778ns	0.2312ns	103.5ns	112.19ns	0.71ns
Location x Treatment	0.1908ns	0.001ns	1268ns	0.2461ns	1.935ns	0.4941ns	0.087ns	0.2587ns	115.03ns	109.8ns	32.23ns
Residual	0.440	0.002	3020	0.5284	3.023	0.772	0.167	0.4965	69.86	72.41	30.14
LSD	1.225	0.0912	101.47	1.342	3.210	1.622	0.755	1.301	15.43	15.71	10.136
CV (%)	12.95	45.18	182.05	112.03	47.58	47.09	23.07	23.07	17.41	23.42	35.05
SE	0.663	0.049	54.95	0.727	1.739	0.8785	0.4087	0.7046	8.358	8.509	5.490

***Significant at 1%, **Significant at 5%, *Significant at 10%, ns=non-significant

Table 1b: Soil physiochemical characteristics in the different land use types

Soil properties	Farming System	District: Masaka	Mpigi	Mubende	Mukono	Wakiso
pH	Annual	5.27^{a}	4.60^{b}	5.31^{a}	4.84^{b}	5.07^{a}
	Banana	5.56^{a}	4.85^{b}	5.70^{a}	5.60^{a}	5.56^{a}
	Coffee	4.42^{b}	4.70^{b}	4.94^{b}	5.16^{a}	5.22^{a}
	Virgin	5.16^{a}	4.81^{b}	5.27^{a}	5.38^{a}	4.80^{b}
Nitrogen (%N)	Annual	0.10^{a}	0.09^{a}	0.15^{a}	0.11^{a}	0.08^{a}
	Banana	0.11^{a}	0.09^{a}	0.15^{a}	0.08^{a}	0.05^{b}
	Coffee	0.14^{a}	0.10^{a}	0.14^{a}	0.06^{b}	0.09^{a}
	Virgin	0.13^{a}	0.09^{a}	0.18^{a}	0.13^{a}	0.11^{a}
Phosphorous (ppm)	Annual	24.53	2.08^{d}	39.55^{bc}	68.07^{b}	1.30^{d}
	Banana	89.35^{a}	15.00^{c}	33.47^{bc}	105.93^{a}	45.39^{ac}
	Coffee	6.29^{d}	4.83^{d}	18.28^{c}	50.06^{ac}	28.90^{bc}
	Virgin	4.90^{d}	2.37^{d}	3.54^{d}	15.91^{c}	34.57^{bc}
K (cmol (+)/kg soil)	Annual	0.30^{b}	0.25^{b}	0.72^{b}	0.41^{b}	0.30^{b}
	Banana	1.46^{a}	0.40^{b}	1.69^{a}	0.75^{b}	0.98^{a}
	Coffee	0.41^{b}	0.34^{b}	0.54^{b}	0.86^{b}	0.57^{b}
	Virgin	0.53^{b}	0.12^{b}	1.39^{a}	0.57^{b}	0.26^{b}
Ca (cmol (+)/kg soil)	Annual	4.89^{a}	1.47^{c}	5.60^{a}	3.39^{b}	3.59^{b}
	Banana	5.04^{a}	2.35^{c}	4.42^{b}	4.77^{a}	4.45^{a}
	Coffee	2.00^{c}	2.31^{c}	4.17^{b}	3.64^{b}	3.41^{b}
	Virgin	3.99^{b}	1.81^{c}	3.62^{b}	4.66^{a}	2.79^{c}
Mg (cmol (+)/kg soil)	Annual	2.58^{a}	0.81^{c}	2.43^{a}	1.69^{b}	1.69^{b}
	Banana	2.54^{a}	1.27^{b}	2.27^{a}	2.16^{a}	2.31^{a}
	Coffee	1.08^{b}	1.15^{b}	2.08^{a}	1.89^{b}	1.85^{b}
	Virgin	2.39^{a}	0.69^{c}	2.23^{a}	2.47^{a}	1.39^{b}
OC (%)	Annual	1.93^{b}	1.18^{b}	2.36^{a}	2.06^{a}	1.63^{b}
	Banana	1.84^{b}	1.33^{b}	2.16^{a}	1.68^{b}	1.74^{b}
	Coffee	1.63^{b}	1.29^{b}	2.16^{a}	1.73^{b}	1.54^{b}
	Virgin	2.28^{a}	1.03^{b}	2.11^{a}	1.89^{b}	1.71^{b}
OM (%)	Annual	3.32^{b}	2.03^{b}	4.07^{a}	3.55^{b}	2.80^{b}
	Banana	3.18^{b}	2.28^{b}	3.72^{b}	2.89^{b}	3.00^{b}
	Coffee	2.80^{b}	2.23^{b}	3.72^{b}	2.97^{b}	2.66^{b}
	Virgin	3.92^{a}	1.77^{c}	3.64^{b}	3.26^{b}	2.95^{b}
% Sand	Annual	38.67^{c}	63.00^{a}	44.67^{b}	40.67^{c}	46.67^{b}
	Banana	43.33^{c}	48.00^{c}	56.67^{b}	52.67^{b}	37.33^{c}

Soil properties	Farming System	District				
		Masaka	**Mpigi**	**Mubende**	**Mukono**	**Wakiso**
	Coffee	38.00^{c}	58.00^{b}	42.00^{c}	44.00^{c}	51.33^{b}
	Virgin	46.67^{c}	63.33^{a}	53.33^{b}	44.00^{c}	52.67^{b}
% Clay	Annual	43.33^{b}	26.00^{c}	36.67^{b}	45.33^{a}	39.33^{b}
	Banana	40.00^{b}	33.33^{c}	30.67^{c}	31.33^{c}	48.00^{a}
	Coffee	48.00^{a}	32.00^{c}	39.33^{b}	39.33^{b}	29.33^{c}
	Virgin	33.33^{c}	32.67^{c}	35.33^{b}	39.33^{b}	30.67^{c}
% Silt	Annual	18.00^{a}	11.00^{c}	18.67^{a}	14.00^{b}	14.00^{b}
	Banana	16.67^{b}	18.67^{a}	12.67^{c}	16.00^{b}	14.67^{b}
	Coffee	14.00^{b}	10.00^{c}	18.67^{a}	16.67^{b}	19.33^{a}
	Virgin	20.00^{a}	14.00^{b}	11.33^{c}	16.67^{b}	16.67^{b}

Note: a,b and c means sharing a letter in their superscript are not significantly different at the .05 level. However, a and b, b and c and c and a are significantly different at 0.05 level.

Table 2a: Source of Variation for selected trace elements by Location and Treatment

Source	dfs	Mn	Fe	Cu	Zn
Location	4	8.36ns	428421**	270.2ns	1055***
Treatment	3	55.26*	75985ns	137.8ns	409.3ns
Location x Treatment	12	24.2	79729ns	93.6ns	191.2ns
Residual	17	20.49	93957	124.9	227.7
LSD		13.5	914.6	33.34	45.03
CV (%)		3.37	40.3	76.99	84.15
SE		4.526	306.5	11.17	15.09

***Significant at 1%, **Significant at 5%, *Significant at 10%, ns=non-significant, df=degrees of freedom

Table 2b: Effect of different land uses on selected trace elements types

		Districts				
Trace elements	**Farming System**	**Masaka**	**Mpigi**	**Mubende**	**Mukono**	**Wakiso**
Mn (ppm)	Annual	136.1^{a}	132.4^{b}	133.5^{b}	132.8^{b}	135.7^{a}
	Banana	134.3^{b}	138^{a}	135.7^{a}	136.8^{a}	134.6^{b}
	Coffee	137.1^{a}	138.5^{a}	132.1^{b}	139.3^{a}	134.2^{a}
	Virgin	121.1^{b}	126.7^{b}	134.7^{a}	135.1^{a}	135.3^{a}
Fe (ppm)	Annual	744.7^{b}	355.8^{c}	337.2^{c}	742.5^{b}	1084.4^{a}
	Banana	947.4^{b}	639.1^{d}	724.4^{c}	1163.8^{a}	799.1^{c}
	Coffee	467^{c}	684.4^{b}	606.7^{b}	1035.8^{a}	1006.9^{a}
	Virgin	1271.4^{a}	294.3^{d}	674.7^{c}	886.6^{b}	1194^{a}
Cu (mg kg^{-1})	Annual	14.49^{b}	7.34^{d}	0.8	10.56^{c}	20.43^{a}
	Banana	40.28^{a}	12.13^{c}	10.1^{c}	16.43^{b}	16.3^{b}
	Coffee	10.47^{b}	10.25^{b}	7.63^{c}	17.71^{a}	17.01^{a}
	Virgin	9.77^{c}	8.31^{c}	9.64^{c}	20.92^{b}	27.41^{a}
Zn (ppm)	Annual	14.58^{b}	5.47^{c}	0	5.43^{c}	29.38^{a}
	Banana	29.6^{b}	17.86^{c}	14.78^{c}	44.68^{a}	24.35^{b}
	Coffee	9.03^{c}	8.24^{c}	2.1^{d}	35.05^{a}	28.97^{b}
	Virgin	0	2.5^{c}	0	36.91^{b}	44.17^{a}

Note: a, b and c means sharing a letter in their superscript are not significantly different at the .05 level. However, a and b, b and c and c and a are significantly different at 0.05 level

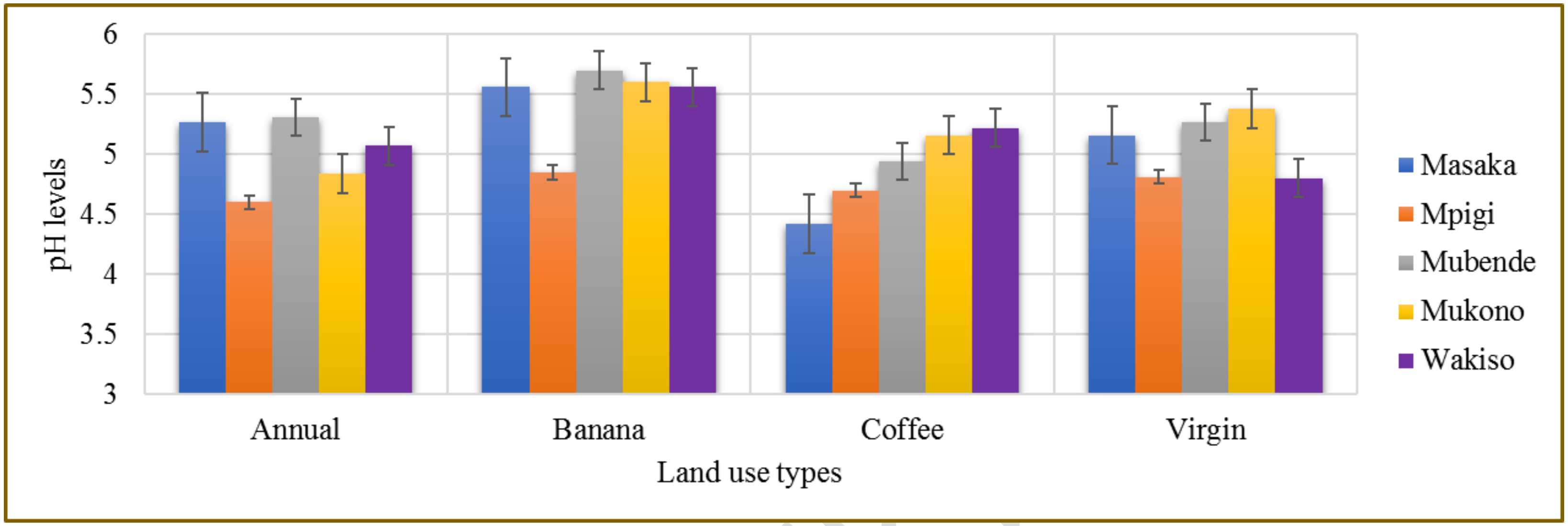

Figure 1: Soil pH variation on farmers' fields in Central Uganda

There is a gradual decrease in the current soil pH across the different land use types in Central Uganda. The soil pH ranges from 4.4 to 5.7 in all the land use types. With the exception of banana fields showing pH 5.6 and 5.7 in Masaka and Mubende, all the other land use types showed very low soil pH below the critical pH of 5.5 at which plants performed best.

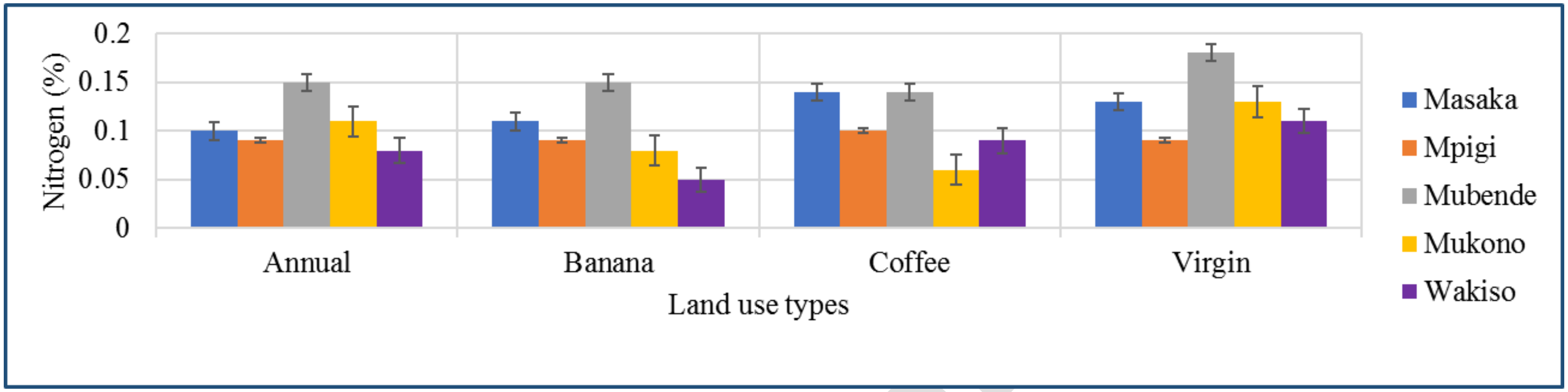

Figure 2: Nitrogen content on Farmers' fields in Central Uganda

Nitrogen decline in the different land use types is influenced by the low soil pH as observed in the study area. Coffee fields in Mpigi, Mukono, Mpigi and Wakiso observed very low soil nitrogen. The lowest soil nitrogen was observed in coffee fields in Mukono. Further evaluation showed that fields cultivated with annual crops also observed very low nitrogen content in Masaka, Wakiso, Mpigi and Mukono. The lowest nitrogen content was observed in annual fields is in Wakiso. The low soil nitrogen in the study area is steady and might worsen overtime if emphasis is not placed on the problem of soil acidity in the region. The declined in soil nitrogen is as well affecting virgin/undisturbed soils as seen in Mpigi District. The current study depicts challenging soil fertility problem in Central Uganda, thus requiring practical steps to ameliorate the problem.

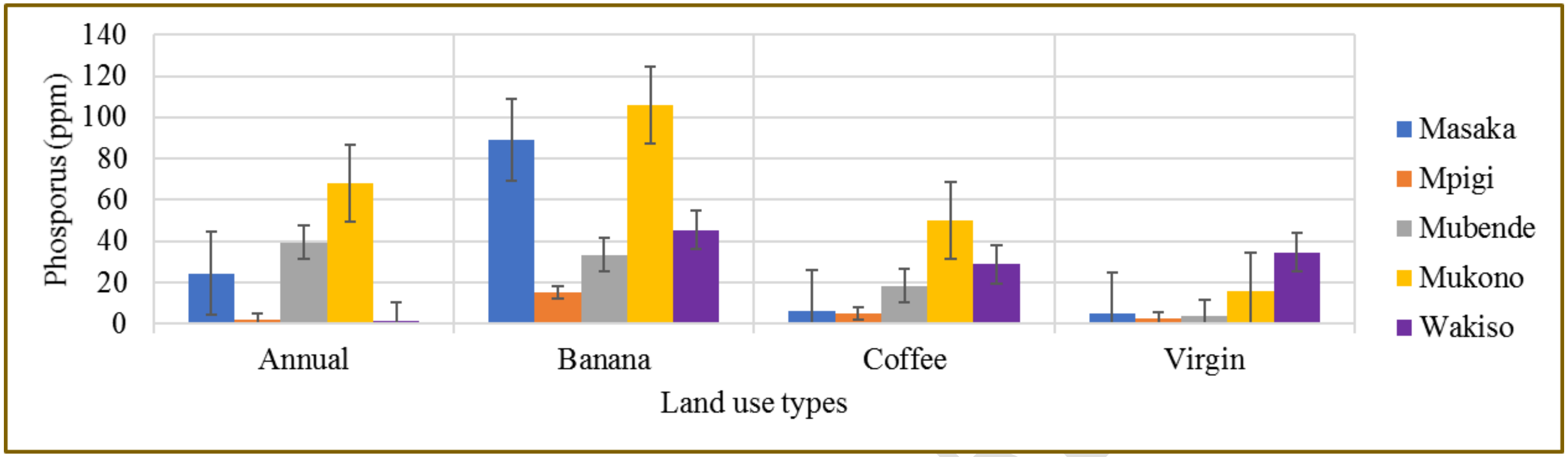

Figure 3: Phosphorus on smallholder farms in Central Uganda

Phosphorus was observed to be low to very low on smallholders' farms in the study area. Figure 3 depicts very low phosphorus in three of the five land use types among annual crops in the study area. Coffee fields in Masaka, Mpigi, Mubende and Wakiso also showed low availability of phosphorus. The study however observed some increase in phosphorus for banana fields in both Mukono and Masaka Districts. The increase could be attributed to the recycling of plant biomass and application of animal manures. Very low to low phosphorus was observed in banana fields in Mpigi. Virgin/undisturbed fields across the study locations were also deficient in available phosphorus, suggesting serious soil fertility decline.

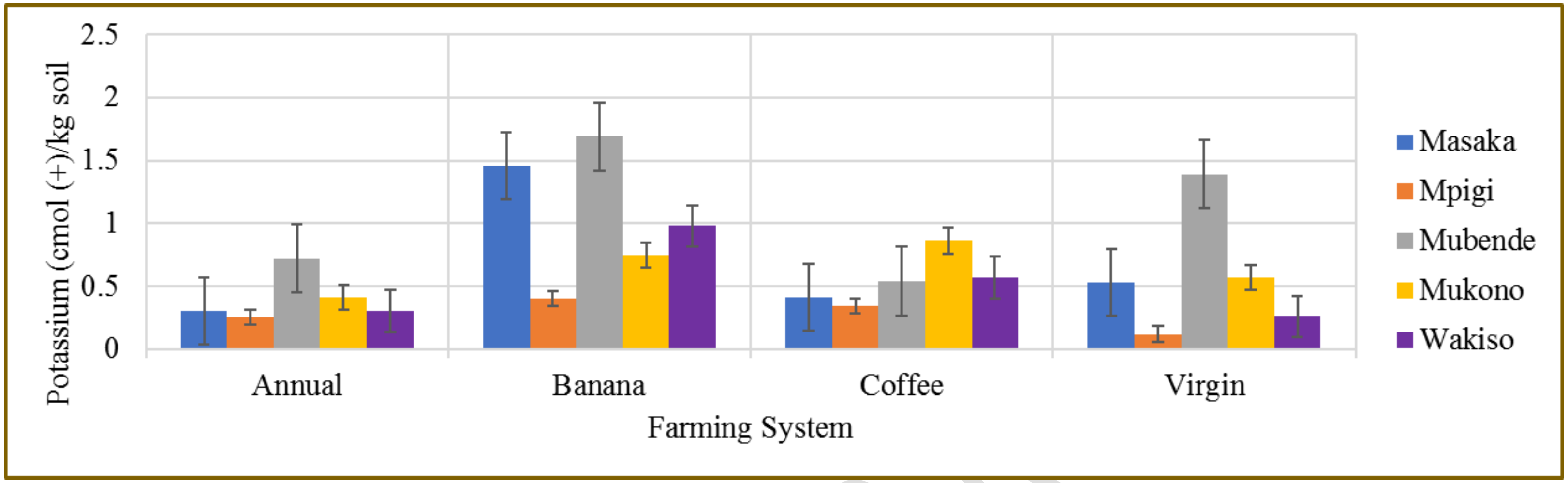

Figure 4: Exchangeable potassium on Farmers' fields in Central Uganda

Exchangeable potassium (K^+) on farmers' fields was observed to be very low to low across the different farming systems in the study area. Fields under annual crops showed significant deficiency in exchangeable K^+ in Mpigi, Wakiso, Masaka and Mukono Districts. Masaka and Wakiso were observed to have the lowest exchangeable K^+ in fields cultivated with annual crops. Further assessment of exchangeable K^+ showed deteriorating K^+ in Coffee fields in Masaka, Mpigi, Mubende and Wakiso. Potassium in these areas ranges from 0.34 cmol (+)/kg soil in Mpigi to 0.86 cmol (+)/kg soil in Mukono. The current findings indicate the fast pace at which soils are declining in fertility in the study area.

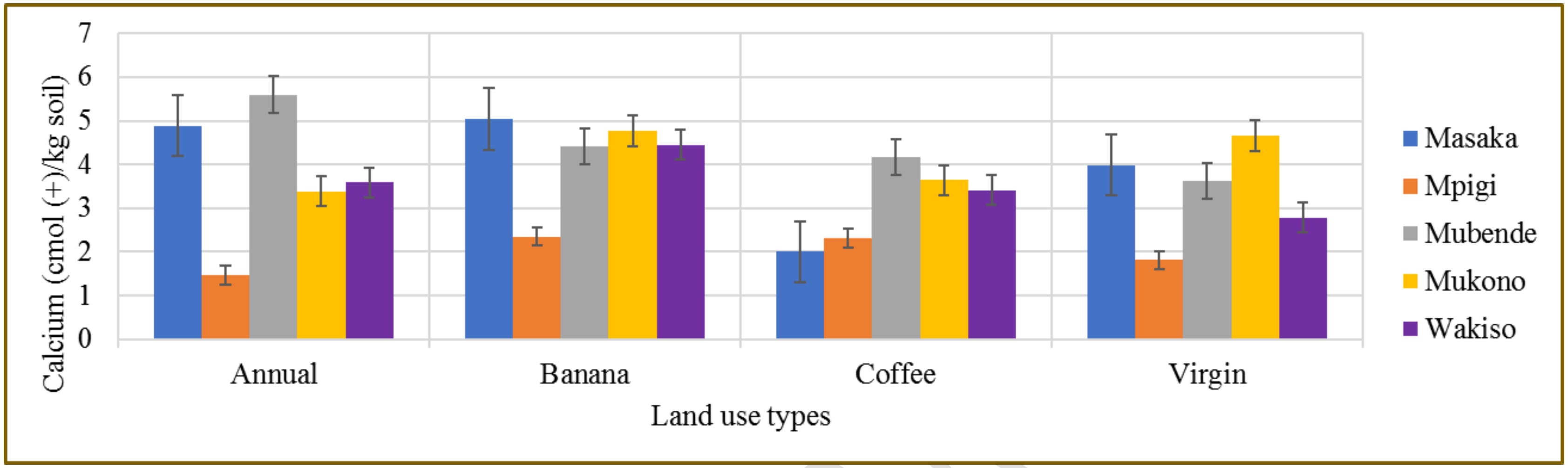

Figure 5: Calcium availability on farmers' fields in Central Uganda

Calcium (Ca^{2+}) is observed to be low to very low in some parts of the study locations, though others showed increased Ca^{2+} levels. Annual fields had low to very low available calcium both in Mpigi (1.47 cmol (+)/kg soil) and virgin/undisturbed fields in Mukono (3.39 cmol/kg soil). Coffee fields in Masaka and Mpigi also showed low (2 cmol (+)/kg soil) to very low (2.31 cmol (+)/kg soil) Ca^{2+} availability though there were some increases in the availability of Ca^{2+} in parts of the study area i.e., Mukono, Wakiso and Mubende. Banana fields in Mpigi had low availability of Ca^{2+} though Masaka, Mukono, Wakiso and Mubende recorded minimum increases in Ca^{2+}. The minimum increases of calcium for banana production can be attributed to the observed soil pH of 5.6 in Masaka, 5.7 in Mubende, 5.6 in Mukono and 5.60 in Wakiso. The low availability of Ca^{2+} recorded in Mpigi correlates with the low soil pH (4.8). The prevailing situation suggests soil fertility decline and nutrient depletion.

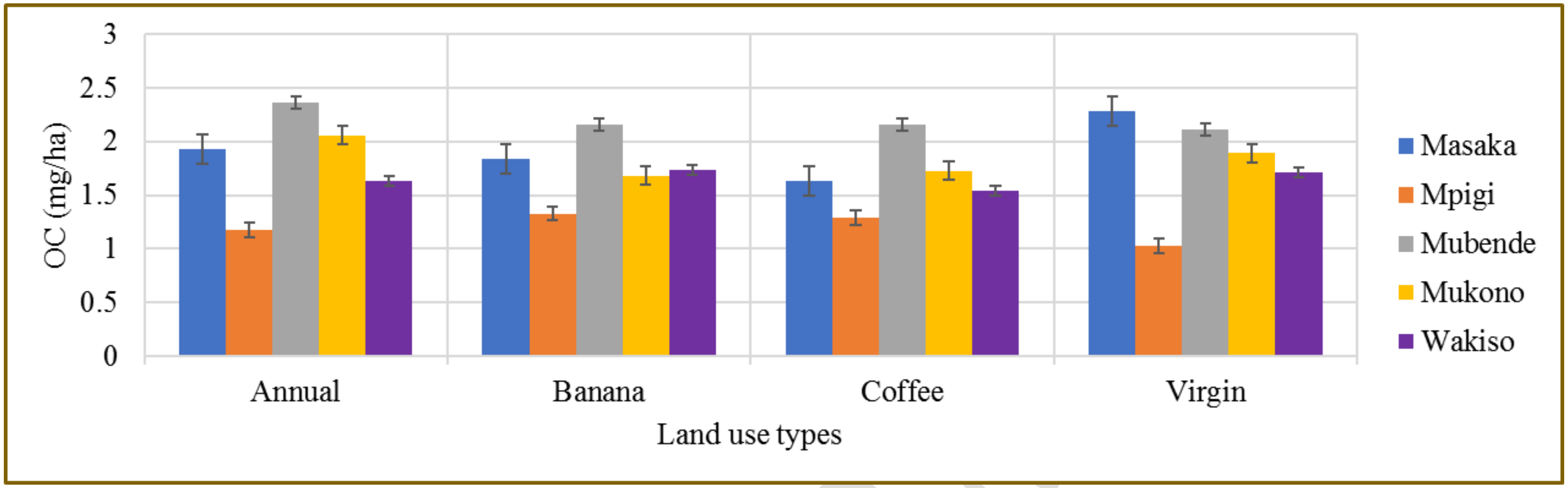

Figure 6: Soil Organic Carbon (SOC) on farmers' fields in Central Uganda

Soil Organic Carbo (SOC) was observed to be optimally available across the different land use types. All the study locations showed SOC accumulation. This is probably due to the recycling of plant biomass in banana, coffee and annual fields in the area. Virgin/undisturbed fields in Masaka were observed to have shown the highest SOC (2.28 mg/ha). Mubende also showed optimum increase in annual fields (2.36 mg/ha). Virgin/undisturbed fields in Mpigi however showed the lowest SOC (1.03 mg/ha) followed by annual fields in Mpigi (1.18 mg/ha). There was gradual decline of SOC as Dan et al. (2011) recommended SOC and OM > 6 % to be favorable for agricultural soils.

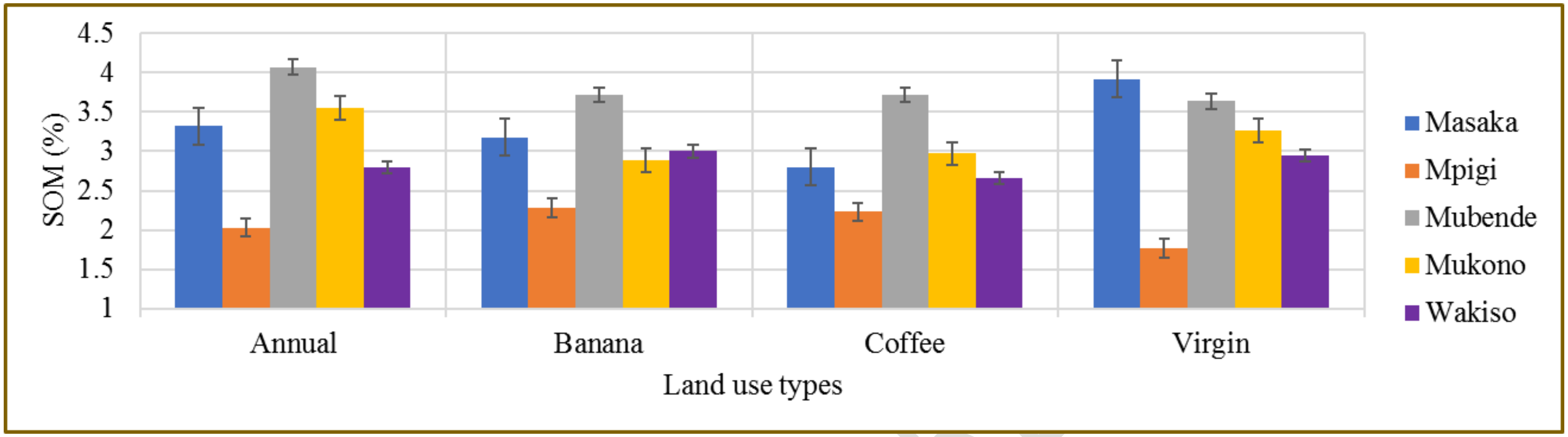

Figure 7: Soil Organic Matter (SOM) on land use types in Central Uganda

Soil Organic Matter (SOM) was comparatively optimum in the study locations, though it seemed a little high as shown from the error bars (Figure 7). SOM was observed to be low across Mpigi for annual crops, banana, coffee and virgin fields. There was low SOM across Mpigi District in the different land use types. The lowest SOM was recorded in virgin/undisturbed fields in Mpigi (1.77%) followed by annual fields in Mpigi (2.03%) and coffee fields in Mpigi (2.23%). A steady increase in SOM in the different land use types in Mubende was observed. Annual fields in Mubende recorded the highest SOM (4.07%) followed by banana fields in Mubende (3.72%), coffee fields in Mubende (3.72%) and virgin/undisturbed fields in Mubende (3.64%).

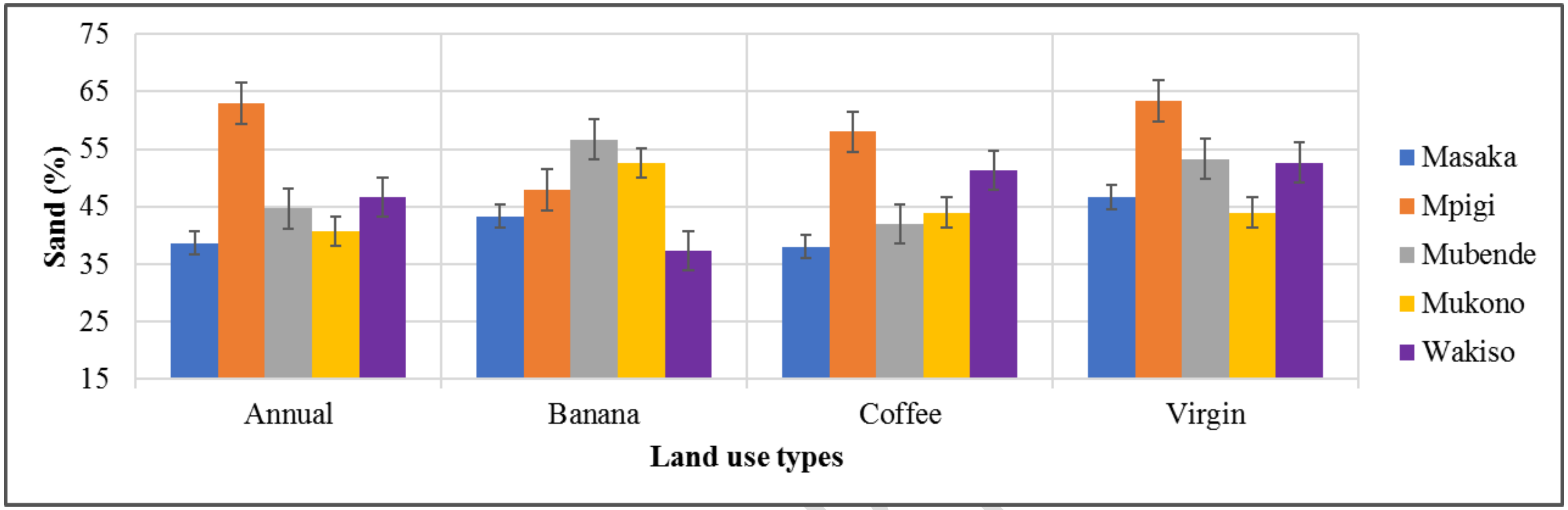

Figure 8: Percentage sand composition on farmers' fields in Central Uganda

Percent sand was observed to be high in all the study locations but was highest in the virgin/undisturbed fields in Mpigi (63.33%) followed by annual fields in Mpigi (63%), coffee fields in Mpigi (58%), virgin/undisturbed fields in Wakiso (52.67%), banana fields in Mukono (52.67%) and coffee fields in Wakiso (52.33%). The high sand content suggests high soil macropores affecting the Water Holding Capacity (WHC) in the different land use types and study locations. Continuous use of organic materials and application of animal manures in agricultural soils help neutralize the high sand content, thus influencing soil physical properties such as Bulk Density (BD) and texture.

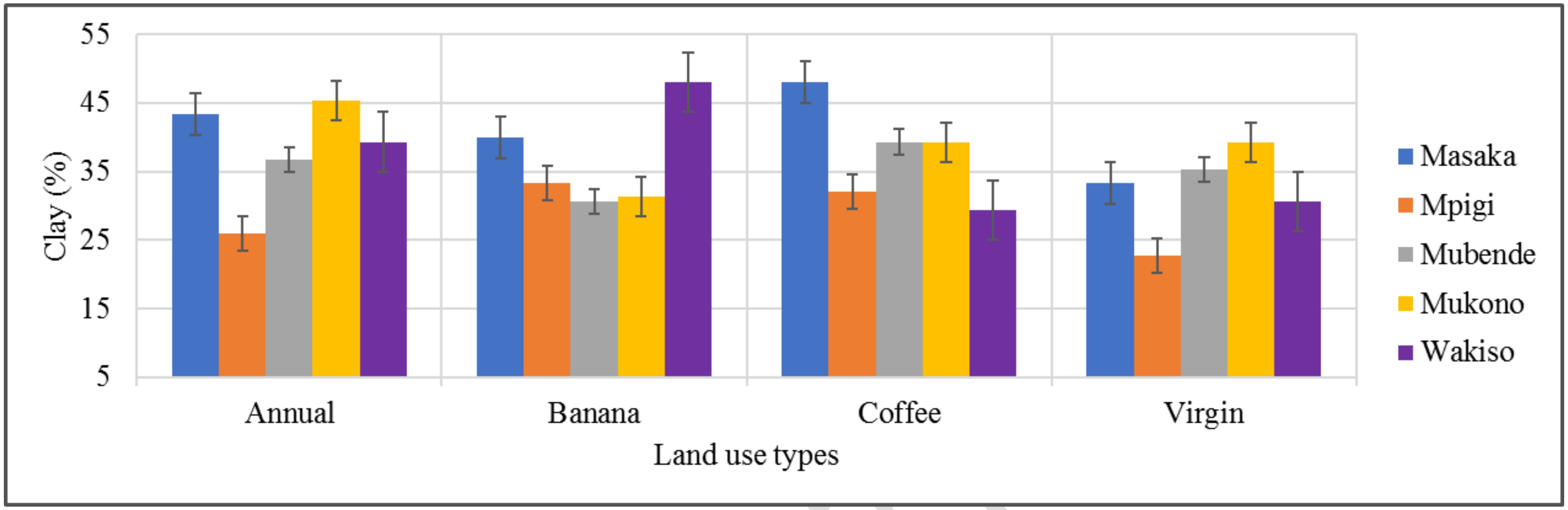

Figure 9: Percent clay composition on farmers' fields in Central Uganda

Clay was observed to be highest in Banana fields in Wakiso (48%) followed by coffee fields in Masaka (48%), annual fields in Mukono (45.33%), annual fields in Masaka (43.33%) and banana fields in Masaka (40%) Districts. Clay was also observed to be relatively high in annual fields in Wakiso (39.33%) and coffee fields in Wakiso (39.33%). However, the low clay content was observed to be steady in the different land use types, suggesting minimum recycling of organic materials in the area.

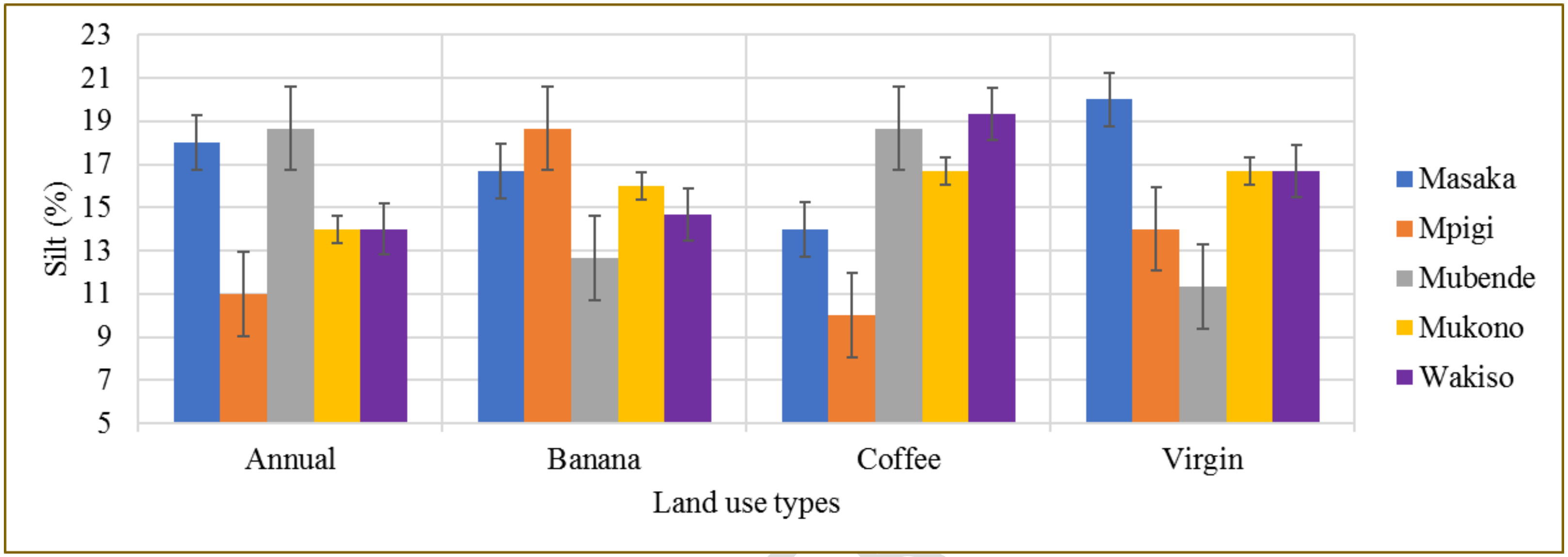

Figure 10: Percent clay composition on farmers' fields in Central Uganda

Silt was observed to be relatively low in the study locations. Virgin fields in Masaka had relatively high silt content (20%) followed by Coffee fields in Wakiso (19.33 %), banana fields in Mpigi (18.67 %), coffee fields in Mubende (18.67 %) and annual crop fields in Mubende (18.67 %). Relatively low silt content was observed to be similar in most of the study locations, suggesting limited silt effects on soil physical properties such as bulk density and texture that may influence soil fertility.

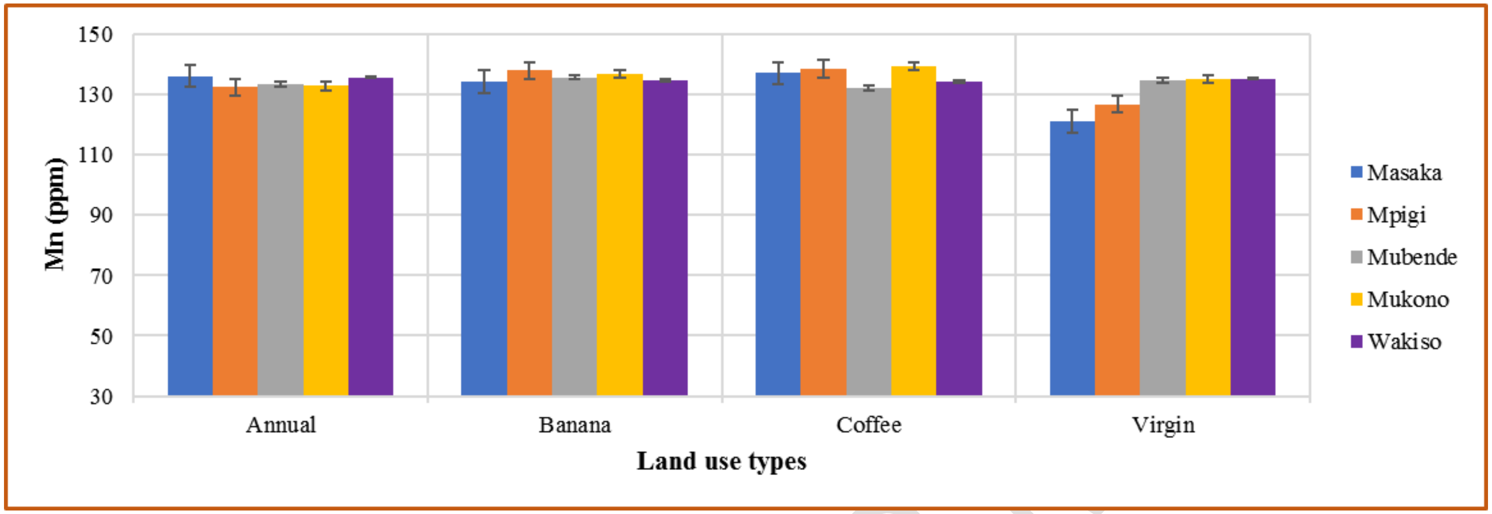

Figure 11: Manganese (Mn^{2+}) in the Ferralsols of Central Uganda

Manganese (Mn^{2+}) was observed to be very high in all the land use types in the study locations. The high Mn^{2+} concentrations across suggest toxicity effects of Mn^{2+} influencing soil acidity. The acidic buildup process in the study area correlates with the low pH.

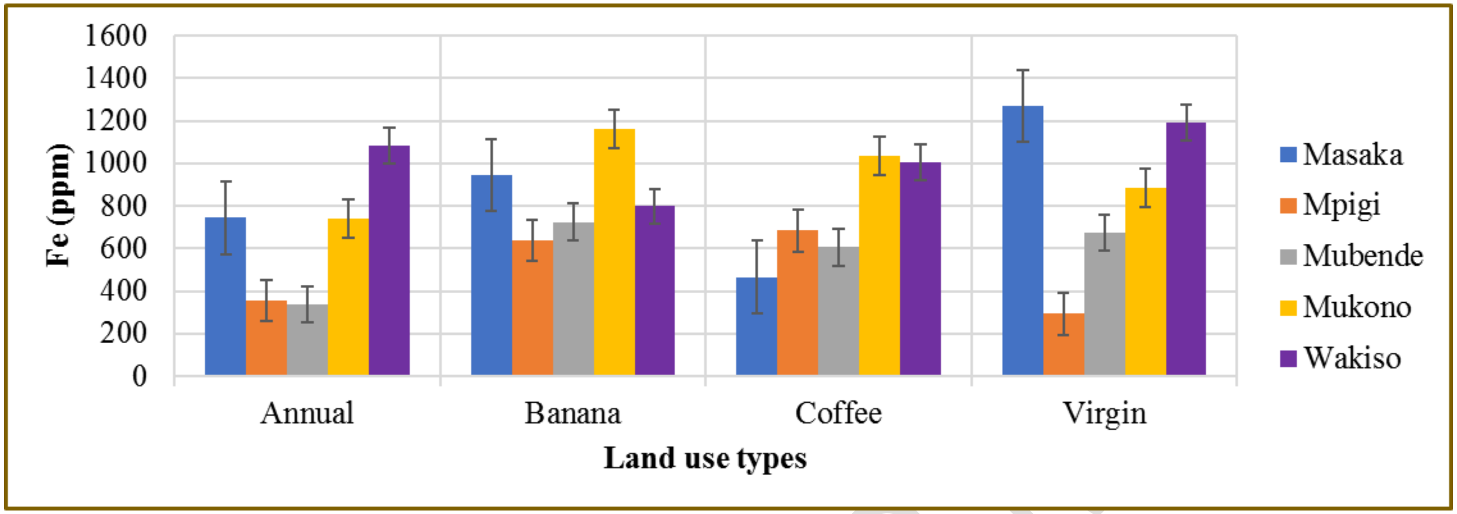

Figure 12: Assessment of Iron (Fe^{2+}) in the Ferralsols of Central Uganda

The study recorded high Fe^{2+} content in the different land use types. Virgin/undisturbed fields had the highestFe^{2+} content (1271.4 ppm) followed by banana fields in Mukono (1163.8 ppm), annual crop fields in Wakiso (1084.4 ppm) and coffee fields in Mukono (1035.8 ppm). There is a relatively high Fe^{2+} content in the land use types, indicating the gradual buildup of soil acidity in the study area.

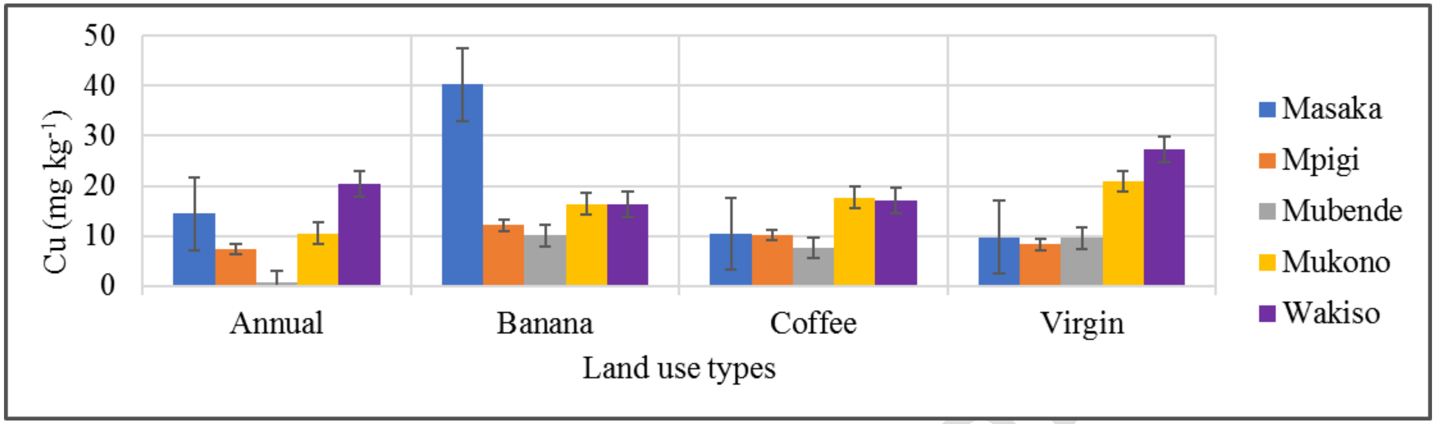

Figure 13: Copper (Cu^{2+}) in the Ferralsols of Central Uganda

Banana fields had the highest Cu^{2+} in Masaka (40.28 mg kg^{-1}) followed by virgin fields (27.41 mg kg^{-1}) and annual crop fields in Wakiso (20.43 mg kg^{-1}). The different land use types across the study locations showed relatively low Cu^{2+} content with annual crop fields having the lowest (0.8 mg kg^{-1}).

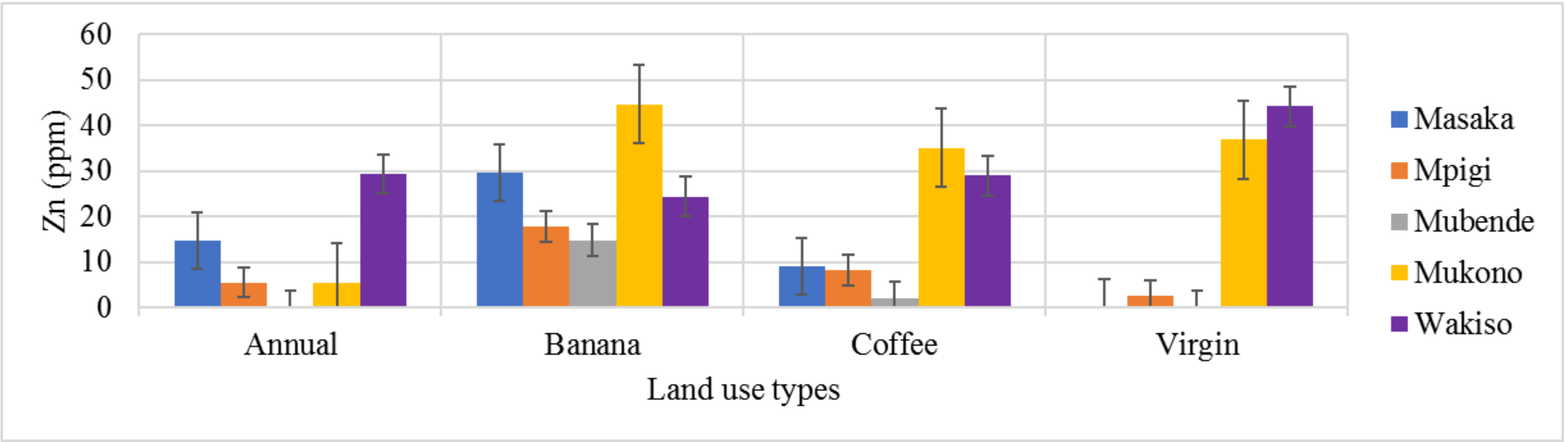

Figure 14: Assessment of Zinc (Zn^{2+}) in the Ferralsols of Central Uganda

The study recorded the highest zinc content among banana fields in Mukono (44.68 %) followed by virgin fields in Wakiso (44.17 ppm). The study location showed relatively low Zn^{2+} content in the different land use types, with practically no zinc recorded in annual and virgin/disturbed fields for Mubende