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Characterisation and Mapping of Soils in Major Coffee Growing Regions of Uganda

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Abstract

There is limited information on the soil nutrient status, site specific fertilizer and agronomic recommendations for coffee in Uganda hence limiting its production and productivity. Therefore, this study was undertaken to characterize the soils under coffee farms and provide fertilizer and land management recommendations for coffee farming in selected districts in Uganda. 717 soil samples were collected from 45 coffee growing districts that were purposively selected to represent the major coffee growing regions of Eastern, Northern, Western, Mid-west and West Nile. 35 districts were sampled from Robusta coffee growing areas and 10 districts from Arabica coffee growing areas. Parameters considered in the laboratory analysis included; pH, total organic carbon, total nitrogen, available P, exchangeable Calcium (Ca), Sodium (Na), Magnesium (Mg), and Potassium (K) and micro elements: Iron (Fe), Zinc (Zn), Copper (Cu), Manganese (Mn) and Boron, soil texture, bulk density and hydraulic conductivity. Soil nutrient levels distribution maps for Robusta and Arabica coffee growing regions were generated in ArcGIS for the entire country. The soil chemical and physical properties were subjected to analysis of variance using Genstat 14th edition. The soil mapping results showed that, the overall average soil macro-nutrients concentrations were significantly different across regions ($p < 0.05$) with Eastern having the highest levels of macro elements (CEC of 19.28 meq/100 g, Base Saturation (BS) of 43.40%, pH of 5.78, N of 0.20%, K of 1.64 meq/100 g, P of 107.68 mg/kg and OM of 3.31%) followed by Western region. No significant difference ($p > 0.05$) was recorded for the micronutrients across the different regions, except Zn ($p < 0.05$). This study showed that Phosphorus and Potassium were generally moderate to high levels in most of the regions sampled while Nitrogen and organic matter were moderate to low. Results from this study provide a general picture of the nutrient status across all coffee growing regions in Uganda and highlight the required modifications for increased production and productivity.

Keywords: coffee, soil, nutrient, productivity, Uganda

1. Introduction

Coffee is the second largest valued commodity in international trade and most widely traded tropical agricultural commodity after petroleum (UCDA, 2021; ICO, 2019). It plays a leading role in the livelihoods of Ugandans and contributes substantially to the national economy (Nahanga et al., 2015). Nearly 42% of farming households grow coffee which has contributed on average 30% of the country's foreign exchange earnings over the past 20 years (UCDA, 2015). Coffee continues to be one of the main cash crops of Uganda, playing a role in providing foreign exchange (NCP, 2013). The crop is grown on an estimated 353,907 hectares of land by about 1.7 million smallholder farmers (a quarter of them being female-headed) and 90% of these smallholder farmers owning gardens ranging between 0.5 and 2.5 hectares in size (Hill, 2005; NCP, 2013; Mugoya, 2018). Uganda grows two types of coffee; Robusta coffee occupies 80% and Arabica coffee, takes the remaining 20%. Contribution of Coffee to Uganda's export and foreign exchange earnings has increased from 8.2% in 1991/1992 to 23% in 2017/2018 Coffee Year in quantity and 14% to 28% in US$ 492 million value respectively (UCDA, 2019). For example, coffee exports for the coffee year (2022/23) totaled 6.14 million bags worth US$ 940.36 million (UCDA, 2023). More than 9 million people in Uganda are estimated to derive their livelihood from coffee-related activities along the value chain (NCP, 2013). It therefore has a very high employment potential, and poverty reduction effect on the smallholder farming households. The Government of Uganda National Development Plan III (NDP III) therefore prioritizes coffee as one of the six commodities for value addition for increased household incomes, exports earnings and import replacement.

In the last decades, smallholder coffee farmers have been experiencing declining agricultural productivity, mostly due to soil fertility depletion (Woniala & Nyombi, 2014), pests and diseases (Jonsson et al., 2015; Merga & Alemayehu, 2019; Nzeyimana et al., 2013) and poor land management (Pender, 2003; Okubal & Makumbi, 2000). Other main contributing processes to soil fertility decline are soil erosion, a decline in organic matter and soil biological activity, degradation of soil structure and loss of other soil physical qualities, reduction in availability of major nutrients (N, P, and K) and micro-nutrients, and an increase in toxicity due to acidification or pollution (Zake et al., 1997; NARO & FAO, 1999; NEMA, 1999). The underlying causes include; population pressure, poverty, land tenure insecurity, bad policies and institutions, poor infrastructure and services, and farmers' lack of knowledge about soil conservation methods (Pender et al., 2001).

Decline in soil fertility is the most limiting constraint particularly to coffee production in Uganda (Bekunda et al., 2002), where most agro-ecosystems remove more nutrients than are provided by external inputs (Edmeades, 2003). Farmers' decisions on the use of fertilizers in production requires an understanding of the expected crop yield which is a function of crop nutrient needs, nutrient supply from indigenous sources and the fate of the applied fertilizers (Bidraban et al., 2015). However, major gaps still exist on the status of nutrients, supply of nutrients from indigenous sources, site specific fertilizer recommendations and the general understanding of soil fertility in coffee ecosystems in Uganda (Wang et al., 2015). Soil mapping was therefore undertaken in 45 districts (35 that grow Robusta coffee, 10 that grow Arabica coffee). The objective was to characterize the soils under coffee farms and understand the regional specific soil nutrient status across coffee farms in Robusta and Arabica growing areas to guide site specific coffee nutrient recommendations.

2. Methodology

2.1 Characterisation of Soils Under Coffee Farms in Selected Districts of Uganda

2.1.1 Selection of Sampling Districts

The study was conducted in coffee growing area in Uganda (Figure 1).

A total of 45 districts were considered in this study for sampling (10 for Arabica and 35 for Robusta growing districts). The Arabica coffee growing districts for this study included: Kapchorwa, Sironko, Mbale, Bukwo, Kasese, Ibanda, Kanugu, Kisoro, Karenga and Zombo district. Robusta coffee growing districts sampled included Koboko, Lira, Arua, Gulu, Nwoya, Kiryandongo, Hoima, Kakumiro, Kagadi, Kyenjojo, Masaka, Mukono, Mityana, Mubende, Luweero, Sembabule, Nakaseke, Kyankwanzi, Bukomansimbi, Rakai, Ntungamo, Sheema, Mitooma, Kiruhura, Rwampara, Kamuli, Mayuge, Iganga, Busia, Pallisa, Luuka, Buliisa, Kabarole, Moyo and Mpigi. The districts sampled were selected purposively to represent the different coffee growing areas and the existing soil types. Uganda grows Robusta coffee and Arabica Coffee on a scale of 8:2. Arabica is grown in the highland areas on the slopes of Mount Elgon in the East, Mt. Rwenzori in the West and Mt. Muhavura in the South Western Region, Okoro highlands in West Nile and other highland areas at an altitude between 1200-2500 m above sea level (UCDA Arabica Coffee Manual, 2019).

Robusta is the major type of coffee grown in Uganda, accounting for about 80% of production. It grows in most low altitude areas of Uganda, covering Central, Eastern, Mid North, West Nile, Western and South Western Uganda that are within 900-1,500 m above sea level. Robusta has Lake Victoria Crescent as its native habitat (UCDA Robusta Coffee Manual, 2019).

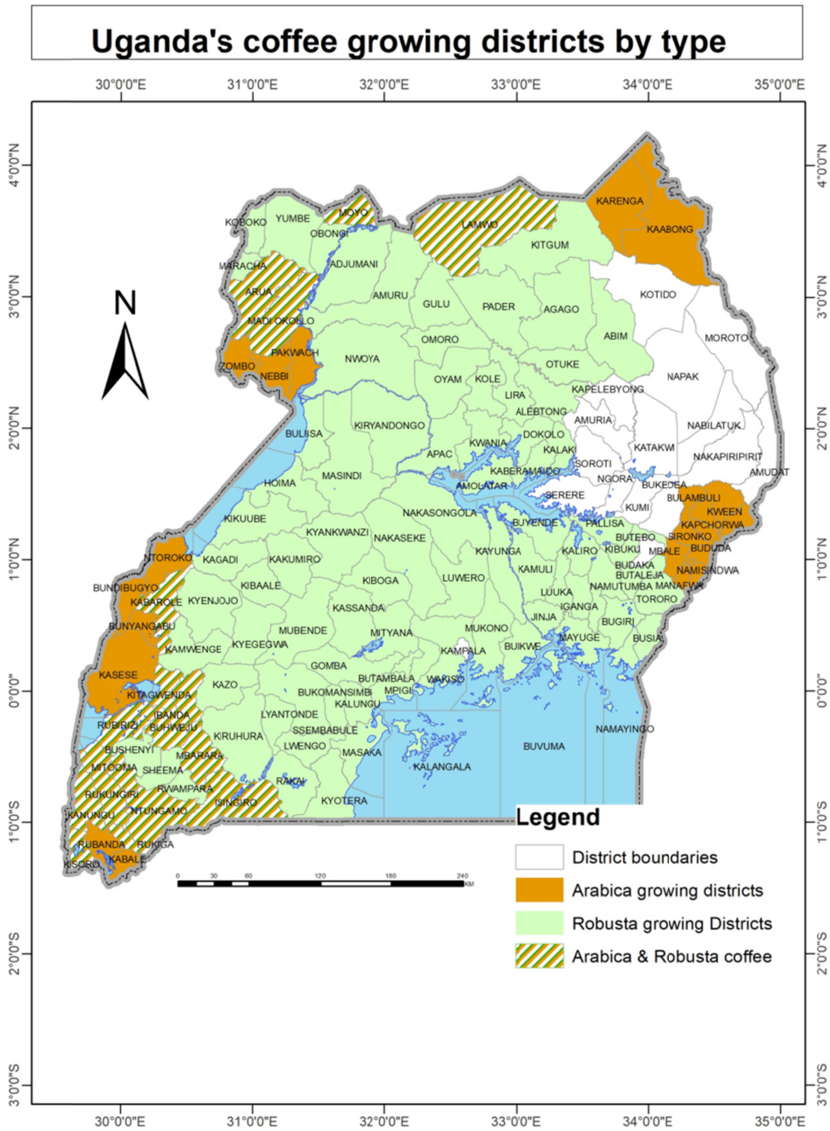

Figure 1. Coffee growing areas in Uganda which were sampled during the study

Source: Uganda Coffee Development Authority: Arabica Coffee Manual 2019.

2.1.2 Soil Sampling and Laboratory Analysis

(1) Collection of Soil Samples from Farmers' Fields and Soil Profiles

Soil samples were collected during the rainy season of May to June 2021 from farmers' coffee gardens in the 45 districts. Soil profiles representing major soil units based on the FAO soil map of Uganda, 1997, were also collected. Five composite samples from coffee farmers' gardens were collected randomly for each of the perceived low and high fertile soils for all the districts. In addition, two soil samples were collected from each soil profiles. For both soil profile and gardens, soil samples were taken at a depth of 0-30 cm, as an agricultural layer. A total of 717 (159 Arabica and 558 Robusta) soil samples were collected for this exercise, 477 from the coffee gardens and 240 for the soil profiles.

Profile data were collected using a well-structured data sheet developed for this purpose following the World Reference Base (WRB 2014) guidelines for the profile and the auger samples. All the soil sampled and profile points were geo-referenced using etrex 10 GPS. Samples that were collected were taken to the laboratory for analysis. The Laboratory analytical data together with the field data were used to assign and confirm the final standard names to the base units basing on the World Reference Base (WRB 2014) guidelines.

(2) Laboratory Analysis

Soil samples were air-dried, ground and sieved through a 2 mm sieve and then analysed using the standard methods (Okalebo et al., 2002). The analysis included: pH, total organic carbon, total nitrogen, available P, exchangeable Calcium (Ca), Sodium (Na), Magnesium (Mg), and Potassium (K) and micro elements Iron (Fe), Zinc (Zn), Copper (Cu), Manganese (Mn) and Boron, soil texture, bulk density and hydraulic conductivity.

Soil pH was measured using a pH meter (1: 2.5 soil: water); SOM and total N were determined using Walkley and Black method and Kjedhal method, respectively. Soil texture was determined using Bouyoucos hydrometer method (Bouyoucos, 1960) while their textural classes were determined according to the FAO classification (FAO, 1990). Copper, zinc, iron and manganese were measured by atomic absorption spectrophotometer method. Exchangeable bases were determined by the procedures described by Okalebo et al. (2002). Five (5 g) of air-dried soil, 100 ml of ammonium acetate was added in a clean plastic bottle and shaken for 30 minutes. The contents were filtered through number 42 Whatman paper and this constituted the extract for measuring Na, K, Ca and Mg. Sodium and K were measured on a flame photometer while Ca and Mg were determined by atomic absorption spectrophotometer at wave length of 422.7 nm and 285.2 nm respectively.

In addition to the procedures used to extract total micro-nutrient (Okalebo et al., 2002), standard solutions for micronutrients (Zn, Cu, Fe, Mn) were prepared in Diethylenetriamine Penta-Acetate (DTPA) extraction solution using Certified Reference Material (CRMs). DTPA metal-extraction principle and protocol was as described by Lindsay and Norvell (1978). Diethylenetriamine Penta-Acetate (DTPA) was used as chelating agent which can effectively bind with water-soluble and weakly adsorbed exchangeable metals in soil. The chelation reactions are slow and required weeks or months to attain the equilibrium state. Therefore, DTPA quantity in solution-to-soil ratio (2:1) was adjusted at a level that can chelate metals equal to 10 times of atomic weight of respective metals. This reduces the competition between metals ions to bind with chelating agent. Calcium Chloride ($CaCl_2$) maintains higher CO_2 level in soil and avoids the release of metals bonded with $CaCO_3$ by inhibiting dissolution of $CaCO_3$ in calcareous soils.

Soil particle analysis to estimate the percentage sand, silt and clay (texture) was determined using the hydrometer method. The hydrometer method of determining the proportions of sand, silt and clay depends on particle size of the differential settling velocities in a water column. The settling velocity is a function of liquid temperature, viscosity and specific gravity of the falling particle. Saturated hydraulic conductivity and bulk density were also determined in all plots surveyed. Saturated hydraulic conductivity was determined using the inverse auger-hole method, while bulk density was determined using the core method.

2.1.3 Statistical Analysis

Data collected on both soil physical and chemical properties during the study was entered into excel and subjected to various types of analyses. Both descriptive and inferential statistical analytical tools were used in the study. Summary statistics (means, variances) were used to compare soil properties from different geographical locations. Analysis of variance was performed on soil chemical properties such as CEC, N, C, P, K and soil physical properties like texture (% sand, silt and clay) was carried out using GenStat 14th Edition statistical package; and significant means were separated using Least Significant Difference (LSD) at the 0.05 probability level.

3. Results and Discussions

3.1 Characteristics of the Soils Under Coffee Farms in Selected Districts in Uganda

Table 1 shows the overall average soil macro-nutrients concentrations across the different regions. These concentrations were significantly different across regions ($p < 0.05$). Generally, the Eastern region had higher levels of CEC of 19.28 meq/100 g, BS of 43.40%, pH of 5.78, N of 0.20%, K of 1.64 meq/100 g, P of 107.68 mg/kg, Na of 0.32 meq/100 g, Ca of 10.32 meq/100 g, Mg of 3.94 meq/100 g, OC of 1.92% and OM of 3.31% compared to other regions except for P which was 107.68. This was followed by Western Region which had levels of CEC of 14.32 meq/100 g, BS of 38.63%, pH of 5.75, N of 0.25%, P of 173.38 mg/kg, K of 1.11 meq/100 g, Na of 0.15 meq/100 g, Ca of 8.86 meq/100 g, Mg of 4.19 meq/100 g, OC of 2.33% and OM of 4.02%.

Table 1. Soil macro-nutrients content by region

Region	CEC	BS	pH	N	P	K	Na	Ca	Mg	OC	OM	Sand	Clay	Silt
Central	10.29	33.89	5.45	0.15	34.21	0.52	0.09	6.25	2.76	1.43	2.46	52.59	33.95	15.11
Eastern	19.28	43.40	5.78	0.20	107.68	1.64	0.32	10.32	3.94	1.92	3.31	47.61	34.15	18.24
Mid-western	11.36	34.27	5.77	0.19	29.37	0.86	0.12	7.47	3.27	1.86	3.21	54.26	31.84	14.95
Northern	8.17	32.15	5.62	0.12	20.91	0.50	0.11	5.37	2.20	1.21	2.06	58.11	32.26	9.63
S-Western	9.10	32.88	4.93	0.23	74.18	0.77	0.09	5.75	2.60	1.64	2.83	50.73	30.97	17.25
West Nile	8.67	32.68	5.66	0.12	34.66	0.67	0.08	5.57	2.34	1.27	2.19	61.93	25.60	12.47
Western	14.32	38.63	5.75	0.25	173.38	1.11	0.15	8.86	4.19	2.33	4.02	53.58	31.21	15.21

There were no significant differences ($p > 0.05$) across the different regions for micro nutrients except Zn.

Table 2. Soil micro-nutrients content comparison by region

Region	Fe	Cu	Zn	B	Mo	Mn
Central	132.53	86.09	84.33	23.62	0.06	55.88
Eastern	217.35	57.00	81.17	24.89	0.02	42.88
Mid-western	98.52	64.99	100.19	33.77	0.10	28.21
Northern	170.91	101.98	61.51	48.76	0.08	63.61
South-western	73.87	44.84	51.61	17.38	0.06	38.55
West Nile	149.22	93.00	174.40	37.74	0.10	57.67
Western	115.39	51.22	94.33	28.23	0.10	31.62

3.2 Distribution of the Major Nutrients in Coffee Growing Regions

3.2.1 Organic Carbon

Organic carbon is related to soil organic matter. The latter affects nutrients in several ways. It is very vital in improvement of the soil structure which is vital for root development. Organic matter is responsible for moisture and nutrient retention. A good soil should have SOM of at least 3%. Figure 2 shows how organic carbon (OC) in the country was distributed. The organic carbon concentration ranges from 1.27 to 6.56 mg/kg with an average of 2.51 mg/kg in the country. The organic carbon concentration in the soil is generally moderate throughout the country. The only patches of high organic carbon concentration were on the western shores of Lake Victoria (Kabarole, Mityana, Masaka and Bukomansimbi districts). The low concentrations of organic carbon in soils were found in west Nile districts, Busia in the east and central districts while the rest of the regions had moderate levels of organic Carbon. The low level of N and carbon in other areas could be due to continuous mining in these sites and its removal through harvest and biomass transfer as observed by Stoorvogel and Smaling (1990) and Gachimbi (2002) while working on nutrient flows and balances. The variability of soil fertility in the land uses depends on the land use, level of nutrient (organic or inorganic) application, type of crop grown which is in most times based on farmers' perception of soil quality in farm unit.

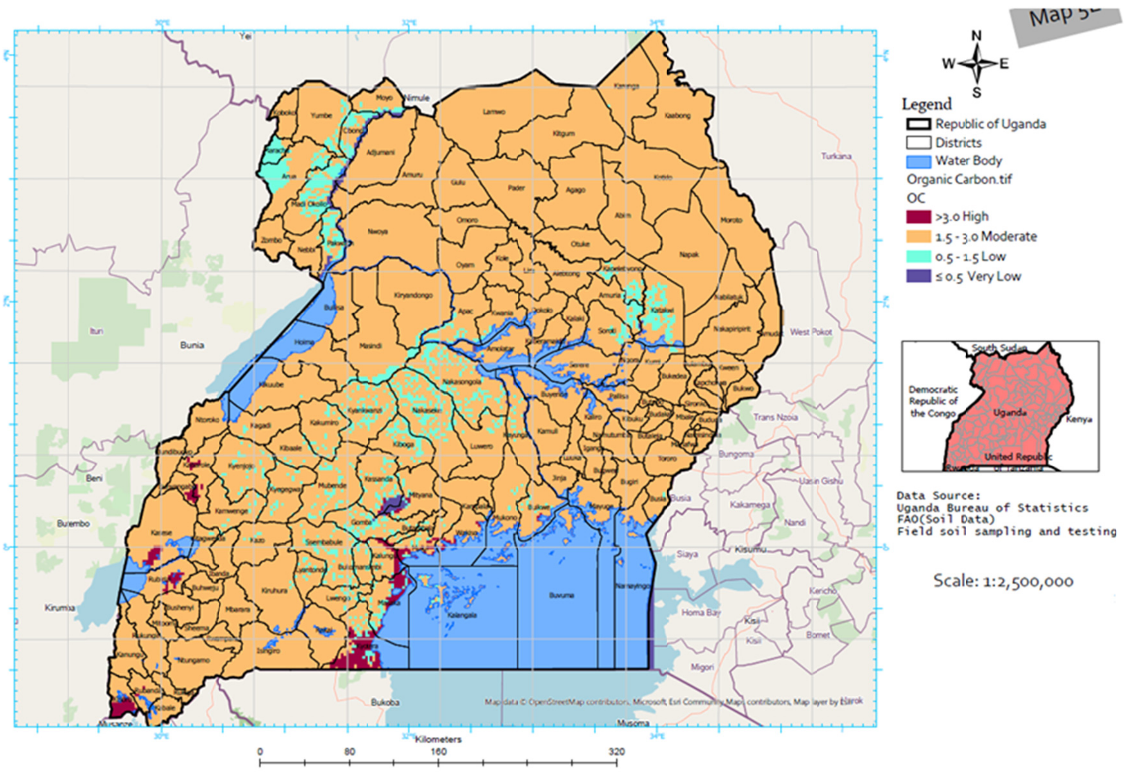

Figure 2. Organic carbon distribution in coffee soils of Uganda

3.2.2 Total Nitrogen

Nitrogen, is a plant nutrient required in the largest quantity by all the plants of all the mineral nutrients known. It is a building block of chlorophyll pigment which is responsible for making leaves and/or some stems green which helps in capturing light energy during photosynthesis. It is a very big component of amino acids, which are the building blocks of proteins and thus a component of nucleic acids. It enables growth and reproduction of plant cells and responsible for plant vigour. A normal soil, N is at least 0.2% for optimum growth of crops.

Figure 3 shows the distribution of nitrogen in the country. The nitrogen concentration ranges from 0.11 to 0.77 mg/kg with an average of 0.27 mg/kg in the country. The total nitrogen concentration in the soil was generally moderate across the country. The only area with a patch of soils with very high nitrogen concentration was found in Kisoro while patches of soils with high concentration of nitrogen were observed in Bukwo, Kapchorwa, a small portion of Kisoro, Kyotera, Masaka, Mpigi, Mbale, Busia, Kisoro, Sironko, and Mayuge. Low concentrations of nitrogen in soils were found in Moyo, small portions of Masaka and Bukomansimbi districts. N trends can be explained by low pH and non-usage of N-fertilizers and continuous removal via crop harvest. Mono-cropping and continuous tillage are regarded as the major inefficient agricultural practices which promotes nutrient loss through leaching, volatization, soil erosion and immobilisation. Nutrient loss from Ugandan soils amounts to 87 kg of nutrients (NPK) per hectare per year; in ratios of 38 kg of nitrogen; 17 kg of phosphorus and 32 kg of potassium (Sunday & Ocen, 2015). Furthermore, Uganda has been cited as one of the countries with very high nutrient mining rates (Bekunda et al., 2004; Nyombi, 2013). Nutrient mining in Uganda arises from the incessant transportation of direct farm harvests from rural farms to urban centres.

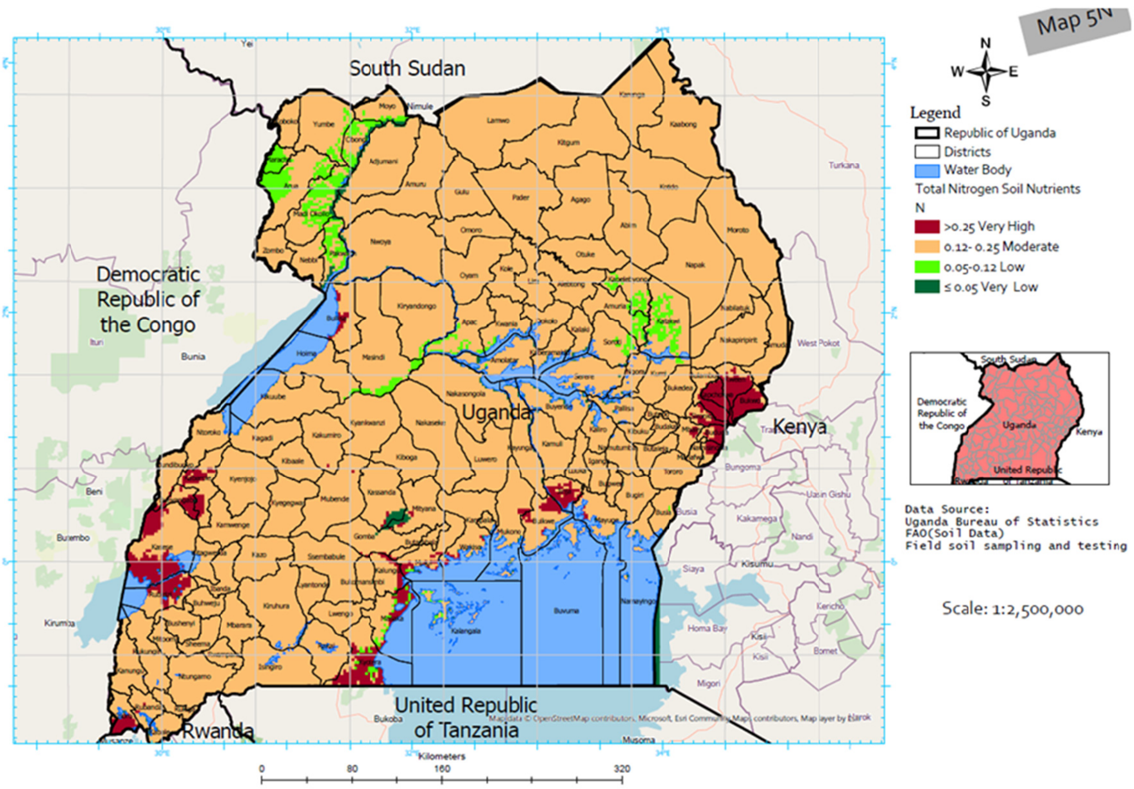

Figure 3. Total nitrogen distribution of coffee soils in Uganda

3.2.3 Available Phosphorus

Phosphorus is a major component of nucleic acids, an energy store which drives many biochemical reactions, and responsible for root development and general plant vigour. It should be at least 15 mg/kg of soil. Figure 4 shows the distribution of phosphorus in the country. The phosphorus concentration ranged from 2.2 to 92.2 mg/kg with an average of 16.2 mg/kg in the country. Like Nitrogen, the total phosphorus concentration in the soil was generally moderate across the country. Patches of soils with high concentration of phosphorus were observed in Bukwo, Sironko, Kyenjojo and Kyotera a small portion of Kisoro and Mitooma. Very high concentrations of phosphorus in soils were found in Zombo, Moyo, Arua, Gulu, Nwoya, and Bukwo. Patches of low available P were observed in Jinja and Mayuge in Eastern Uganda, Miyana and Kasanda districts in Central and Kasese in Western Uganda. The isolated low P trends can be explained by low pH and non-usage of P-fertilizers and continuous removal via crop harvest.

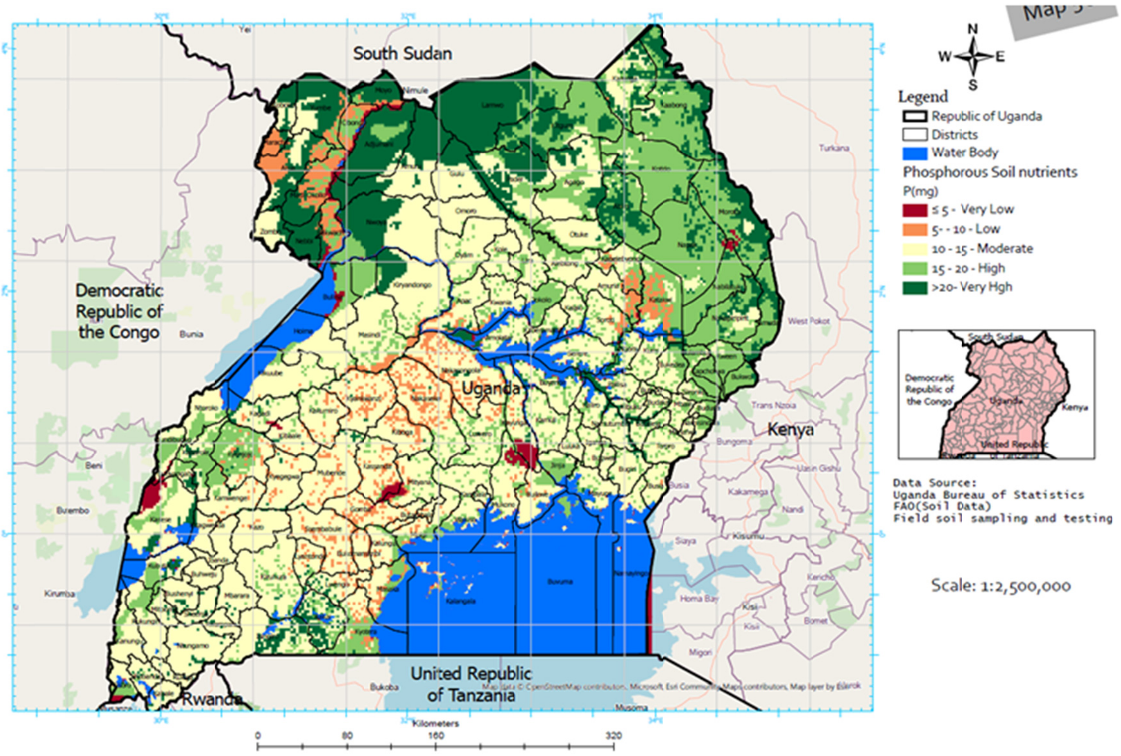

Figure 4. Distribution of available Phosphorus in the major coffee growing regions of Uganda

3.2.4 Potassium

Potassium is the second to nitrogen in nutrient uptake by the plants. It increases photosynthesis and water use efficiency, essential to protein synthesis, fruit formation and seed quality in plants. It also activates enzymes involved in many biochemical activities and controls their reaction rates as well as increases disease resistance in plants. Potassium is responsible for prevention of pests and diseases.

Figure 5 shows the distribution of potassium in the country. The potassium concentration in the soil is generally high to very high. The potassium concentration ranged from 168.9 to 999.7 mg/kg with an average of 448.7 mg/kg in the country. The very high to high potassium concentration included mainly almost the entire country. The only patches with low levels of potassium were found in Moyo, and Mityana. This indicated non-usage of potassium containing fertilizers on soils that are already K deficient and luxury use of K fertilizers at some sites.

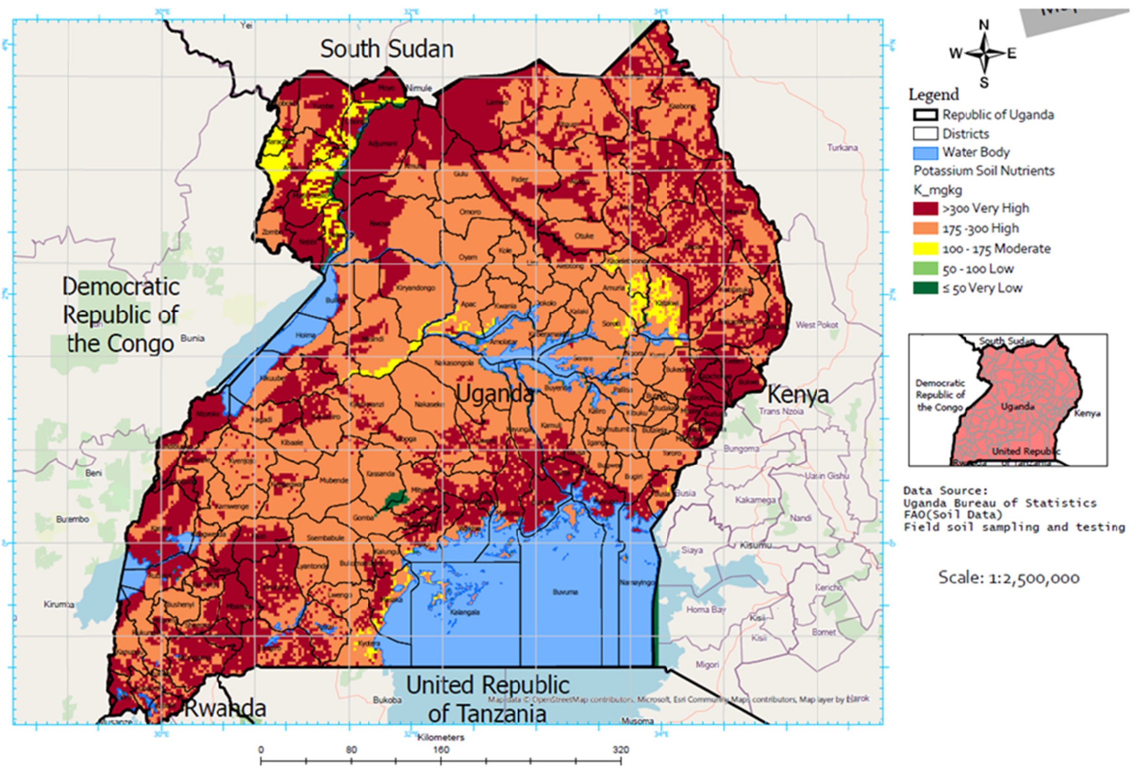

Figure 5. Potassium distribution in coffee growing regions of Uganda

3.2.5 Cation Exchange Capacity

Figure 6 shows the distribution of the cation exchange capacity in soils of the whole country. The base saturation concentration ranges from 7.4 to 33 cmol/kg with an average of 16.2 cmol/kg in the country. The cation exchange capacity in soils is generally moderate throughout the country. Patches of very high CEC were observed in Kisoro, Masaka, Sironko and Bukwo. Small patches of high CEC were detected in Kabarole. Patches of low CEC were observed in scattered places of the central region of Nakaseke, Kyankwanzi and the north-western in Arua, and Moyo. Cation exchange capacity is an important indicator of the fertility potential. Soils with high CEC retain cation plant nutrients against leaching and these cations are subsequently released for plant uptake. Soils rich in clay and organic matter have higher CEC whereas sandy soils have very low/minimal CEC (Zhang et al., 2017). For the same reason, there is high nutrient leaching under sandy soil and low leaching in clayey and high organic matter soils. Further influence of CEC is on the management of fertilizers. In soils with low CEC, fertilizer application should match plant uptake since such soils cannot store the unabsorbed nutrients. Soils normally have a net negative charge and it is for this reason that they are able to absorb the cations which are positively charged.

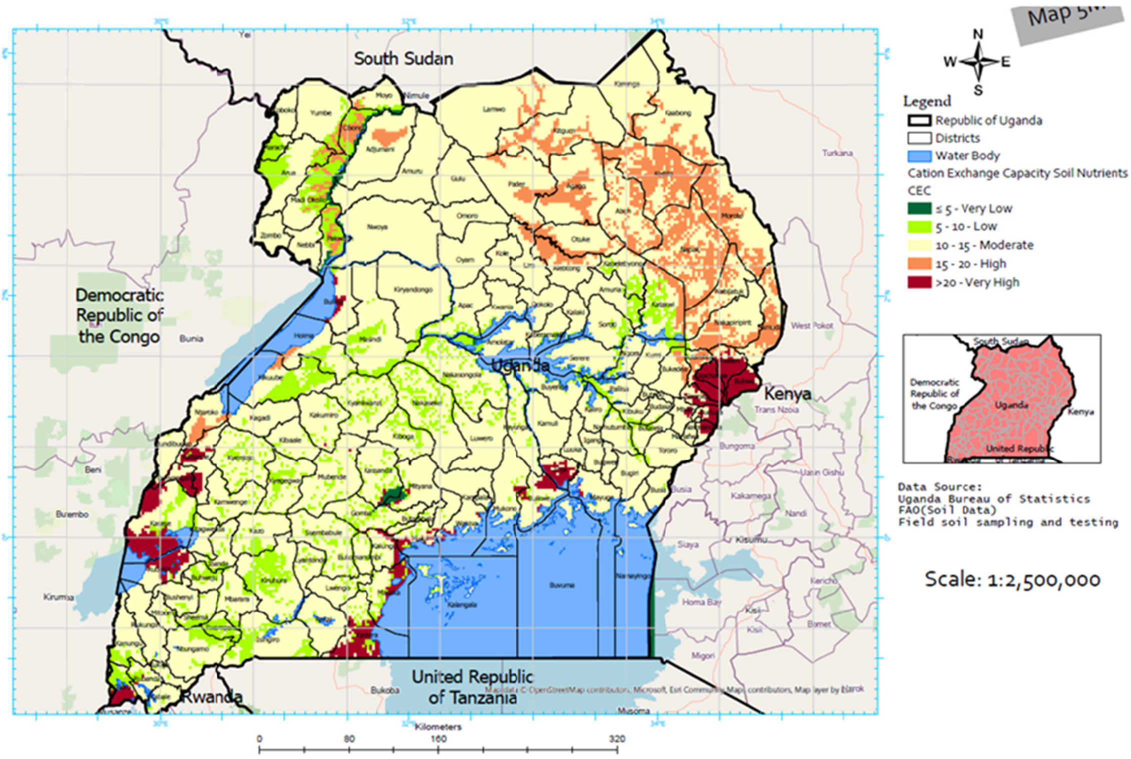

Figure 6. Cation Exchange Capacity of soils in Coffee growing regions in Uganda

3.2.6 Base Saturation

Figure 6 shows the distribution of the saturation of bases in soils of the whole country. The base saturation concentration ranges from 28 to 77% with an average of 43.3% in the country. The base saturation concentration in soils is generally moderate throughout the country. Patches of very high base saturation were observed in Bukwo, while small patches of high base saturation were detected in Kabarole, Masaka, Bukomansimbi and part of Kisoro too.

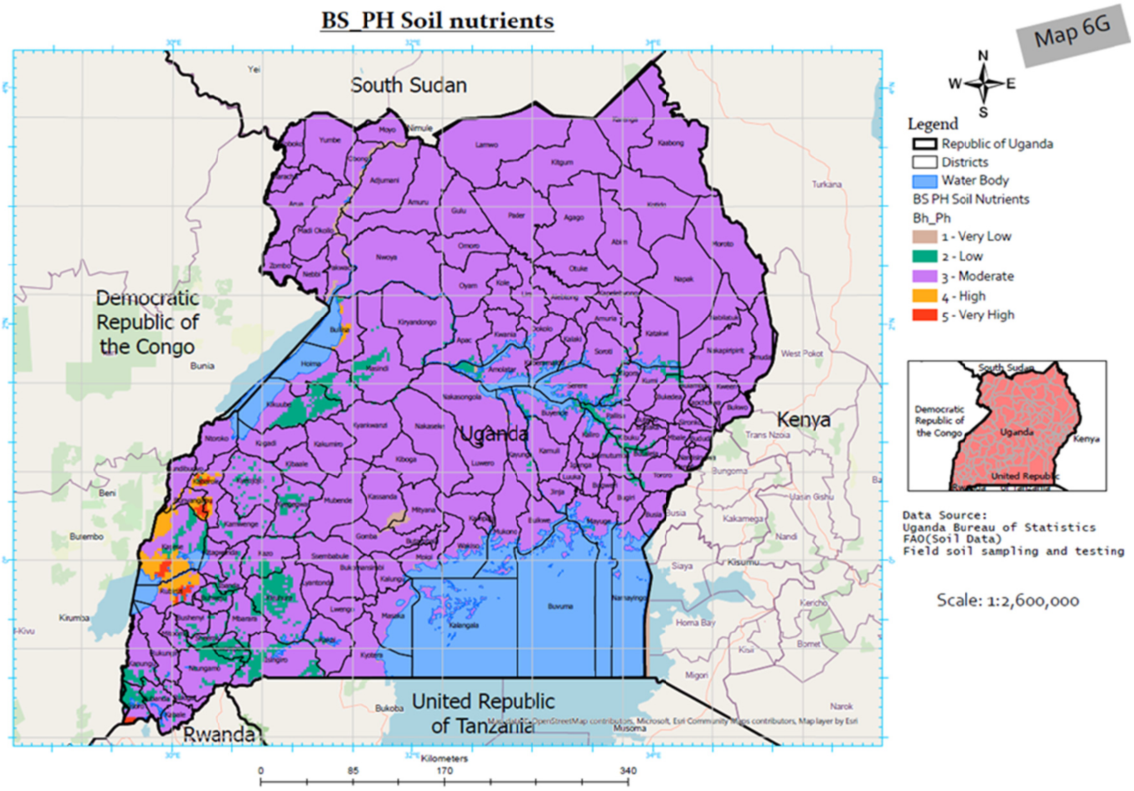

Figure 7. Base saturation and pH of major coffee growing regions of Uganda

The combination of base saturation and pH is also shown in Figure 7. The majority of the country is rated moderate. Patches with high and very high factor rating are located around Kisoro. Patches with low factor rating are located in Kiruhura, Rwampara, Kyenjojo, Mitooma, Ntungamo, Kiryandongo and the soil around the Lake Kyoga. In these circumstances phosphorus and other nutrients like molybdenum will not be available to plants as it tends to be fixed on soil clay surfaces. The low pH would be responsible for low available P in most sites. At extremely low pH, (pH 3.61 to pH 5.5) phosphorus is susceptible to precipitation by iron and aluminium. Both non-acidifying and acidifying fertilizers will be selectively recommended depending on the soil pH at respective sites. Soils with high percentage base saturation have a higher pH; therefore, they are more buffered against acid cations from plant roots and soil processes that acidify the soil (nitrification, acid rain, etc.). They contain greater amounts of the essential plant nutrient cations K^+, Ca^{2+} and Mg^{2+} for use by plants.

3.2.7 Texture Classes

Soil texture is regarded as the permanent property of the soil that cannot be altered easily. It can influence most of all soil properties. For example, if sandy it can lead to loss of all the nutrients away from the root zone through leaching. It is composed of soil particles, *i.e.*, sand, clay and silt. Based on location and soil depth, a total of four soil textural classes were observed. They are: loam (L), clay loam (CL), silty clay (ZL) and clay (C).

4. Conclusion

Soils of the targeted districts presented differences in soil chemical properties. From the results, it is clear that soils under coffee in Western region are characterized by low phosphorus; West Nile region has low nitrogen, potassium and phosphorous,

South-western, Mid-western and Northern regions are experiencing low pH, nitrogen, potassium and phosphorus, Eastern region has low nitrogen, phosphorus and potassium while Central region is experiencing low nitrogen, phosphorus and pH. Each region requires a specific corrective measure to sustainably increase coffee production and productivity. Farmers are encouraged to test their soils regularly and apply specific corrective measures.

5. Recommendations

Based on the findings of this study, regional specific recommendations can now be calculated and applied. Farmers can also apply the following fertilizer formulations and land management practices to improve coffee production in their regions.

Table 3. Site specific fertilizer and land management practices for different coffee growing regions

Region	Nutrient (Deficient or Limiting)	Current Nutrient Status Levels per Study	Nutrient Classes Range	Recommendations
Central Masaka, Mukono, Mubende,Mityana, Luwero, Sembabule, Rakai, Nakaseke, Mpigi, Bukomansimbi	N (%)	0.14	High > 0.25 Moderate 0.12-0.25 Low 0.05-0.12 Very low < 0.05	The moderate nitrogen concentration levels in Central Uganda will require incorporation of compost manure. Furthermore, addition of coffee specific fertilizers to such soils in particular NPK 22:6:12 + Mg + S + Zn + B) is encouraged. Incorporation of agroforestry and cover crops such ascrotalaria (*Crotalaria spectablis*), cowpea (*Vigna unguiculata* L. Walp.), and *Brachiaria brizantha* (*Urochloa brizantha*) can also help. These can be ploughed back into the soil at harvest to incorporate nitrogen
Eastern Kapchorwa, Sironko, Mbale, Bukwo, Iganga, Kamuli, Mayuge, Luuka, Pallisa, Busia	P (mg/kg)	12.66	> 15	Application of fertilizers that contain Phosphorus such as Di Ammonium Phosphate (DAP) and Tri Super Phosphate (TSP) is suggested. Manure should also be applied if available.
Mid-Western Buliisa, Kyankwasi, Kiryandongo, Hoima, Kakumiro, Kagadi	P (mg/kg)	6.3	> 15	Application of fertilizers that contain Phosphorus such as Di Ammonium Phosphate (DAP) and Tri Super Phosphate (TSP) is suggested. Manure should also be applied if available.
Northern Lira, Gulu, Nwoya, Karenga	N (%)	0.11	Highl; > 0.25 Moderate 0.12-0.25 Low 0.05-0.12 Very low < 0.05	Integrated soil fertility management involving addition of manure and inorganic fertilizers is recommended. Application of coffee specific fertilizers in particular NPK 22:6:12 + Mg + S + Zn + B) is also recommended.
	P (mg/kg)	6.31	> 15	Application of fertilizers that contain Phosphorus e.g. DAP is recommended. Addition of organic matter inform of compost will also help buffer soil pH while also adding P.
South Western Uganda Ntungamo, Sheema, Mitooma, Kiruhura, Rwampara, Kanungu, Ibanda, Kisoro	P (mg/kg)	10.8	> 15	Integrated soil fertility management involving adding manure, inorganic fertilizers and growing legumes with coffee will help add nitrogen. It is also recommended to add coffee specific fertilizers in particular NPK 22:6:12 + Mg + S + Zn + B).
West Nile Moyo, Arua, Zombo,Koboko	N (%)	0.10	High > 0.25 Moderate 0.12-0.25 Low 0.05-0.12 Very low < 0.05	Integrated soil fertility management involving adding manure, inorganic fertilizers and growing legumes with coffee will help add nitrogen. It is also recommended to add coffee specific fertilizers in particular NPK 22:6:12 + Mg + S + Zn + B) applied in two splits.
	P (mg/kg)	7.00	> 15	Apply fertilizers that contain Phosphorus such as DAP and TSP. Apply manure and intercrop with cover crops like Mucuna, *Brachiaria brizantha*. Addition of coffee specific fertilizers in particular NPK 22:6:12 + Mg + S + Zn + B).
Western Kabarole, Kyenjojo, Kasese	P (mg/kg)	4.72	> 15	Apply fertilizers that contain Phosphorus such as DAP and TSP. Apply manure and intercrop with cover crops like Mucuna, *Brachiaria brizantha*. Addition of coffee specific fertilizers in particular NPK 22:6:12 + Mg + S + Zn + B).

References

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal, 53*, 464-465. https://doi.org/10.2134/agronj1962.00021962005400050028x

FAO (Food and Agriculture Organization). (1990). *Soil units of the soil Map of the World*. FAO-UNESCOISRIC, Rome, Italy. https://doi.org/10.2136/sh1982.4.0003

FAO (Food and Agriculture Organization). (2019). FAOSTAT. Crops, National production, FAO, Rome, Italy.

ICO (International Coffee Organization). (2015). *Statistics of production 2015*. Retrieved May 5, 2022, from http://www.ico.org

ICO (International Coffee Organization). (2019). Retrieved May 12, 2022, from http://www.ico.org

Jonsson, M., Raphael, I. A., Ekbom, B., Kyamanywa, S., & Karungi, J. (2015). Contrasting effects of shade level and altitude on two important coffee pests. *Journal of Pest Science, 88*, 281-287. https://doi.org/10.1007/s10340-014-0615-1

Merga, W., & Alemayehu, D. (2019). Effects of climate change on global arabica coffee (*Coffea arabica* L.) production. *Greener Journal of Plant Breeding and Crop Science, 7*(1), 23-30. https://doi.org/10.20431/2454-6224.0511004

Nahanga, V., Bamwesigye, D., & Antwi, S. D. (2015). *Analysis of Coffee Production and Exports in Uganda*. Brno: Faculty of Regional Development and International Students Mendel University.

NARO (National Agricultural Research Organization), & FAO (Food and Agriculture Organization). (1999). *Soil Fertility Initiative Concept Paper* (pp. 3-18). Ministry of Agriculture, Animal Industry and Fisheries (MAAIF), Kampala, Uganda.

Nkonya, E., Place, F., Kato, E., & Mwanjalolo, M. (2015). Climate Risk Management through Sustainable Land Management in Sub-Saharan Africa. In R. Lal, B. Singh, D. Mwaseba, D. Kraybill, D. Hansen, & L. Eik (Eds.), *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa* (pp. 75-112). Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-09360-4_5

Nzeyimana, I., Hartemink, A. E., & de Graaff, J. (2013). Coffee farming and soil management in Rwanda. *Outlook on Agriculture, 42*(1), 47-52. https://doi.org/10.5367/oa.2013.0118

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). Laboratory methods of soil and plant analysis: A working manual second edition. *Sacred Africa, Nairobi, 21*, 25-26.

Pender, J., Jagger, P., Nkonya, E., & Sserunkuuma, D. (2004). Development pathways and land management in Uganda. *World Development, 32*(5), 767-792. https://doi.org/10.1016/j.worlddev.2003.11.003

Sunday, G., & Ocen, D. (2015). *Fertilizer consumption and fertilizer use by crop in Uganda* (pp. 1-37). Ministry of Agriculture, Animal Resources and Fisheries.

UCDA (Uganda Coffee Development Authority). (2015). *Coffee report—Uganda coffee development*. Retrieved from http://bit.ly/2X49pII

UCDA (Uganda Coffee Development Authority). (2019). *Coffee Report—Uganda Coffee Development Authority Annual Report, 2019*. Kampala, Uganda.

UCDA (Uganda Coffee Development Authority). (2021). Chapter 2: Strategy and Business Development. *Uganda Coffee Development Authority Annual Report 2018/19*.

UCDA (Uganda Coffee Development Authority). (2023). Chapter 3: Value Addition and Quality Improvement. *Uganda Coffee Development Authority Annual Report 2018/19*.

Vaast, P., Harmand, J. M., Rapidel, B., Jagoret, P., & Deheuvels, O. (2016). Coffee and cocoa production in agroforestry—A climate-smart agriculture model. *Climate Change and Agriculture Worldwide* (pp. 209-224). https://doi.org/10.1007/978-94-017-7462-8_16

Wang, N., Jassogne, L., van Asten, P. J., Mukasa, D., Wanyama, I., Kagezi, G., & Giller, K. E. (2015). Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. *European Journal of Agronomy, 63*, 1-11. https://doi.org/10.1016/j.eja.2014.11.003

Woniala, J., & Nyombi, K. (2014). Soil fertility management by smallholder farmers and the impact on soil chemical properties in Sironko district, Uganda. *Res J Agric for Sci*., *2320*, 6063.

World Reference Base for Soil Resources. (2014). International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. *World Soil Resources Reports No. 106*. FAO, Rome.

Zake, J. S., Charles, N., & Magunda, M. K. (1999). In H. Nabhan, A. M. Mashali, & A. R. Mermut (Eds.), *Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and East Africa: Proceedings of the Expert Consultation*. Harare, Zimbabwe: Food and Agriculture Organization of the United Nations.

Zake, J. Y., Magunda, M. K., & Nkwiine, C. (1997). *Integrated Soil Management for Sustainable Agriculture and Food Security: The Ugandan case*. Paper presented at the FAO workshop on integrated soil management for sustainable Agriculture and Food security in southern and Eastern Africa, December 8-12, 1997, Harare, Zimbabwe.

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Authors Contributions

Dr. Gerald Kyalo was responsible for conceptualization, design, survey, interpretation of results, and manuscript writing and review; Mr. Peter Charles Apunyo was responsible for data collection, analysis, manuscript writing and review; Prof. Majaliwa Mwanjalolo was responsible for design of the survey, analysis of soil samples, generation of maps and interpretation; Mr. Charles Kizza Luswata was responsible for data collection, analysis of soil samples and review of manuscripts; Mr. Ronald Kawooya was responsible for data collection, manuscript writing and review and Dr. Emmanuel Iyamulemye Niyibigira was responsible for conceptualization and manuscript review. All authors read and approved the final manuscript.

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No additional data are available.