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Soil Fertility Status of Smallholder Farms in Northern Highlands, Tanzania

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Abstract

Real-time information on soil fertility status is crucial in predicting the decline in soil quality, to help design appropriate management options. This research was undertaken to explore the fertility status of the soils from smallholder farms in northern highlands of Tanzania for sustainable crop production. Thirty-one composite soil samples were collected from different farmers' fields and analyzed for physical-chemical properties, then used to rate the soil fertility status. Results indicated that the major soil fertility constraints in the Mbulu district were high exchangeable acidity levels in 40% of the farms, low nitrogen and organic carbon in 100% of the farms, low Mg and phosphorous in 66.67%, low calcium (Ca) and zinc (Zn) in 13.33% and 6.67% respectively, and presence of excessive iron and manganese in 100% and 50% of the farms respectively, that would lead to toxicity of crops. Moshi soil was constrained by very high acidity levels (pH<5.0), deficient in exchangeable bases (calcium, magnesium, and potassium), and excessive in exchangeable micronutrients (Zn, Fe, and Cu) which might affect the productivity of various crops cultivated. It is recommended that soil fertility management options should be worked out for specific farms and crops for improved crop production in the northern highlands of Tanzania.

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Introduction

Reduction of soil productivity and increased food insecurity in most developing countries including Tanzania, and especially among smallholder farmers, is associated with the decline in soil fertility status (Malley *et al.*, 2006; Mohammadi and Sohrabi, 2012; Kiriba *et al.*, 2019). Other factors constraining crop production include; widespread soil acidity with soil pH values <5.5 and salinity (Hartemink and Van Kekem, 1994; Makoi and Ndakidemi, 2007; Gudu *et al.*, 2009; Reyes *et al.*, 2009; Opala *et al.*, 2010), rainfall variability resulting in terminal droughts, and limited resources (Bekunda *et al.*, 1997).

Literature reports that, the northern agro-ecological zone could greatly contribute to the provision of raw materials to the Tanzanian food industry, given its good weather conditions which support the cultivation of diverse crops including maize (Zea mays), wheat (Triticum spp.), coffee (Coffea spp.), beans (Phaseolus vulgaris), rice (Oryza sativa L.), banana (Musa spp.), and assorted horticultural crops (Nyaki, 1993; Makoi and Ndakidemi, 2008). However, this zone is reported to be affected by the presence of sodicity and soil acidity (pH<5.5) (Hartemink and Van Kekem, 1994; Makoi and Ndakidemi, 2007; Reyes *et al.*, 2009), which is associated with depletion of important nutrients such as potassium, cation elements (Ca, Mg, etc.), micronutrients (especially Zn and Cu), soil organic matter and nitrogen, fixation of phosphorus, topsoil erosion as well as the deterioration of other physical soil properties (Ndakidemi and Semoka, 2006; Makoi and Ndakidemi, 2008; Masunga *et al.*, 2019). The aforementioned problems may be attributed to poor agronomic practices and overgrazing (Scoones, 2001).

Northern highlands are among the potential areas of Tanzania where important crops of national interest such as maize (*Zea mays*), wheat (*Triticum* spp.), common beans (*Phaseolus vulgaris*), pigeon peas (*Cajanus cajan*) are cultivated (Rahhi, 2011; Masunga *et al.*, 2019). However, some soils in the northern highlands are reported to be severely affected by nutrient depletion due to intensive cultivation without nutrient replenishment (Makoi and Ndakidemi, 2008). Additionally, it has been reported that the decline of soil fertility in the northern highlands is attributed to leaching of nutrients by excess rainfall and irrigation water, depletion of soil nutrients through crop removal, erosion, and inadequate use of fertilizers (Hede *et al.*, 2001; Hedley and Bolan, 2003; Rengel and Tang, 2003; Amani, 2004; Ndakidemi *et al.*, 2006).

However, there are little or no studies that have been carried out to assess the fertility status of soil in the northern highlands. Additionally, there is very limited literature that establishes the soil fertility status of Tanzanian soils (Ndakidemi and Semoka, 2006; Makoi and Ndakidemi, 2008), and if present, most of the soil fertility surveys are at a larger scale such as country or regional level which sometimes do not represent site-specific nutrient requirements for various cropping systems (Makoi and Ndakidemi, 2008). Furthermore, the interactions and confounding factors such soil quality management options, farming practices in each location, and climate change variability have complicated soil fertility assessment and in ascertaining its effects on crop productivity in the northern highlands, thus, threatening food security in the zone (Ngailo *et al.*, 2001; Makoi and Ndakidemi, 2008).

It is hypothesized that the lower yields of various crops obtained in the northern highlands are being attributed to a decline in soil fertility (Nyaki, 1993; Ndakidemi *et al.*, 2006; Makoi and Ndakidemi, 2008), this calls for studies to pinpoint how site-specific loss of crop productivity is influenced by reduced soil fertility and thus, establish best soil fertility management options for increasing crop yields. Similarly, studies conducted elsewhere in African countries (Smaling and Braun,1996;Scoones,2001) report a decline in soil fertility because smallholder farmers cultivate their farms and harvest grains without replenishing soil fertility, similar to the scenario prevailing in the northern highlands. Therefore, reduced yields in northern highlands might be attributed to the decline in soil nutrients. Important indicators of soil fertility reported elsewhere have focused on quantifying levels of soil reaction, soil organic carbon and soil organic matter contents; soil cation exchange capacity; amount of secondary cations (Mg and Ca), salinity and acidity status, total N, amount of extractable P and K, and extractable micronutrients (Zn, Fe, Mn, B, etc.) (Schoenholtz *et al.*, 2000; Brady and Weil, 2002; Makoi and Ndakidemi, 2007; Makoi and Ndakidemi, 2008).

A regular evaluation of the aforementioned parameters are crucial to establish levels in the soil for sustained crop productivity in different cropping systems. It is also imperative to understand the soil fertility status, particularly given the current climate change trends, for efficient and sustainable use of soil resources and maintenance of soil health, which in turn will influence crops yields and livelihood of communities around (Sebastiani *et al.*, 2005; Kibblewhite *et al.*, 2007).

Therefore, the objective of the study was to evaluate soil fertility status as a piece of evidence that might contribute to design soil fertility management options that are site and soil specific in selected districts of the northern highlands of Tanzania .

Materials and methods

Description of the study districts

The study was conducted in Mbulu and Moshi Districts, located in the northern highlands of Tanzania. Mbulu District lies within latitudes 3°28' to 4°14' S and longitudes 34°53' to 35°46'E. The surveyed farms were in different physiographic units based on elevation varying from 1000 to 2400 meters above sea level.

Mbulu district has a bimodal rainfall regime with an average of 600 mm rainfall per annum, generally considered as a limitation for reliable agriculture. The short rainy season begins from October through December followed by the long rainy season in March through May. The average monthly temperature varies from 15°C to 20°C and the relative humidity (RH) per annum is 65%. Dominant soils reported in the Mbulu district are classified as Phaeozems, Nitisols and Planosols (Ngailo *et al.*, 2001; Roy and Nabhan, 2001; Makoi and Ndakidemi, 2008), the first two are soils which are globally considered to be highly fertile and hence productive.

On the other hand, Moshi rural lies within latitudes 3.3277° S and longitudes 37.5108° E. The district receives an rainfall ranging from 1000–1700 mm per annum with a mean annual temperature of 23.3°C (Masunga *et al.*, 2019). The district experiences a bimodal rainfall regime with two rainy seasons, identified as short rainy season from November to December and the long rainy season from March to June (Masunga *et al.*, 2019). Soils dominating the Moshi rural district include; Nitisols, Andosols, and Cambisols which arise from volcanic eruptions. Despite their rich volcanic origin, these soils have severely weathered, poorly supporting the growth and yields of crops grown. Thus, to achieve maximum crop yields, these soils of Moshi rural needs to be fertilized or supplemented by rhizobia based commercial inoculants, organic or inorganic fertilizers (Ngailo *et al.*, 2001; Roy and Nabhan, 2001; Ndakidemi *et al.*, 2006; Mmbaga *et al.*, 2015; Nyoki and Ndakidemi, 2016, 2017, 2018).

Soil sampling for soil fertility assessment

A soil survey was conducted in different smallholder farms in Mbulu and Moshi districts during the 2019/2020 cropping season. A quick inspection was carried out in different farmers' fields to assess the growth status of various crops prior collecting soil samples. After the appraisal, soil samples were randomly collected from different smallholder farms across diverse physiographic units and wards, using auger guided by the standard soil sampling protocols (Vågen *et al.*, 2010). A total of 30 composite samples at a depth of 0-20 cm were collected in each surveyed farm. Each composite sample was compounded by mixing together samples from 4 sampling then quartering into a single sample. Then, the location of the sampled farm was georeferenced the Global Positioning System (GPS) (OREGON 400t), the samples were packed in sampling bags, labeled, and sent to the National Central Soil Laboratory where they were air-dried, crushed, and passed through a 2 mm sieve for analysis of physical-chemical parameters.

Furthermore, one composite soil sample was sampled from one farm in Moshi rural district that has a known history of soil acidity and used to evaluate its soil fertility status in to be a piece of evidence that might be useful in designing soil fertility management options that would be site-specific for improved productivity of various crops grown in that soil.

Routine Soil analyses

Soil physical and chemical analyses were done using standard analytical methods. Particle size distribution was determined by the hydrometer method and textural classes were worked out as per the USDA textural triangle classification system (Moberg, 2000). Soil reaction was determined with a pH meter both in water and 1 N KCl at 1:2.5 soil: water and KCl ratio following the method suggested by Okalebo *et al.* (2002). Soil cation exchange capacity (CEC) was determined by the method described by Okalebo *et al.* (2002), while exchangeable bases were analyzed using the procedure by Moberg (2000).

The Ca and Mg ions were quantified using atomic absorption spectrophotometer, while potassium (K) and sodium (Na) ions by flame photometer. Percent base saturation (%BS) was calculated as the ratio of the total exchangeable bases (TEB) to the CEC x 100% (Okalebo *et al.*, 2002). The soil organic carbon (SOC) was determined by the wet oxidation method (Moberg, 2000), and the percent soil organic matter (SOM) was obtained by multiplying the percent SOC by the conversion factor of 1.724 (Moberg, 2000). Total nitrogen was determined using the micro-Kjeldahl wet-digestion method as suggested by Rutherford *et al.* (2007). The C: N ratio was calculated by dividing the value of organic carbon by the total nitrogen. Available phosphorous (P) was determined as described by the Bray-1 method (Moberg, 2000) and the molybdenum blue method (Moberg, 2000). Then, the amount of available P was established by a spectrophotometer at a wavelength of 884 nm. Extractable micronutrients zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) were determined as proposed by Okalebo *et al.* (2002) and quantified using atomic absorption spectrophotometer in comparison with standards at 213.9 nm, 248.3 nm, 279.5 nm, and 324.7 nm wavelength for Zn, Fe, Mn, and Cu, respectively. Soil exchangeable Al and H^+ were determined using KCl as an extraction solution and then quantified by titration as described by Okalebo *et al.* (2002). Soil exchangeable sodium percentage (ESP %) was obtained as a ratio of soil exchangeable sodium (Na^+) to the soil CEC x 100%.

Results and discussion

Soil texture

The physico-chemical properties of the surveyed soils in Mbulu and Moshi rural districts are presented in Table 1. Analysis of particle size distribution revealed variability in the sand, clay, and silt contents (Table 1) between soils and topographic units. The surveyed farms in the Mbulu district had textural classes ranging from clay (30%) to sandy clay loam (50%), sandy loam (3.3%), sandy clay (6.7%), and clay loam (10%) (Msanya, 2012). On the other hand, the Moshi farm had a loam textural class. Variability in the textural classes reported in this study might be due to differences in the topography of the farmer's fields and the volcanic nature of the parent material (gneiss, granite, alluvium and schist and pyroclastic) in the Mbulu district which give rise to soils classified as Phaeozems, Nitisols and Planosols (Ngailo *et al.*, 2001; Roy and Nabhan, 2001; Makoi and Ndakidemi, 2008).

The high clay fraction in most soils of the surveyed farms in the Mbulu district shows that the soils are fertile and can retain most nutrients that support crop production. However, as the soils are subjected to erosion or removal of crop residues, most of the major nutrients (P and K) and cations (Ca and Mg) accumulated by the crops (Table 1 and Table 3) when harvested are taken away in grains and stover which is usually used to feed animals (Ndakidemi and Semoka, 2006). Findings by Ndakidemi and Semoka (2006) in the Western Usambara Mountains of northern highlands showed that the soils in these mountains were highly affected by erosion, making these soils infertile, a scenario that also applies in most farms of Mbulu district. The soils from the surveyed farms of northern highlands were generally rated as clayey (36.7%) to loamy soils (63.3%) (Msanya, 2012).

Table 1. Soil physico-chemical properties of smallholder farms in Mbulu and Moshi rural Districts, Northern Tanzania

Mbulu District								
Farm	Sand	Silt	Clay	Texture[a)]	pH[b)]	Exch H	Exch Al	Al Sat
	%	%	%			cmol(+)kg^{-1}		%
Farm 1	42	12	46	C	5.8	0.05	0.10	1.09
Farm 2	74	10	16	SL	6.3	-	-	
Farm 3	64	16	20	SCL	6.4	-	-	
Farm 4	52	12	36	SC	7.1	-	-	
Farm 5	46	24	30	SCL	6.3	-	-	
Farm 6	64	12	24	SCL	6.4	-	-	
Farm 7	58	8	34	SCL	6.3	-	-	
Farm 8	44	22	34	CL	5.5	0.68	0.66	6.82
Farm 9	50	19	31	SCL	6.2	-	-	
Farm 10	25	28	47	C	6.2	-	-	
Farm 11	35	9	56	C	6.6	-	-	
Farm 12	44	28	28	CL	5.2	1.27	0.49	5.46
Farm 13	40	18	42	C	5.0	2.60	2.30	25.99
Farm 14	58	16	26	SCL	5.3	0.68	0.48	4.63
Farm 15	60	14	26	SCL	5.3	0.89	0.67	4.86
Farm 16	56	14	30	SCL	5.1	1.28	0.81	14.92
Farm 17	46	24	30	SCL	5.6	0.30	0.20	1.75
Farm 18	42	16	42	C	5.3	0.74	0.86	9.77
Farm 19	56	18	26	SCL	5.8	0.20		
Farm 20	42	26	32	CL	5.4	0.54	0.40	4.87
Farm 21	41	13	47	C	6.2	-	-	
Farm 22	52	15	30	SCL	6.2	-	-	
Farm 23	54	10	22	SCL	6.2	-	-	
Farm 24	36	7	58	C	6.4	-	-	
Farm 25	39	19	43	C	5.6	0.19	0.39	3.97
Farm 26	53	11	37	SC	6.6	-	-	
Farm 27	27	26	48	C	5.8	0.03	0.10	1.10
Farm 28	56	13	27	SCL	6.3	-	-	
Farm 29	51	18	30	SCL	6.1	-	-	
Farm 30	58	15	31	SCL	6.2	-	-	
Std	11.04	5.99	10.34		0.50	0.70	0.59	7.10

Moshi rural District								
Farm	Sand	Silt	Clay	Texture[a)]	pH[b)]	Exch H	Exch Al	Al Sat
	%	%	%			cmol(+)kg-1		%
Farm 1	44	38	18	L	4.2	1.61	1.82	70.80
Std	1.41	0.14	0.71		0.07	0.01	1.03	0.32

[a)]C= clay, CL = clay loam, L=Loam, SCL = sandy clay loam, SC = sandy clay, SL=Sandy loam; [b)]pH in water; Exch H= Exchangeable hydrogen ions, Exch Al= Exchangeable Aluminium; Al sat= Aluminium saturation.

Soil pH

Soil pH values in water (Table 1) of the surveyed fields in the Mbulu district are very variable ranging from 5.0 to 7.1 which is rated as very strongly acid to neutral. The results indicate that 7 (23.3%) out of the 30 farms had pH values <5.5 and the remaining 23 (76.7%) farms had pH values varying from 5.5 to 7.1, which are the suitable range for most crops (Sanchez *et al.*, 2003; Msanya, 2012) cultivated by smallholder farmers in Mbulu district. Moshi farm had a soil pH of 4.2 (Table 1) which is rated as extremely acid (Msanya, 2012).Tropical soils are generally acidic except soils formed under the influence of volcanic eruption which have a medium basic pH except in highly leached landscapes where exchangeable bases are leached through pedological and human-induced processes. Research established that topographic and human activities including poor and continuous cultivation, removal of crop grains and residues, and use of certain kind of fertilizers accelerate soil erosion and surface floods which carry away basic cations leaving behind hydrogen, manganese and aluminum, the acidic cations on soil colloids (Hede *et al.*, 2001; Kunhikrishnan *et al.*, 2016; Dative and Xavier, 2018).

Table 1. (Continued). Soil physical-chemical properties of smallholder farms in Mbulu and Moshi rural Districts, Northern Tanzania

		Mbulu District			
EC	OC	OM	TN	P	CEC
dsm^{-1}		$g\ kg^{-1}$		$mg\ kg^{-1}$	$cmol(+)kg^{-1}$
0.04	6.50	11.18	0.60	0.79	14.28
0.04	6.30	10.84	0.70	15.87	6.24
0.02	3.00	5.16	0.30	6.39	9.76
0.06	5.80	9.98	0.60	6.65	21.92
0.06	6.50	11.18	0.60	5.93	21.76
0.03	5.90	10.15	0.50	4.48	14.08
0.03	2.90	4.99	0.20	3.56	8.76
0.05	5.50	9.46	0.70	5.27	15.44
0.09	2.60	4.47	0.20	15.67	13.52
0.16	5.70	9.80	0.40	11.72	17.32
0.12	5.60	9.63	0.60	53.95	15.64
0.07	5.90	10.15	0.50	9.88	15.12
0.06	6.90	11.87	0.60	1.91	13.20
0.07	2.90	4.99	0.30	8.83	16.80
0.10	9.20	15.82	1.00	6.39	25.32
0.07	8.50	14.62	0.80	5.14	8.80
0.08	6.30	10.84	0.70	6.52	20.16
0.05	6.80	11.70	0.70	5.14	22.56
0.18	6.60	11.35	0.90	7.31	26.64
0.06	5.30	9.12	0.60	7.64	14.24
0.20	5.60	9.63	0.30	0.80	14.25
0.09	2.60	4.47	0.40	5.68	13.46
0.12	5.80	9.98	0.50	5.38	15.13
0.10	5.90	10.15	0.40	52.98	15.42
0.22	5.60	9.63	0.80	6.35	16.21
0.16	6.10	10.49	0.90	6.76	15.43
0.02	6.10	10.49	0.40	4.78	15.16
0.07	2.70	4.64	0.20	6.23	14.38
0.15	2.80	4.82	0.30	4.57	8.63
0.08	2.50	4.30	0.20	12.17	7.58
0.05	1.78	3.07	0.23	12.38	4.97

		Moshi rural District			
EC	OC	OM	TN	P	CEC
dsm-1		g kg-1		mg kg-1	cmol(+)kg-1
1.02	21	36.2	5.5	3.33	35.92
0.01	0.01	0.01	0.01	0.02	0.01

EC=Electric conductivity; OC=Organic carbon; OM=Organic matter; TN= Total nitrogen; Avail. P= Available Phosphorous; CEC=Cation exchange capacity; Std= Standard deviation.

Exchangeable Aluminum and Aluminum saturation

Exchangeable aluminum (Al) was revealed in 12 farms (40%) out of the 30 surveyed farms. The values for exchangeable Al varied from 0.10 to 2.30 cmol (+) kg^{-1}, while the values of Aluminum saturation (Al Sat) varied from 1.09% to 25.99% (Table 1). Results indicate that one farm in Nambisi Ward (Nambisi-Farm13) had values of both exchangeable Al and Al saturation above the critical levels for the toxicity of 1.0 cmol(+) kg^{-1} and 10%, respectively, (Ndakidemi and Semoka, 2006; Simon *et al.*, 2014). In another farm of the Nambisi ward (Nambisi-Farm 16), the A1 saturation was observed to be above 10%. Furthermore, Moshi farm had exchangeable aluminum of 1.61 cmol (+) kg^{-1} with an aluminum saturation (Al sat) value of 70.8% (Table 1).

Table 2. Selected chemical properties of soils collected from smallholder farms in Mbulu and Moshi rural Districts, Northern Tanzania

Mbulu District									
Site/Farm	Ca	Mg	K	Na	ESP	Zn	Fe	Mn	Cu
		cmol(+)kg^{-1}			%		mg kg^{-1}		
Farm 1	7.32	1.76	0.28	0.08	0.56	0.45	213.70	231.15	8.15
Farm 2	2.93	0.83	0.63	0.07	1.12	1.05	117.70	155.15	1.65
Farm 3	4.23	1.13	0.52	0.08	0.82	0.35	130.70	241.15	1.15
Farm 4	16.20	4.29	0.32	0.37	1.69	2.25	761.70	569.15	5.65
Farm 5	12.21	2.97	0.59	0.08	0.37	1.25	156.70	144.15	3.35
Farm 6	7.82	3.06	0.24	0.08	0.57	0.75	146.70	149.15	2.65
Farm 7	4.43	1.28	1.05	0.10	1.14	1.05	114.70	479.15	4.95
Farm 8	6.42	2.60	0.17	0.08	0.52	1.25	258.70	364.15	1.65
Farm 9	8.32	1.11	0.72	0.10	0.74	0.45	147.70	12.15	1.45
Farm 10	10.31	1.87	0.75	0.10	0.58	0.95	222.70	27.15	1.65
Farm 11	9.32	2.43	1.24	0.16	1.02	1.65	158.70	51.15	1.35
Farm 12	6.52	1.97	0.42	0.10	0.66	2.35	210.70	78.15	0.95
Farm 13	5.22	1.33	0.20	0.19	1.44	1.05	631.70	95.15	1.55
Farm 14	8.02	1.86	0.34	0.11	0.65	1.15	781.70	36.15	2.45
Farm 15	10.41	2.71	0.47	0.16	0.63	1.25	426.70	38.15	2.25
Farm 16	3.83	0.79	0.28	0.17	1.93	0.35	134.70	14.15	1.65
Farm 17	9.02	2.18	1.44	0.13	0.64	0.95	180.70	26.15	1.85
Farm 18	6.12	1.82	0.27	0.10	0.44	1.05	251.70	76.15	3.35
Farm 19	14.61	3.12	0.29	0.14	0.53	3.65	471.70	119.15	4.75
Farm 20	6.82	1.00	0.18	0.20	1.40	1.15	461.70	41.15	1.05
Farm 21	7.29	1.74	0.26	0.09	0.63	0.46	210.60	230.96	8.13
Farm 22	8.29	1.15	0.69	0.12	0.89	0.46	148.90	11.98	1.43
Farm 23	7.78	3.08	0.22	0.07	0.46	0.69	147.60	150.12	2.63
Farm 24	9.30	2.40	1.22	0.14	0.91	1.03	113.90	480.01	4.89
Farm 25	6.74	2.70	0.19	0.06	0.37	1.36	257.90	357.14	1.59
Farm 26	7.90	3.54	0.30	0.09	0.58	0.73	144.80	150.01	2.69
Farm 27	7.30	1.73	1.78	0.07	0.46	0.47	212.98	230.82	8.19
Farm 28	8.43	1.13	0.70	0.16	1.11	0.48	149.01	12.01	1.39
Farm 29	11.45	3.02	0.97	0.09	1.04	1.07	116.86	150.15	3.26
Farm 30	7.23	4.01	1.64	0.16	2.11	0.49	132.67	12.16	3.69
Std	2.92	0.95	0.46	0.06	0.46	0.70	187.54	154.76	2.15

Moshi rural District									
Site/Farm	Ca	Mg	K	Na	ESP	Zn	Fe	Mn	Cu
		cmol(+)kg^{-1}			%		mg kg^{-1}		
Farm	0.54	0.13	0.19	0.06	0.17	53.85	249.7	21.15	40.15
Std	0.03	0.01	0.01	0.01	0.02	0.01	0.14	0.01	0.01

Ca=Calcium; Mg=Magnesium; K=Potassium; Mg:K= Magnesium potassium ratio, Ca:Mg= Calcium magnesium ratio; Zn= Zinc, Fe= Iron, Mn=Manganese, Cu= copper, Na= sodium, ESP=exchangeable sodium percentage; Std= Standard deviation.

The values of both exchangeable Al and Al saturation are above the critical levels for the toxicity of 1.0 cmol(+) kg^{-1} and 10%, respectively, (Ndakidemi and Semoka, 2006). Therefore, the values for soil acidity recorded in most farms of the Mbulu district and that of Moshi was high and hence threatening crop production (Simon *et al.*, 2014).

Soil Organic Carbon (SOC) and Total Soil Organic Matter (SOM)

Soil organic carbon (SOC) for the Mbulu district varied from 2.50 to 9.20 g kg^{-1} corresponding to 4.30 and 15.82 g kg-1 of soil organic matter, respectively (Table 1), which is rated as very low to low (Msanya, 2012). Furthermore, the Moshi farm had a soil organic carbon value of 21 g kg^{-1} (Table 1) and was rated as medium (Ndakidemi and Semoka, 2006). The SOC critical level is 20.0 g kg^{-1} (Ndakidemi and Semoka, 2006; Msanya, 2012) and a decline in SOC values bring about a decline in soil quality. The results indicate that all 30 farms surveyed (100%) in Mbulu district had SOC lower than the critical value indicated above while Moshi farm had medium SOC levels.

Table 3. Soil fertility status legend of soils collected from smallholder farms in Mbulu District, Northern Tanzania.

District	Soil fertility Unit	Land form characteristic	Slope	pHa)	N	OC
			%			%
Mbulu	Farm 1	Almost flat	<1	MA	VL	VL
Mbulu	Farm 2	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 3	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 4	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 5	Almost flat	<1	N	VL	VL
Mbulu	Farm 6	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 7	Slightly sloping	<2	N	VL	VL
Mbulu	Farm 8	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 9	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 10	Almost flat	<1	SLA	VL	VL
Mbulu	Farm 11	Gently sloping	<3	SA	VL	VL
Mbulu	Farm 12	Almost flat	<1	SA	VL	VL
Mbulu	Farm 13	Almost flat	<1	VSA	VL	VL
Mbulu	Farm 14	Gently sloping	<3	SA	VL	VL
Mbulu	Farm 15	Almost flat	<1	SA	VL	VL
Mbulu	Farm 16	Gently sloping	<3	SA	VL	VL
Mbulu	Farm 17	Almost flat	<1	MA	VL	VL
Mbulu	Farm 18	Almost flat	<1	SA	VL	VL
Mbulu	Farm 19	Almost flat	<1	MA	VL	VL
Mbulu	Farm 20	Almost flat	<1	SA	VL	VL
Mbulu	Farm 21	Almost flat	<1	SA	VL	VL
Mbulu	Farm 22	Almost flat	<1	SA	VL	VL
Mbulu	Farm 23	Almost flat	<1	SA	VL	VL
Mbulu	Farm 24	Slightly sloping	<2	SA	VL	VL
Mbulu	Farm 25	Almost flat	<1	MA	VL	VL
Mbulu	Farm 26	Almost flat	<1	N	VL	L
Mbulu	Farm 27	Almost flat	<1	MA	VL	L
Mbulu	Farm 28	Almost flat	<1	SA	VL	VL
Mbulu	Farm 29	Slightly sloping	<2	SA	VL	VL
Mbulu	Farm 30	Slightly sloping	<2	SA	VL	VL
Moshi	Farm 31	Almost flat	<1	EA	H	M

[a)]pH in water; Classification: According to Msanya (2012) and Motsara and Roy (2008) guidelines. EA= Extremely acid, VSA= Very strongly acid, SA= strongly acid, MA=medium acid, SLA= slightly acid, N=Neutral, VL=Very low, L=Low, M=Medium, H=High and VH= Very high, Df=Deficiency, Ad= Adequate, Ex= Excessive.

This lower values of SOC in most of the surveyed farms of the Mbulu district might have resulted from little or no-addition of organic matter from the crop residues or other plant materials that are taken from the field by farmers to feed their livestock. Findings of the investigations by Sanchez *et al.* (2003) and Asadu *et al.* (1997) established that organic matter contains nitrogen (N), phosphorus (P), and sulfur (S) nutrients, thus, considered as a reservoir and a ready source of most plant nutrients in any ecosystem (Boyle *et al.*, 1989).

Table 3. (continued). Soil fertility status legend of soils collected from smallholder farms in Mbulu District, Northern Tanzania

District	Soil fertility Unit	K	Ca	Mg	CEC	P	Zn	Fe	Mn	Cu	ESP
			cmol(+)kg^{-1}					mg kg^{-1}			
Mbulu	Farm 1	Ad	Ad	Df	M	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 2	Ad	Df	Df	L	M	Ad	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 3	Ad	Df	Df	L	L	Df	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 4	Ad	Ad	Df	M	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 5	Ad	Ad	Ad	M	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 6	Ad	Ad	Df	M	L	Ad	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 7	Ad	Df	Ad	L	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 8	Ad	Ad	Ad	M	L	Ad	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 9	Ad	Ad	Ad	M	M	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 10	Ad	Ad	Df	M	M	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 11	Df	Ad	Ad	M	H	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 12	Ad	Ad	Df	M	M	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 13	Ad	Ad	Df	M	L	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 14	Ad	Ad	Df	M	M	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 15	Ad	Ad	Ad	H	L	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 16	Ad	Df	Df	L	L	Df	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 17	Ad	Ad	Ad	M	L	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 18	Ad	Ad	Df	M	L	Ad	Ex	Ad	Ex	Non-sodic
Mbulu	Farm 19	Ad	Ad	Ad	H	M	Ad	Ex	Ad	Ex	Non-sodic
Mbulu	Farm 20	Df	Ad	Df	M	M	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 21	Ad	Ad	Df	M	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 22	Ad	Ad	Df	M	L	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 23	Ad	Ad	Ad	M	L	Ad	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 24	Ad	Ad	Ad	M	H	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 25	Df	Ad	Ad	M	L	Ad	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 26	Ad	Ad	Ad	M	L	Ad	Ex	Ex	Ad	Non-sodic
Mbulu	Farm 27	Ad	Ad	Df	M	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 28	Ad	Ad	Df	M	L	Ad	Ex	Ad	Ad	Non-sodic
Mbulu	Farm 29	Ad	Ad	Ad	L	L	Ad	Ex	Ex	Ex	Non-sodic
Mbulu	Farm 30	Ad	Ad	Ad	L	M	Ad	Ex	Ad	Ex	Non-sodic
Moshi	Farm 31	Df	Df	Df	H	L	Ex	Ex	Ad	Ex	Non-sodic

Classification: According to Msanya (2012) and Motsara and Roy (2008) guidelines. EA= extremely acid, VSA= Very strongly acid, SA= strongly acid, MA=medium acid, SLA= slightly acid, N=Neutral, VL=Very low, L=Low, M=Medium, H=High and VH= Very high, Df=Deficiency, Ad= Adequate, Ex= Excessive.

Similarly, Asadu *et al.* (1997); Makoi and Ndakidemi (2007); Opala *et al.* (2010), and Facelli and Pickett (1991) reported that SOM is vital in increasing soil CEC, improving soil aggregate stability, provision of a source of food for sustaining soil microbes, and enhancing the capacity of soils to hold water and nutrients. This proves that SOM positively helps in the replenishment of macro and micronutrient status in the soil. The findings from this work indicate that SOM levels are low, implying reduced fertility levels in soils (Tables 1 and 3).

Therefore, given the above reasons, it is important to sensitize smallholder farmers in the northern highlands on the need to carry out Integrated Soil Fertility Management (ISM) practices that would incorporate cheap and locally available organic sources such as crop residues, farmyard manure, and composites, the materials that will contribute to replenishing the fertility levels of soils in their farms.

Total Nitrogen

Total nitrogen (N) levels in the surveyed farms of the Mbulu district varied from 0.20 to 1.00 g kg^{-1} (Table 1) which is rated as low while that of Moshi farm was 5.5 g kg^{-1} and rated high (Simon *et al.*, 2014). According to Msanya (2012) and Simon *et al.* (2014), the recommended critical level of N that would support the growth of the majority crops in Tanzanian soils is 2.0 g kg^{-1}. Findings from this study showed that 100% of the surveyed farms (30 farms) in the Mbulu district contained nitrogen below the recommended critical value (< 2 g kg^{-1}), thus rated as low (N deficiency) (Table 3). This may be attributed to low SOM content (Facelli and Pickett, 1991), therefore, supplementary nitrogen from either organic or inorganic sources is necessary if sustainable production is desired in the Mbulu district and similar areas in the northern highlands of Tanzania. Nitrogen is one of the major nutrients needed for crop nutrition (Ndakidemi and Semoka, 2006; Kalala *et al.*, 2017; Nyoki and Ndakidemi, 2018; Masunga *et al.*, 2019), and its application is necessary to optimize soil N for increased agricultural outputs.

Available Phosphorus

Phosphorous is among the major nutrients required by the plant for growth and development (Kalala *et al.*, 2017; Nyoki and Ndakidemi, 2018). The study results indicate that phosphorus levels in soils of the Mbulu district ranged from 0.79 to 53.95 mg Pkg^{-1} (Table 1). According to Simon *et al.* (2014), the critical level for P deficiencies in the soil is 10-15 mg P kg^{-1}. Additionally, the results of this study established that 66.67% of the surveyed farms in Mbulu district are P deficient while the Moshi rural farm had soils with available phosphorous levels of 3.33 mg Pkg^{-1}, which was rated as low(Simon *et al.*, 2014).

The low P values in the studied farms in the northern highlands might be due to P-fixation attributed to the presence of exchangeable Al^{3+}, Fe^{3+}, and Mn^{2+} that were the common cations in the studied strongly acidic soils. Similar results have been reported by (Schwertmann and Herbillon, 1992) that in strongly acidic soils there are free cations of aluminum, iron, and manganese that strongly fix-P making complex compounds that are unavailable for plant uptake especially when the soil pH values falls below 5.5 (Landon, 2014). This necessitates the design of appropriate management options that will optimize P availability or application of external P sources for supplementation of P. Management options include the use of commercial P fertilizers with other effective and readily available organic and inorganic P sources from plants such as *Tithonia diversifolia* (Hemsl.) A. Gray), *Vernonia subuligera* O. Hoffn.) and *Vernonia arnyridiantha* (Hook, J.) and should focus on the farms diagnosed to have lower P levels to optimize P levels in these soils for sustained productivity.

The effectiveness of these inexpensive and readily available P sources from plants have been tested by Ndakidemi (2015) in the Western Usambara Mountains of Northern Tanzania and proved to improve crop yields. Thus, the same materials can further be tested in the farming conditions of northern highlands and if effective, they can be utilized as one of the Integrated Soil Fertility Management (ISFM) packages for improved crop production in P deficient soils of northern highlands of Tanzania.

Cation exchange capacity (CEC)

Cation exchange capacity (CEC) of the studied farms in the Mbulu district ranges from 6.24 to 26.64 cmol kg^{-1} (Table 1) rated to be low to medium while that of Moshi farm was 35.92 and was rated as high (Simon *et al.*, 2014). It was established that 20 percent of studied farms in the Mbulu district had CEC < 12.1 cmol kg^{-1} soil while the remaining 80 percent had CEC > 12.1 cmol kg^{-1} soil (Table 1), rated as low to medium, respectively (Simon *et al.*, 2014).

The low CEC levels in 20% of the studied farms might be attributed to low SOM (Table 1) due to poorly available residues as the fields are used to graze animals after harvest, leaving little to no residues. The low CEC is also attributed to soil parent materials are pedological processes including high weathering and leaching due to highly erratic rains ad varied topographic settings which accelerated soil erosion (Sanchez and Logan, 1992; Ludwig *et al.*, 2001). The high level of CEC for Moshi farm and the medium levels of the CEC of most soils of Mbulu district (80%) support the growth of most crops cultivated. Therefore, to realize productivity potential in these soils of northern highlands, various interventions such as the application of manure and inorganic fertilizers are recommended for accelerating soil organic matter built up and hence CEC that would play a big role in the retention of essential nutrients needed by plants.

Exchangeable bases (Mg, Ca, and K)

Exchangeable Ca^{2+} in the surveyed soils of the Mbulu district ranged from 2.93-16.20 cmol (+) kg^{-1} while Moshi farm had an exchangeable Ca^{2+} of 0.54 cmol (+) kg^{-1} soil. The recommended critical levels of Ca^{2+} in soil supporting the growth of crops is 5 cmol $^{(+)}$ kg^{-1}soil (Simon *et al.*, 2014). Results show that 86.67% of the farms studied in the Mbulu district had higher Ca^{2+} levels above the threshold value. Moshi farm had Ca^{2+} levels below the threshold value. Therefore, these areas of northern highlands are possible for $Ca^{2+,}$ deficient require supplementation of calcium as either foliar fertilizers.

Furthermore, results show that exchangeable Mg^{2+} content in Moshi farm to be 0.13 cmol (+) kg^{-1} soil which is below the critical levels (2 cmol kg^{-1} soil) for Mg^{2+} that support the growth of most crops (Ndakidemi and Semoka, 2006; Simon *et al.*, 2014). On the other hand, the surveyed farms in the Mbulu district had exchangeable Mg^{2+} content ranging from 0.79 to 4.29 cmol (+) kg^{-1} soil (Table 2). Based on the critical levels for Mg^{2+} that support the growth of most crops, it was established that 66.67% of the studied farms in the Mbulu district had exchangeable Mg that was below the critical level, signifying that magnesium levels in these soils were lower and it affects sustainable production and productivity of crops. Additionally, the results also showed exchangeable K values in the Moshi soil to be 0.19 cmol (+) kg^{-1} soil and it was below the critical level for exchangeable K of 0.20 cmol(+) kg^{-1} soil (Anderson, 1973; Simon *et al.*, 2014). Exchangeable K in Mbulu soils varied from 0.17 to 1.78 cmol (+) kg^{-1}soil (Table 1) and it was established that 90% of farms in the Mbulu district had exchangeable K above the recommended critical levels.

Exchangeable sodium or exchangeable sodium percentage (ESP)

Soil exchangeable sodium in Mbulu soils varies from 0.06 to 0.37 cmol (+) kg^{-1} soil and with exchangeable sodium percentage (ESP) values that range between 0.37 and 2.11% respectively (Tables 2). Moshi soil had exchangeable sodium of 0.06 cmol (+) kg^{-1} soil and with an exchangeable sodium percentage (ESP) value of 0.17 %. The critical values of ESP which show sodium hazard is 15% (Lebron *et al.*, 2002; Msanya, 2012), for which growth and yields of most crops (including maize and beans) are affected. The results indicate a non-sodic status, thus having no effects on plant development and crop yields in these soils of northern highlands.

Extractable Zinc, Iron, Manganese, and Copper

Extractable Zn contents in the soils of the Mbulu district varied from 0.35 to 3.65 mg kg^{-1} (Table 2) while that of Moshi soil was 53.85 mg kg^{-1} (Table 2). The critical level for Zn deficiency (DTPA) in the soil was 0.4-0.6 mg kg^{-1} and values higher than 10-20 mg kg^{-1} were regarded as excess (Ndakidemi and Semoka, 2006). The results show that 93.33% and 6.67% soils of Mbulu had adequate and deficient Zn levels respectively (Fig 2) while Moshi soil had excess Zn levels. In all soils surveyed, Fe levels were observed to be excessively indicating a possibility of causing toxic effects to the crops in Mbulu and Moshi districts. Ndakidemi and Semoka (2006) established that the deficiency level of extractable Mn is between 2 to 5 mg Mn kg^{-1} soil and Mn above 140 mg kg^{-1} soil is regarded as excessive, with possible toxicity to crops. The soils of Mbulu showed a similar tendency for Mn and Cu indicating a possibility for toxicity.

Conclusions

Based on the results presented above, the following conclusions and recommendations are made. Most of the studied farms in the Mbulu district had clayey soils generally characterized to be of poor to moderate soil fertility and strongly acidic (low pH), and few farms had aluminum toxicity problems.

The majority of farms in the Mbulu district are deficient in nitrogen and organic carbon (OC), available phosphorous, exchangeable bases (magnesium and calcium), while had excessive manganese, iron, and copper that can lead to toxicity in crops grown. Moshi farm had extremely acidic soil (low pH), aluminum toxicity problem, deficient in exchangeable bases (calcium, magnesium, and potassium), and excessive in exchangeable micronutrients (Zn, Fe, and Cu) that might affect the productivity of various crops cultivated. It is therefore recommended that site-specific nutrient fertilization management options should be worked out for optimizing and sustaining crop productivity and production in Mbulu and Moshi rural Districts that form the northern highlands. Additionally, low soil pH should be addressed by testing appropriate lime rates that will be part of the management option together with tested fertilizer rates.

Author contributions

This work was carried out in collaboration between both authors. Author DSK designed the study, wrote the protocols (methodology), the first draft of the manuscript. Author KM, FW and PAN, revised the protocols (methodology), guided field data collection, data analysis and interpretation, and during reviewing and editing of the drafted manuscript. Both authors read and approved the final manuscript.

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Competing interests

Authors declare no conflict of interest

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