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Research article

Soil fertility and land sustainability in Usangu Basin-Tanzania

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ABSTRACT

Soil fertility determines crop growth, productivity and consequently determines land productivity and sustainability. Continuous crop production exploits plant nutrients from soils leading to plant nutrient imbalance, thus affecting soil productivity. This study was conducted to monitor soil fertility status in soils of Usangu agro-ecosystem to establish management strategies. To assess soil fertility status in Usangu agro-ecosystem in Southern Highland Tanzania; 0–30 cm depth soil samples were taken for organic carbon, soil pH, N, P, Ca, K, Mg, S, Al, and micronutrients such as Zn, Mn, Cu, Fe, and Cr analyses by various established standard analytical methods. The results indicated most micronutrients were available in the deficient amount in many studied sites except for Fe and Mn, which were observed to be above optimum requirement. Based on critical levels established in other areas, 90 % of the soils were ranked as N, P, K, and Mg deficient. The micronutrients (Cu, Fe, and Zn) were inadequate in all soils resulting in limited crop growth and productivity. A high concentration of trace metals was detected in agricultural soils, this might affect plant nutrients availability and leading to environmental contamination affecting land productivity and sustainability. The study found that Usangu agro-ecosystem has deprived of soil fertility leading to poor crop growth and productivity. The authors recommend the addition of supplemental materials rich in plant nutrients such as inorganic fertilizer, manure, crop residues, and treated wastes to improve soil fertility for improved productivity and land sustainability.

1. Introduction

Worldwide increasing world population has increased land demand for housing, industry, and infrastructures, resulting in decreased available arable land for increased crop production required to meet increasing food demand (Chen et al., 2019; Coulibaly and Li, 2020; Doos, 2002). The projection shows that in the next three decades there will be 30 to 60 million hectares loss of arable land, and 100–200 million hectares of reserved land will be under agriculture and other anthropogenic activities (Coulibaly and Li, 2020; Doos, 2002). The decrease in arable land has increased pressure in the available arable land to achieve higher production, this resulted in arable land degradation including a decline in soil fertility and land quality, increased soil erosion, and accumulation of toxic metals as results of excessive use of agro-chemicals required to achieve high yield in poor and degraded arable land (Gomiero, 2016; Halbac-Cotoara-zamfir et al., 2020; Hossain et al., 2020; Lead et al., 2019). Degradation of arable land is likely to affect crop production and sustainability in many agro-ecosystems of Sub-Saharan Africa (SSA) as many of these effects are not easily reversed. The prominent problem in land degradation is soil fertility because of excessive exploitation and little nutrient replenishment (Souri et al., 2018c, 2019, 2019; 2019; Souri and Hatamian, 2019; Tekulu et al., 2020). Decline and low soil fertility and inefficient management are major production challenges in Sub-Saharan Africa that affect smallholder farmers' productivity (Belay, 2015; Henryson et al., 2018; Nájera et al., 2015). Agriculture currently in SSA has been shifted from mixed cropping to monoculture farming practice, monoculture has increased dependence on inorganic fertilizer and other inorganic agro-chemicals as a key soil nutrient management option, but it is unsustainable, as it leads to soil degradation and environmental pollution (Bationo et al., 2005; Henryson et al., 2018; Stewart et al., 2020; Vanlauwe et al., 2014). Therefore, smallholder farmers may rarely realize their full crop potential because of poor soil fertility and limited access to inorganic fertilizer (Stewart et al., 2020). To ensure sustainable land management and crop productivity in arable land, detailed soil fertility monitoring and

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management are required. Usangu agro-ecosystem (USB) is a large basin in Southern Highland Tanzania with more than 28000 squares kilometers important for irrigation paddy rice farming in Tanzania (Fox, 2004; Kashaigili et al., 2006). The area is dominated by large-scale farmers and many smallholder farmers, with low income and resources to purchase synthetic fertilizers and associated agro-chemicals for soil fertility management (Ngailo et al., 2016). There is a dark side on the sustainability of crop productivity in Usangu agro-ecosystem because of decreasing soil fertility and increasing accumulation of trace metals (Cu, Mn, Ni, Cd, As, Pb, Cr, etc.) in agricultural soils through intensified agrochemicals use as these trace metals are impurities in most agrochemicals used (Lema et al., 2014; Lema and Mseli, 2017; Mng'ong'o et al., 2021). These metals negatively decrease the availability of plant nutrients such as zinc, calcium, phosphorus, and nitrogen (Hatamian et al, 2020a, 2020b; Pathak, 2010). Farming areas in the Usangu agro-ecosystem experience an extensive decrease in soil fertility as a result of intensively continuous cropping (Mowo et al., 1993; Senkoro et al., 2017). Over years, paddy productivity in Usangu basin experienced low productivity (less than 2.1 tons/ha) compared to the average production potential of 6.6 tons/ha. This is caused by soil fertility deterioration (Funakawa et al., 2012; Kadigi et al., 2004; Lankford, 2004; Mwaseba et al., 2007). Soil degradation has an enormous impact on crop production and sustainability of Usangu basin (Belay, 2015; Havlin and Heiniger, 2020; Henryson et al., 2018; Kharal et al., 2018; Nájera et al., 2015). Therefore, characterization of soil nutrient status in USB is crucial to predict productivity and sustainability and recommend best practices for crop production. To date, assessment of soil nutrient status in Tanzania has been limited to few areas because of the high cost required and limited access to soil science laboratories in most areas, leaving a lot of soils and land capabilities unknown (Mowo et al., 2006; Muchena and Kiome, 1995). The lack of data from soil testing laboratories and published literature in Usangu agro-ecosystem and other agricultural lands in Tanzania has limited fertility management plans required to ensure sustainable crop production, since 1980 when the agricultural intensification was set to increase production and expand the area under cultivation. The detailed data on time series are required to ascertain the trend in soil fertility in Tanzanian agro-ecosystem soils which currently is not available. Therefore, this study analyzed the soil fertility status of the Usangu agro-ecosystem in Mbarali district Tanzania to establish baseline information required for further monitoring research to ensure sustainable land productivity.

2. Material and methods

2.1. Study area and soil collection

The study area was in Usangu Basin (USB) Mbeya-Tanzania, latitudes 7°41′and 9°25′ South and longitudes 33°40′ and 35°40′ East. The study area covers 20,800 square kilometers, divided into two parts; the hilly south, which is covered by forests and has an annual precipitation of 1000–1600 mm. The northern part is wide flat land dominated by alluvial soils that support both irrigated and rainfed farming. It has an average annual precipitation of 700 mm. The basin receives rainfall from December to March and seven dry months. The basin has a temperature range of 11.2–25.7 °C and an annual average temperature of 18.4 °C. The area depends on inorganic fertilizers and organic manure as a long-term plan for soil fertility management, the area has little incorporation of crop residues as to the nature of paddy farming which requires fine tilth for transplanting. Usually, fertilizer application involves fertilizer broadcasting in the field followed by flooding after three days, a practice that might impact soil fertility. In total 198 soil samples from 66 sampling sites were collected from 10 irrigation schemes (Moto mubaya, Igalako, Ihahi, Chimala, Uturo, Kapunga, Ilaji, Mubuyuni, Isenyela, and

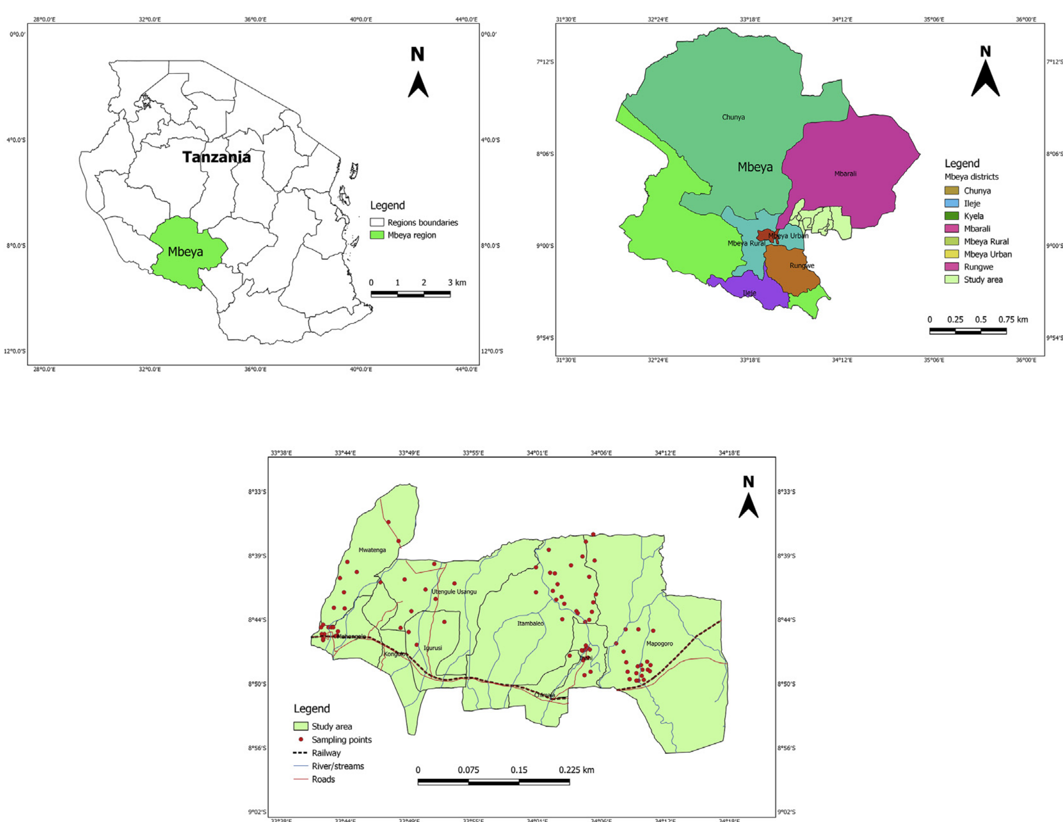

Figure 1. The map showing study area and sampling sites -Usangu basin-Mbeya Tanzania.

Mabadaga in November to December 2019 (Figure 1). Three (3) soil samples were collected at each sampling site, three-meter from the center of each selected point then mixed thoroughly and divided into quarters where some soils were discarded to remain with approximately 500 g. Soils samples were collected at a depth of 0–30 cm representing the plough layer common in paddy farming and stored in the plastic bags and transported to the drying shed immediately.

2.2. Soil nutrient extraction and determination

The air-dried soil samples were ground to pass a 2 mm sieve to get fine earth. 100 g of soil were taken and stored in a plastic container and later analyzed for plant nutrients and other soil properties (such as pH, OC, trace metals, moisture content). The determination of P, Ca, K, S, Al, Mg, and micronutrients such as Zn, Mn, Cu, Fe, Co, Ni, and Cr, were determined by Mehlich 3 method (M3); which extracts readily available plant nutrients, both macro and micronutrients (Mehlich, 1984). Two grams of air-dried soils were weighed into 50 ml centrifuge tubes, 20 ml of M3 were added and tied, shaken for five minutes, at 180 rpm, and filtered into 10 ml volumetric flask through an acid-resistant filter (Whatman No. 42) to obtain clear filtrates. A stock solution of 1000 mg/L was used to prepare standards for different elements by successive dilutions. ICP-OES (Thermo Scientific iCAP 7400 ICP-OES Pickles) and ICP-MS (Thermo Scientific iCAP TQ MS Ermentrude) were used to determine nutrient concentration in Mehlich 3 soil extracts. Glass electrode method of Chaturvedi and Sankar (2006) were used to determine soil pH at a water to soil ratio of 2.5:1. The chromic acid titration method was used to determine soil organic carbon (OC) (McLeod, 1973). The concentration of total nitrogen in soil samples was determined by Dumas and Kjeldahl (Nelson and Sommers, 1980). Eutric Fluvisols, Eutric Leptosols, Haplic Acrisols, Haplic Lixisols, and Umbric Nitisols (Figure 2) were major the soil types found in the study area (FAO, 2014; Wickama and Mowo, 2001).

Quality control and assurance: To monitor determination quality certified reference materials SCP-S150123029 obtained from SCP Science-Qmx laboratories,-UK was used. The Dilute 10 % HNO_3 (v/v) and 10 % HCl, (v/v) was used to wash all glassware, followed by distilled and finally Milli-Q water to avoid contamination, all reagents were prepared in Milli-Q water. The instrumental and method detection limits (LOD) for measured elements were determined (Table 1). The recovery of samples spiked with standards ranged from 83 % to 105 %.

Table 1. Detection limits (LODs inmg/L) for chosen nutrients in soil samples, experimental and reference values of certified reference materials (SCP EnviroMAT S150123029).

Element	Instrumental LOD	M3		
		Method LOD	Experimental Values	Reference Values
Ca	0.031	0.032	0.402	0.407
Cu	0.020	0.020	0.015	0.0165
Fe	0.050	0.050	0.026	0.0305
Mg	0.005	0.006	0.039	0.0452
Mn	0.003	0.003	0.005	0.0059
P	0.100	0.100	0.004	0.00404
Zn	0.010	0.010	0.042	0.0435
Mo	0.0004	0.001	0.022	0.0227
Al	0.0001	0.002	0.0201	0.0203

2.3. Statistical analysis

Statistical methods were applied to analyze data of studied parameters. All collected data were statistically analyzed by the Jamovi 1.2.25 and IBM SPSS Statistics 24 programs (IBM: Chicago, IL, USA). A descriptive statistical analysis (mean, maximum, standard deviation, etc.) was performed to define physical and chemical soil properties from ten (10) studied areas. The computed mean values were compared to critical and recommended values to evaluate the magnitude of soil fertility and potential phytotoxicity to plants of some trace metals in agricultural soils. The statistical difference among irrigation schemes, land uses, and sampling points within and between irrigation schemes were determined by ANOVA, and Tukey posthoc tests ($P < 0.05$). The study site and sampling points maps were generated by QGIS 3.10.7 software.

3. Results and discussion

From the certified reference material, 83 %–105 % recovery was obtained from samples spiked with standards. The instrumental and method detection limits (LOD) for measured nutrients are shown in Table 1. This indicates that data obtained are reliable for further actions and implementations. The nutrient concentration status in the area was

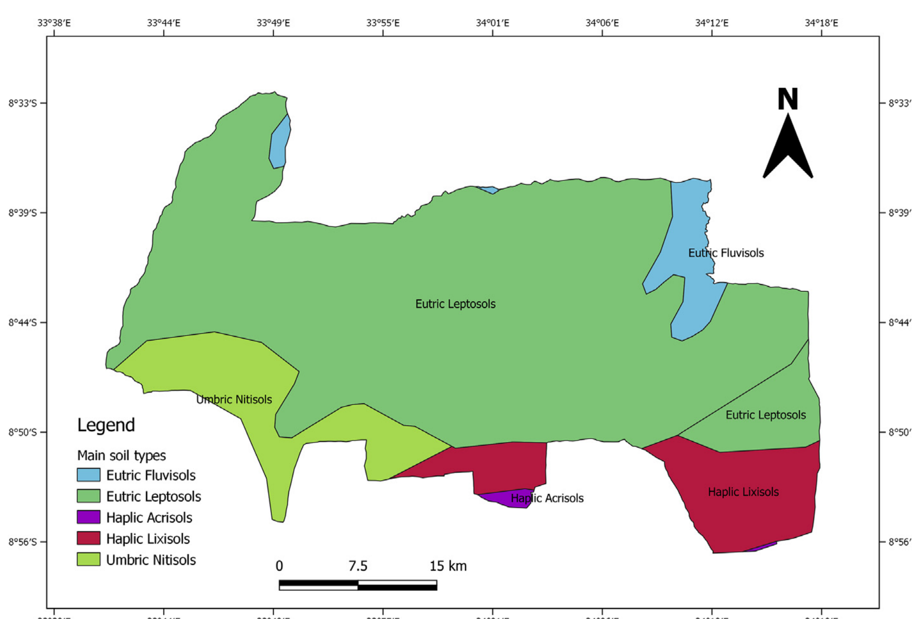

Figure 2. The map of Usangu illustrating dominant soil types common in the area (Source: Author).

Table 2. The estimated soil properties from soil samples from Usangu basin.

Irrigation schemes	EC (dS/cm)	pH	N (%)	OC (%)
Chimala	88.00	7.11	0.054	0.600
Igalako	128.00	6.88	0.064	0.680
Ihahi	69.70	6.92	0.066	0.800
Ilaji	196.00	7.22	0.173	2.370
Isenyela	71.40	6.60	0.063	0.750
Kapunga	89.00	7.35	0.039	0.450
Mabadaga	78.50	7.39	0.105	1.330
Mahangole	91.70	6.41	0.11	1.370
Mubuyuni	83.00	7.64	0.029	0.370
Uturo	100.90	6.65	0.16	1.990
Mean	**102.23**	**6.44**	**0.109**	**1.507**

generated (Table 2) and later analyzed based on the land uses to estimate soil fertility status across land use and irrigation schemes providing spatial nutrient distribution in the landscape (Table 4). The soil pastes electric conductivity (EC) in the area was 69.70–128.00 dS/cm (Table 2). The determined EC (69.70–128.00 dS/cm) were in the range of medium to high, that likely to affect the availability of plant nutrients. The study observed high EC in Ilaji, Uturo, and Igalako (196.00, 100.90, and 128.03 dS/cm), respectively.

3.1. Soil pH

Soil pH influences soil biogeochemical processes and is considered a master soil variable that controls biological, chemical, and physical properties of soil, affecting plant growth and biomass yield. Firstly, soil pH constituent availability and mobility of plant nutrients. The soil pH in almost all samples was in the range of 6.4–7.6 (Table 2), where among 198 samples 19 had soil pH below 6.5 indicating they are acidic conditions, which might affect availability of plant nutrients such as N, P, Ca, Mg, S, K, and other bases. The remaining soil samples had pH values in the range of 6.5–7.6, where these values were within the favourable and acceptable pH ranges for crop growth and production for most cultivated crops in USB. Soil pH as an essential indicator of soil chemical characteristics have a negative correlation with CEC, example soils with pH below 6.5 had a substantial negative relationship with CEC ($P < 0.05$, r = 0.82) of the soil, which indicates reduced capacity of soil to holder cations which are required for plant growth. Furthermore, the studied soils were observed to have high extractable Al (93.21–792.97 mg/kg) which indicates the availability of extractable acidity. In such acidity, Al and Mn toxicities problems have been reported (Ndakidemi and Semoka, 2006). The observed soil pH in the study area was lower than recommended level by Kamprath (1970) for lime application because the pH ranges are unlikely to result in serious phytotoxicity effects to crop production. However, the addition of organic manure is recommended to improve further the biogeochemical reactions and nutrient availability, especially for nitrogen, phosphorus, calcium, potassium, and magnesium which are likely to be adsorbed by Al and Fe at low soil pH (Cakmakci and Sahin, 2021; Nahar and Khan, 2021; Ngoc et al., 2021; Souahi et al., 2021).

3.2. Plant available phosphorus (P)

The concentration of available P (P_{M3}) was determined by Mehlich 3 method (Mehlich, 1984) a standard method for soil P test in many laboratories in the world which has a strong correlation with other standard methods like Olsen, Bray 1 P, and other methods popular for soil P test (Kleinman and Sharpley, 2002; Sims et al., 2002). The P_{M3} concentration was in the range of 0.52–48.87 mg/kg. Based on FMANR (1990) suggestion of P for upland soils to be greater than 15.0 mg/kg, most of the studied sites had a mean value below 15.0 mg/kg, which indicates soils, had low P concentration, which might limit plant growth. Therefore, additional P from organic and inorganic fertilizer is important for sustainable crop production. The concentration of P_{M3} in different land use was observed to vary significantly ($P < 0.05$) across land uses (Table 3 and Figure 3a) such as conserved areas (0.99–35.79 mg/kg) and mean value of 13.49 mg/kg, maize farming area (15.2–40.32 mg/kg) with a mean value of 25.73 mg/kg, and paddy farming area (0.52–49.87 mg/kg) with mean values of 7.7 mg/kg. Maize farming areas were observed to have P_{M3} concentrations greater than 15 mg/kg appreciable for crop growth, this might be associated with fertilizer and crop residues application and less soil erosion (Wasonga et al., 2010). The spatial distribution of P concentration among land use was variable, where paddy farming areas had low P_{M3} content than other two land uses; even though farmers in paddy farming areas have high use of nitrogenous and phosphatic fertilizer. Low P_{M3} in paddy farming areas might have resulted from high soil erosion through surface water runoffs, little addition of crop residues because always crop residues are removed out of the field to get fine earth for easy paddy transplanting. Although conserved areas are protected from human activities left for natural vegetation to grow, the P_{M3} concentration was observed to range from low to high (0.99–35.79 mg/kg) which is enough to allow natural vegetation growth and regeneration, and this is associated with decomposition of plant residues.

Spatial soil P concentration distribution among irrigation schemes in the study area was significantly ($P < 0.05$) different among irrigation schemes. Where Igalako, Mahongole, Kapunga, and Ihahi observed high P concentrations, i.e., 22.1, 40.32, 21.5, and 49.85 mg/kg, respectively (Figure 3b and Table 4). These schemes are located in lowland areas of the Usangu agro-ecosystem receiving runoffs from the upper parts of the Usangu basin and are among schemes that are highly intensified (Machibya and Mdemu, 2005; Ngailo et al., 2016). The remaining schemes such as Mubuyuni, Isenyela, Ilaji, Chimala, Uturo, and Mabadaga (Figure 3b and Table 4), had low P concentration as these are smallholder farmers schemes with less fertilizer input and no or very low manure applications. The study by Ngailo et al. (2016) in the Usangu basin reported that smallholder farmers with less capital to buy fertilizer and other agriculture inputs experienced low productivity per unit area and their fields observed to have low

Table 3. Soil nutrient composition (in mg/kg) in the different land use in Usangu agro-ecosystem, Mbarali District-Tanzania.

	Land Use	Al	Ca	Cu	Fe	K	Mg	Mn	P	S	Zn
Mean	Conserved areas	214.9	919.7	1.8	174.8	500.1	301.0	152.9	13.5	16.7	3.5
	Maize farming	193.6	1362.6	0.7	107.0	647.1	286.9	220.5	25.7	23.1	3.6
	Paddy farming	294.1	806.9	2.0	214.8	399.8	238.6	137.0	7.7	22.4	2.1
Minimum	Conserved areas	125.4	194.8	0.2	97.9	113.0	116.0	25.8	1.0	5.4	1.6
	Maize farming	124.9	1318.6	0.5	91.6	612.5	253.5	169.1	15.2	15.5	3.2
	Paddy farming	93.2	95.1	0.1	81.1	28.8	42.2	12.8	0.5	2.1	0.3
Maximum	Conserved areas	337.5	2010.7	3.7	314.1	1087.1	520.2	312.6	35.8	29.5	7.5
	Maize farming	278.2	1415.2	1.0	127.8	678.2	316.9	241.0	40.3	39.0	4.1
	Paddy farming	793.0	2494.4	7.2	470.6	1484.2	1069.2	503.1	49.9	128.8	5.5

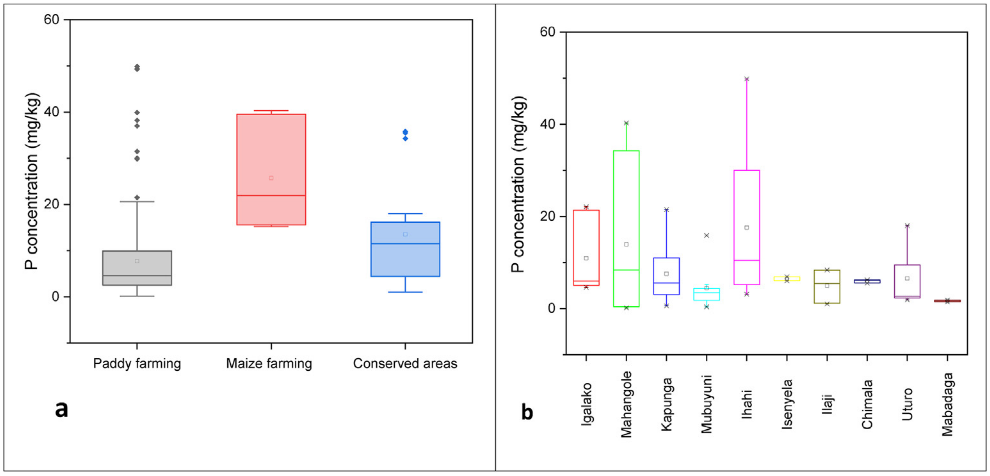

Figure 3. Boxplot showing soil P concentration in different land use (a) and irrigation schemes (b) in Usangu agro-ecosystem, during November–December 2019.

Table 4. Soil nutrient composition (in mg/kg) in different irrigation schemes in Usangu agro-ecosystem, Mbarali District-Tanzania.

	Irrigation Scheme	Al	Ca	Cu	Fe	K	Mg	Mn	P	S	Zn
Mean	Chimala	182.19	482.61	2.29	324.08	263.48	183.49	119	5.98	16.61	2.47
	Igalako	320.96	1420.45	0.55	182.79	432.36	253.8	159.1	10.94	23.2	1.97
	Ihahi	188.54	1060.09	0.81	158.31	579.64	215.31	226.91	17.56	21.39	3.38
	Ilaji	277.06	422.47	1.53	248.68	254.48	180.66	141.61	4.97	11.87	2.43
	Isenyela	210.72	755.58	0.31	107.89	263.75	101.3	147.85	6.35	23.35	1.46
	Kapunga	346.16	785.38	1.83	190.58	487.8	232.22	104.52	7.55	29.29	1.81
	Mabadaga	201.95	2387.82	2.11	155.81	241.27	1031.78	64.51	1.66	35.34	0.46
	Mahangole	287.42	1126.13	0.68	154.62	663.23	291.24	201.27	13.87	18.59	3.16
	Mubuyuni	285.44	452.71	3.44	288.81	146.88	196.03	98.92	4.44	12.38	2.02
	Uturo	199.15	811.53	4.14	245.48	284.13	339.29	171.84	6.57	19.64	2.94
Minimum	Chimala	179.81	471.14	2.06	319.22	258.19	180.57	118.81	5.54	14.76	2.27
	Igalako	133.79	471.68	0.23	124.71	190.55	178.98	106.11	4.61	5.65	1.03
	Ihahi	93.21	446.5	0.53	81.14	229.34	89.42	125	3.15	6.47	1.12
	Ilaji	204.63	194.82	0.15	142.68	113.02	115.99	25.75	0.99	5.43	1.61
	Isenyela	204.85	746.34	0.1	105.92	257.86	100.75	144.79	6.03	11.72	1.11
	Kapunga	117.7	205.27	0.48	85.84	157.9	75.88	12.75	0.57	8.05	0.76
	Mabadaga	188.38	2310.68	1.96	149.7	211.45	1009.98	61.1	1.44	33.6	0.34
	Mahangole	130.88	623.64	0.03	97.9	437.61	195.56	122.42	0.52	8.87	1.03
	Mubuyuni	118.11	95.1	1.22	118.12	28.75	42.18	39.91	0.38	2.12	0.75
	Uturo	125.36	584.75	3.1	182.73	128.2	186.25	92.79	1.9	5.43	1.4
Maximum	Chimala	184.3	495.6	2.55	326.97	268.96	188.39	119.18	6.22	18.21	2.79
	Igalako	563.72	2467.91	0.97	235.18	678.2	296.31	200.56	22.1	39	3.59
	Ihahi	367.55	1627.17	1.27	289.54	1131.54	409.1	503.08	49.87	53.97	5.53
	Ilaji	337.51	654.66	2.96	314.08	396.78	245.43	274.43	8.39	23.31	2.97
	Isenyela	222.35	762.25	0.51	111.38	266.88	101.86	152.66	6.93	34.37	1.7
	Kapunga	662.23	1481.94	4.12	321.6	1484.17	334.16	231.66	21.5	128.81	4.11
	Mabadaga	214.83	2494.35	2.3	165.35	265.38	1069.21	69.49	1.86	36.29	0.54
	Mahangole	739.25	2010.72	1.11	197.24	1087.11	445.81	312.64	40.32	32.31	6.41
	Mubuyuni	792.97	1558.84	7.21	470.59	331.56	707.26	193.52	15.89	29.8	3.88
	Uturo	312.28	1274.94	5.96	332.93	430.76	520.2	213.59	18.02	30.9	7.47

nutrient levels such N, K, P due to poor soil fertility management, the same scenario is observed in this study. Therefore, soil fertility management is dependent on the capacity of farmers or land users to apply materials required to replenish plant nutrients for increased productivity.

3.3. Exchangeable Al, Fe, and Ca

Soil Al, Fe, and Ca concentrations as important nutrients for plant growth were determined in all ten (10) sites and across land uses. The concentration of Al, Fe, and Ca varied among land uses where the general

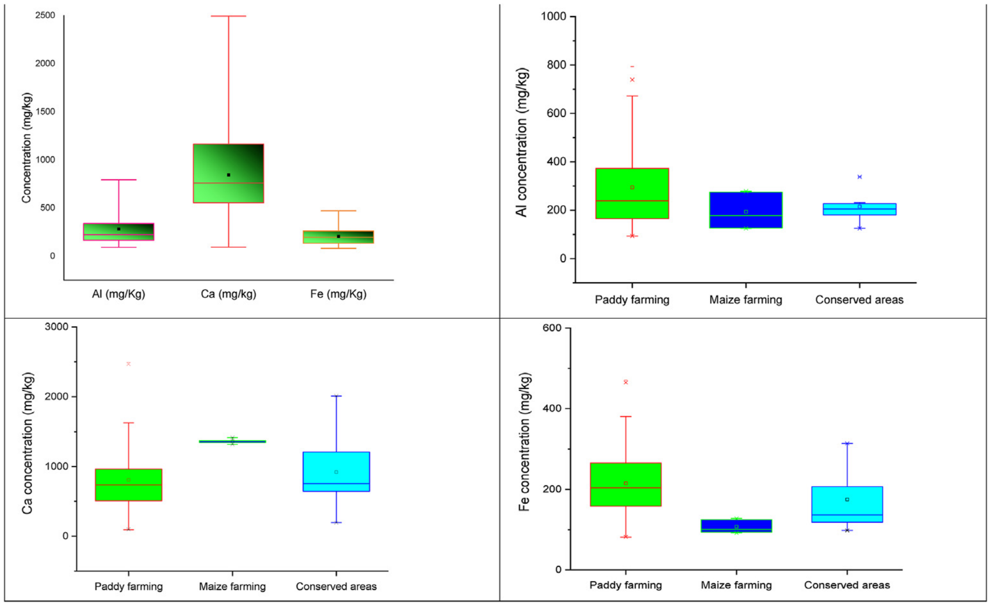

Figure 4. The distribution of Al, Fe, and Ca in different land uses (maize, paddy farming, and conserved) in Usangu basin-Tanzania.

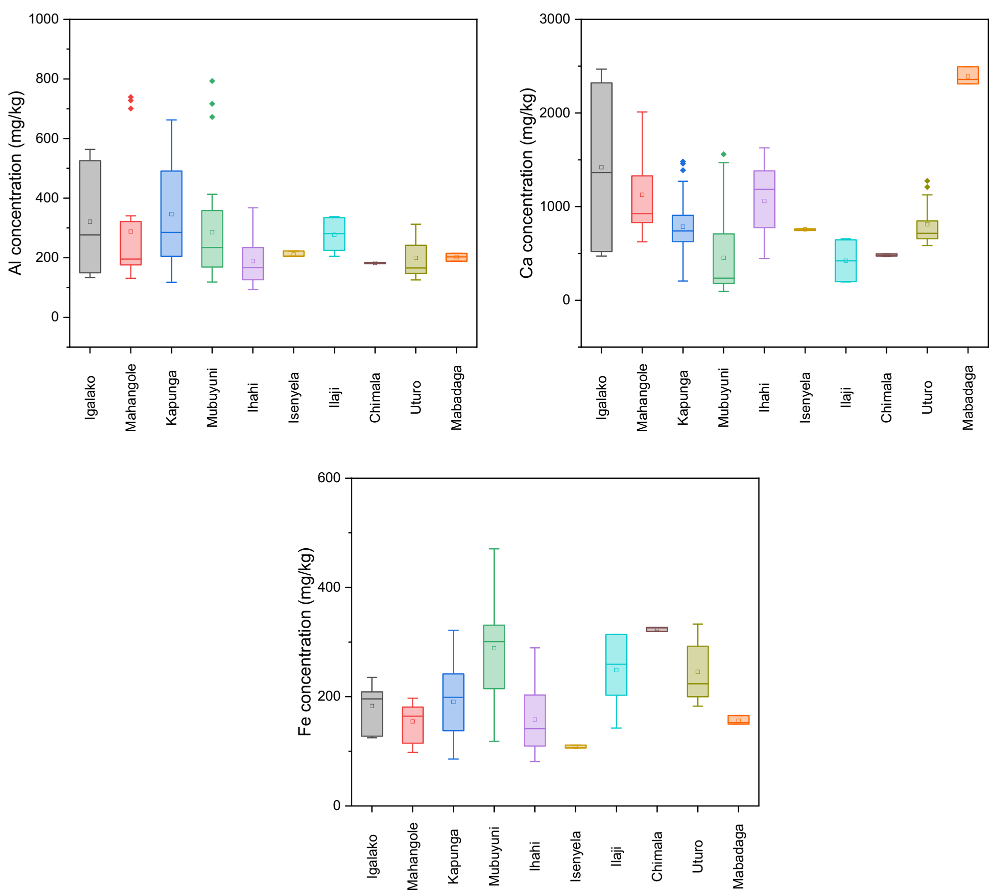

Figure 5. Al, Fe and Ca distribution among irrigation schemes in the Usangu basin Tanzania.

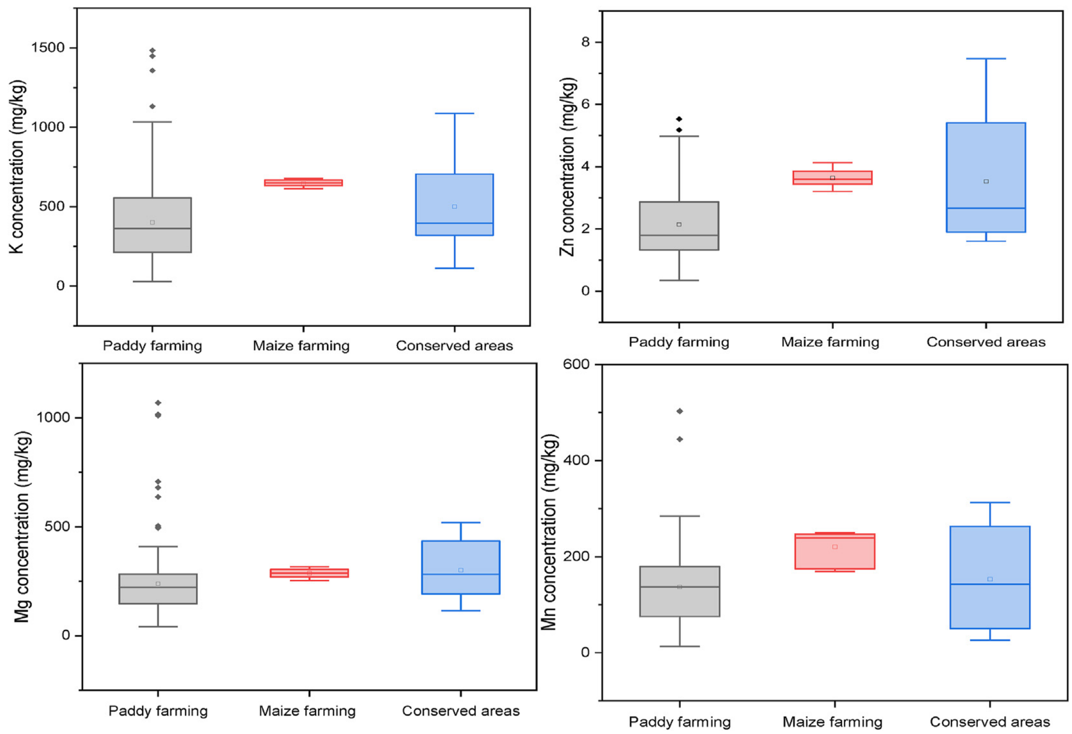

Figure 6. Boxplot showing soil spatial distribution of K, Zn, Mg, and Mn among land use in Usangu basin Tanzania.

concentration trend observed higher values in farming areas (maize and paddy) compared to conserved areas (Figure 4 and Table 3), this might be due to human interventions such as fertilizer and manure application. The concentration of Fe and Ca were observed to be higher in conserved areas (Fe,174.83 mg/kg; Ca 919.65 mg/kg) than maize (Fe 107.3 mg/kg; Ca 1362.55 mg/kg) and paddy farming area (Fe 214.81 mg/kg; Ca 806.89 mg/kg) respectively, this might be due to continuous exploitation of nutrients in farming areas with little replenishment because Fe and Ca are taken up by plants, therefore upon little replenishment could result in a decline in agricultural productivity.

The spatial distribution of available Al, Fe, and Ca among irrigation schemes in the Usangu basin was observed to be highly variable (Table 4 and Figure 5). The study found that Kapunga, Igalako, Mahongole, Mubuyuni, Ilaji, and Uturo irrigation schemes have higher Al, Fe, and Ca concentrations than the others (Figure 5 and Table 4). High values of Ca and Fe is important for crop growth as they are involved in important plant biochemical reactions (Ca and Fe) such as photosynthesis, but extreme concentration could limit the availability of other elements such as phosphorus through fixation and sorption reaction, but also, they have toxicity effect to plants at extreme concentrations (Ndakidemi and Semoka, 2006). The level of Al, Fe, and Ca observed in the study area were within the acceptable range (1000 mg/kg) for crop production and other nutrient availability (Horneck et al., 1999). The study also determined that Ca was the most dominant cation on the soil colloids and P availability determinants for plant uptake and saturations. The available Fe in soils in the study area ranged 81.14–470.5 mg/kg values which were higher than those observed by Ndakidemi and Semoka (2006) in Usambara mountains Northern Tanzania where Fe ranged 16.0–86.0 mg/kg. The proposed critical level of Fe for various crops varied from 0.3 to 10 mg/kg (Lindsay and Norvell, 1978). Therefore, the concentration of Fe observed in the study area were very high for plant uptake but also may affect the availability of other nutrients especially phosphorus, nitrogen, potassium, sulphur, and magnesium at soil pH less than 5.5 (Amuri et al., 2012; Karlsson and Messing, 1980; Mhoro and Anthony, 2015).

3.4. Extractable Mg, Zn, Mn, and K

The concentration of Mg, Zn, K, and Mn in the study area were observed to vary ranges across land uses and irrigation schemes (Tables 2 and 3). The general trend were K (28.75–1484.17 mg/kg) with mean value of 420.76 mg/kg, Mg (42.18–1069.21 mg/kg) with mean of 246.7 mg/kg, Zn (0.34–7.47 mg/kg) with mean value of 2.34 mg/kg while Mn concentration were 12.75–503.08 mg/kg with mean value of 142.43 mg/kg (Table 2). The spatial distribution of Mg, Zn, K, and Mn were observed to vary among land uses (Table 3 and Figure 6), where high values of K were observed in maize farming areas (647.11 mg/kg), conserved areas (500.0 mg/kg) and paddy farming areas (399.75 mg/kg). The same trend was observed for Mn and Zn while for Mg high values were observed in conserved areas (300.97 mg/kg), compared to maize farming (286.87 mg/kg) and paddy farming (238.59 mg/kg) areas. Based on the proposed critical levels in most crops of 2 cmol/kg (Schwartz and Corrales, 1989), some locations had elements below critical levels of Mg, Zn, K which required addition or supplemental nutrients to ensure maximum crop growth and productivity.

The Mg:K ratio determines the availability of Mg and K for plant uptake (Ndakidemi and Semoka, 2006). The calculated Mg:K ratio was observed to be below 2 which is recommended for better K and Mg availability for optimum crop growth, hence Mg and K were available in deficiency level limiting the crop growth. Therefore, fertilizer and other materials rich in Mg and K must be added to ensure better crop growth and high yields. In all soils, available Mn ranged from 3.0 to 384 mg/kg, where the proposed deficiency level for Mn (DTPA) in the soil varied from 2.0 to 5.0 mg/kg, and values of greater than 140 mg/kg were regarded as excess (Sillanpää, 1982). In this study, five sites (Ihahi (226.91 mg/kg), Mahongole (201.27 mg/kg), Igalako (159.10 mg/kg), Isenyela (147.85 mg/kg), and Ilaji (141.61 mg/kg)) had excessive Mn that could lead to Mn toxicity in crops, and other five had deficient levels (Table 4). Available Zn in the soil ranged from 0.34 to 7.47 mg/kg, which were above the proposed range of Zn deficiency for Zn (0.4–0.6 mg/kg), where anything greater than 10–20 mg/kg is considered as the excess

Table 5. The distribution of trace metals and micronutrients in schemes of Usangu basin Southern Highland Tanzania.

	Irrigation Scheme	Cu (mg/kg)	Co (μg/kg)	Cr (μg/kg)	Mo (μg/kg)	Ni (μg/kg)
Mean	Chimala	2.29	699.57	101.46	ND	1086.71
	Igalako	0.55	572.35	26.14	2.25	244.42
	Ihahi	0.81	489.30	13.46	11.80	110.46
	Ilaji	1.53	291.19	46.08	ND	134.54
	Isenyela	0.31	325.74	6.09	16.44	93.28
	Kapunga	1.83	631.04	39.60	0.72	307.89
	Mabadaga	2.11	912.72	99.03	1.35	1770.17
	Mahangole	0.68	455.84	13.49	5.67	74.14
	Mubuyuni	3.44	987.06	84.92	0.18	1278.17
	Uturo	4.14	1619.78	55.81	3.45	799.26
Minimum	Chimala	2.06	666.77	89.27	0.00	1048.16
	Igalako	0.23	365.44	9.29	0.00	53.34
	Ihahi	0.53	164.21	1.17	0.00	84.45
	Ilaji	0.15	135.99	10.95	0.00	49.00
	Isenyela	0.10	321.38	0.95	14.92	86.08
	Kapunga	0.48	45.16	6.93	0.00	25.22
	Mabadaga	1.96	838.51	92.37	0.00	1708.89
	Mahangole	0.03	280.16	0.00	0.00	34.70
	Mubuyuni	1.22	409.28	18.26	0.00	170.66
	Uturo	3.10	752.11	40.09	0.00	520.92
Maximum	Chimala	2.55	719.95	107.82	ND	1112.72
	Igalako	0.97	883.46	48.84	7.34	510.18
	Ihahi	1.27	1045.42	52.60	65.87	175.73
	Ilaji	2.96	468.57	85.74	ND	216.22
	Isenyela	0.51	332.78	9.19	18.28	102.22
	Kapunga	4.12	1728.17	97.86	7.67	725.18
	Mabadaga	2.30	1023.17	102.92	3.23	1883.60
	Mahangole	1.11	647.26	27.04	22.11	110.20
	Mubuyuni	7.21	1822.17	222.78	2.18	4497.32
	Uturo	5.96	2684.30	68.74	13.03	1299.45

ND; means not detected.

amount, therefore the concentration of Zn in the study area was adequate for most crops growth (Ndakidemi and Semoka, 2006).

3.5. Total soil organic carbon

Soil organic carbon is an important source of plant nutrients in agricultural soils and determines the availability of plant nutrients as it influences solubility of minerals, charges, CEC, and soil pH (Ndakidemi and Semoka, 2006). Organic carbon is a proxy for organic matter (OM), OM upon mineralization releases plant nutrients such as nitrogen, phosphorus, and sulphur. Soil organic carbon (OC) in the collected soil samples were studied in the collected soil samples. The total OC was observed to range from 0.37% to 2.37 % with a mean value of 1.51 % (Table 2). Some irrigation schemes observed high OC such as Ilaji (2.37 %), Mabadaga (1.33 %), Mahongole (1.37 %), and Uturo (1.99 %) while other schemes had OC below 0.80 %. OM is a key in maintaining soil health and biodiversity; therefore, soils with low OM content are likely to be deficient in plant nutrients because of reduced soil microbial activity (Ebrahimi et al., 2021; Najarian and Souri, 2020). The study found a positive correlation between OC and Zn, Cu, and Mn. As the range of OC was in the range of 0.37–2.37 % (equivalent to 0.37–23.7 g/kg) where the critical threshold of soil organic carbon is 20.0 g/kg. Therefore a value of OC in this study mostly was below recommended levels, this indicates soil quality degradation and reduced soil microbial activities (Ndakidemi and Semoka, 2006).

Higher OC in maize and conserved areas than in paddy farming is exemplified by increased incorporation of crop residues, organic manure, and decomposing plant material that were abundant in the sampling period. Promotion of activities that enhance OM return to the USB soil is highly recommended, as this would improve soil fertility replenishment. This could be possible via the application of crop residues and organic manure in both maize and paddy farming areas such as the inclusion of green legumes and composting will increase organic matter.

3.6. Total N

The determined total N in the soil ranged from 0.29 to 1.73 g/kg and a mean value of 1.09 g/kg. The 2.0 g/kg is a proposed critical level for most crops in Tanzania and all 198 soil samples (100 %) had N concentration below the recommended critical levels (Ndakidemi and Semoka, 2006). This shows N in most studied soils was in deficient levels to sustenance plant growth (Aslani and Souri, 2018; Souri et al., 2018b; Souri and Dehnavard, 2017). Therefore, the application of nitrogenous fertilizer is important to ensure better plant growth and yields. The problem of N deficiency is projected to further intensify in the future since farmers in the USB do apply fertilizers on their farms but mainly inorganic fertilizer which requires yearly application and is hampered by increasing price (Ngailo et al., 2016). However, all studied schemes had total N concentration below critical levels; some schemes had appreciable total N concentration such as Mabadaga (1.05 g/kg), Uturo (1.65 g/kg), Ilaji (1.73 g/kg), and Mahongole (1.10 g/kg) while other schemes had total N below 0.29 g/kg (Table 2). Since N is one of the vital elements for plant growth, needed for optimum crop production in the USB values below the required amount could be supplemented from organic and

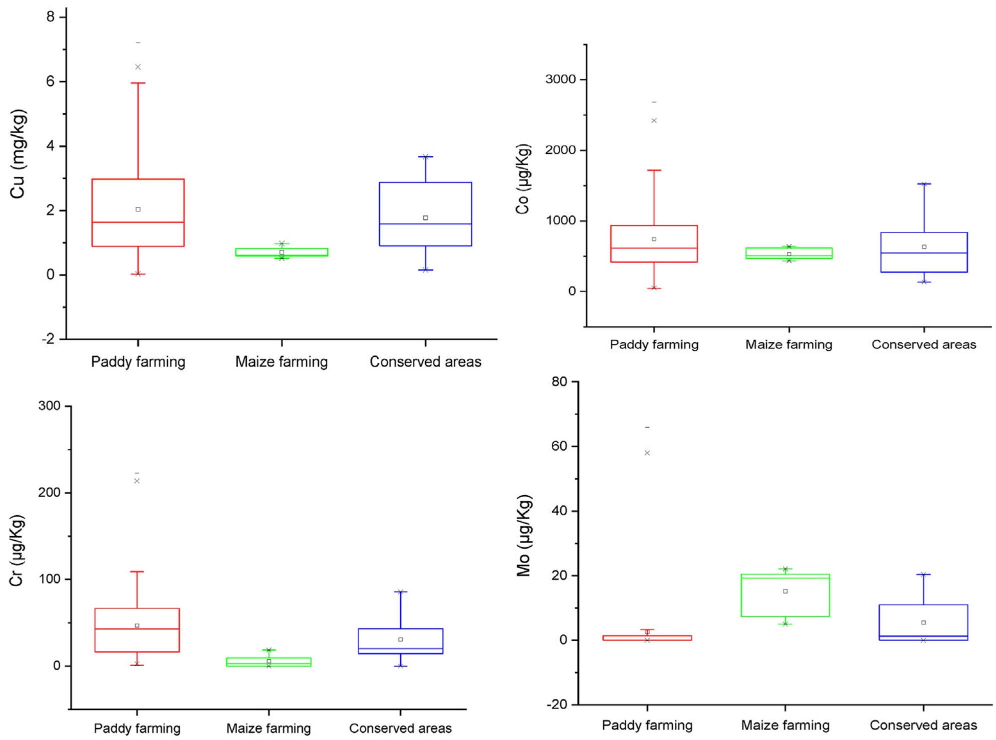

Figure 7. The soil distribution of micronutrients (micronutrient concentration in Y-axis) and in different land uses (in X-axis) in Usangu basin-Tanzania.

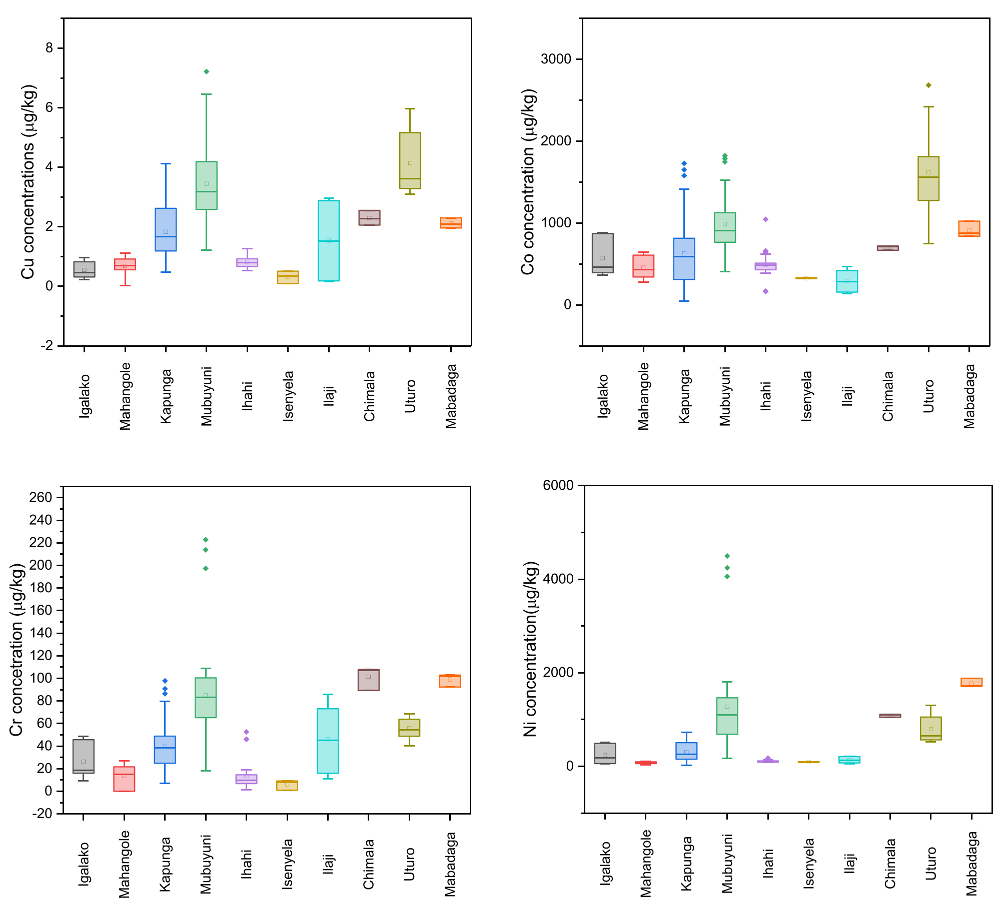

Figure 8. The soil distribution of micronutrients (micronutrient concentration in Y-axis) in irrigation schemes (in X-axis) in Usangu-Tanzania.

Table 6. The distribution of trace metals and micronutrients in different land uses in the study sites in Usangu basin Southern Highland Tanzania.

	Land Use	Cu (mg/kg)	Co (μg/kg)	Cr (μg/kg)	Mo (μg/kg)	Ni (μg/kg)
Mean	Conserved areas	1.78	634.29	30.72	5.45	320.38
	Maize farming	0.70	530.85	5.47	15.18	109.07
	Paddy farming	2.03	740.90	46.81	2.53	535.17
Minimum	Conserved areas	0.15	135.99	0.00	0.00	49.00
	Maize farming	0.52	435.56	0.00	5.00	61.49
	Paddy farming	0.03	45.16	0.95	0.00	25.22
Maximum	Conserved areas	3.67	1523.96	85.74	20.39	804.44
	Maize farming	0.97	639.05	18.50	22.11	183.99
	Paddy farming	7.21	2684.30	222.78	65.87	4497.32

inorganic fertilizer or inclusion of legumes crops, which can fix nitrogen from the atmosphere, but also the production of crop varieties with high N use efficiency will be a best and sustainable option to ensure high yield from low N uptake.

3.7. Trace metal accumulation in Usangu agro-ecosystem

The study analyzed the availability of micronutrients such as copper (Cu), cobalt (Co), nickel (Ni), chromium (Cr), and molybdenum (Mo) (Tables 4 and 5) as they are required for plant growth, but its extremes are toxic to plants, plant product user and soil microbial biodiversity activities.

Copper (Cu): The concentration of available Cu was observed to range from 0.03-7.21 mg/kg (Table 5). For DTPA-extractable Cu and which is highly correlated with M3-extractable Cu, soil Cu concentration of 0.2 mg/kg is considered as a minimum limit, values below it provide insufficient Cu for plant growth (Lindsay and Norvell, 1978). Almost all soils had a Cu concentration more than the proposed minimum limit for crop productivity, indicating that Cu was available in the study area in sufficient concentrations for plant growth (Table 5). The distribution of Cu based on land uses in the study area were observed to vary among land uses. For example, Cu in conserved area ranged 0.15–3.67 mg/kg, with mean of 1.78 mg/kg; in maize farming 0.52–0.97 mg/kg with mean of 0.7 mg/kg; and paddy farming 0.03–7.21 mg/kg with mean of 2.03 mg/kg. The available Cu was observed to be high in paddy farming than in conserved and maize farming areas. This might be due to the high use of copper-based pesticides and fertilizer enriched with copper as a micronutrient in paddy farming than in other land uses. The spatial distribution of Cu among irrigation schemes was observed to be significantly different ($p < 0.05$) where the mean Cu concentration (in mg/kg) in different schemes were Igalako (0.55), Ihahi (0.81), Ilaji (1.53), Isenyela (0.31), Kapunga (1.83), Mabadaga (2.11), Mahongole (0.68), Mubuyuni (3.44), and Uturo (4.14). Chimala, Ilaji, Kapunga, Mubuyuni, and Uturo irrigation schemes (Figure 8) were observed to have a high copper content, which might interfere with the plant growth and availability of other nutrients.

Cobalt (Co): The overall available Co were ranged 45.16–2684.3 μg/kg with a mean value of 721.06 μg/kg. The Co distribution in agricultural soils in different land uses observed to be significantly different ($P < 0.01$), where the distribution was as follows; conserved areas (135.99–1523.96 μg/kg) and mean value of 634.29 μg/kg (Table 5 and Figure 7), maize farming (435.56–639.05 μg/kg) and mean value of 530.85 μg/kg, and in paddy farming (135.99–2684.31 μg/kg) with a mean value of 740.90 μg/kg. The spatial distribution of Co over the study area was significantly different between schemes (Table 5 and Figure 8), where Chimala (666.77–719.28 μg/kg), Igalako (365.44–883.46 μg/kg), Ihahi (164.21–1045.42 μg/kg), Ilaji (135.99–468.57 μg/kg) and other schemes as shown in Figure 8 recorded high values. Cobalt is a beneficial micronutrient required by plants in micro-dose as important in several enzymes and increases the drought resistance of seeds, and nitrogen fixation by bacteria in legumes (Akeel and Jahan, 2020). The values observed in this study were enough to support plant growth; however, in some sites values were very high, imposing a phytotoxicity effect on plants and soil microbial diversity.

The available Cr, Mo, and Ni: The concentration of available Cr, Mo, and Ni were Cr (0.00–222.78 μg/kg), Mo (0.00–65.87 μg/kg, and Ni (25.22–4497.32 μg/kg) across irrigation schemes and land uses in the study area (Table 5 and Table 6). Among schemes with a high concentration of Cr were Ilaji (46.08 μg/kg), Kapunga (39.60 μg/kg), Mabadaga (99.03 μg/kg), Mubuyuni (84.92 μg/kg), and Uturo (55.81 μg/kg) (Table 5) were determined. At the same time, Mo was high in Ihahi, Isenyela, and Mahongole, i.e., 11.80, 16.44, and 5.67 μg/kg, respectively. For Ni, higher values were observed to be greater than 74.14 μg/kg. The concentration of Cr, Mo, and Ni were observed to vary among soils from different land uses as higher concentration Cr were observed on conserved area ranged 0–85.74 μg/kg and mean value of 30.72 μg/kg, and paddy farming 0.95–222.78 μg/kg and mean value 46.81 μg/kg than maize farming area 0–18.50 μg/kg and mean value of 5.47 μg/kg. For Mo, high values were observed in paddy farming ranged 0–65.87 μg/kg and mean of 2.53 μg/kg, in maize farming ranged 5.00–22.11 μg/kg and mean of 15.18 μg/kg, and in the conserved area ranged 0.0–20.39 μg/kg and mean value of 5.45 μg/kg, where the same trend was observed for Ni (Table 6). The higher values may be associated with the application of fertilizer, pesticides, herbicides, and decomposition of plant materials and residues, these values were observed to be enough to support plant growth and plant reactions (Noroozlo et al., 2019; Souri et al., 2018a).

4. Conclusion

The study conducted in 66 sites in USB when compared to reference values (critical levels) from other areas showed vital variations in soil nutrients. The results indicate that major soil nutrients constraints were N, P, K, Ca, and Mg. some soils were observed to have exchangeable Al, and metallic micronutrients (Cu, Co, Cr, Ni and Mo, Fe and Zn) were at adequate levels. Other sites were observed to have high Mn that could lead to toxicity in crops. Overall, these results point out that there is a challenge in maintaining soil fertility in the Usangu agro-ecosystem hence limiting agricultural productivity and sustainability. In locations with deficient, mineral nutrients intervention measures to rectify the challenges must be undertaken. This calls for farmer-based research on soil fertility management such as the use of farmyard manure, organic manure, inorganic fertilizers, and crop improvement to achieve higher yields under low soil fertility. Additional integrative strategies to combat soil fertility decline must be a research agenda to ensure sustainable soil fertility management in the area.

Declarations

Author contribution statement

All authors listed have significantly contributed to the investigation, development and writing of this article.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Akeel, A., Jahan, A., 2020. Role of cobalt in plants: its stress and alleviation. In: Contaminants in Agriculture. Springer, pp. 339–357.

Amuri, N., Mhoro, L., Munishi, J.A., Msanya, B.M., Semu, E., Malley, Z., 2012. Pedological Characteristics and Implication on Soil Fertility of Selected Soils of Mbeya Region, Tanzania the 3 rd RUFORUM Biennial Conference.

Aslani, M., Souri, M.K., 2018. Growth and quality of green bean (Phaseolus vulgaris L.) under foliar application of organic-chelate fertilizers. Open Agric. 3, 146–154.

Bationo, A., Waswa, B., Kihara, J., Kimetu, J., 2005. Advances in Integrated Soil Fertility Management in Sub-saharan Africa: Challenges and Opportunities.

Belay, Y., 2015. Integrated soil fertility management for better crop production in Ethiopia. Int. J. Soil Sci. 10, 1–16.

Cakmakci, T., Sahin, U., 2021. Productivity and heavy metal pollution management in a silage maize field with reduced recycled wastewater applications with different. J. Environ. Manag. 291, 112602.

Chaturvedi, R.K., Sankar, K., 2006. Laboratory Manual for the Physico-Chemical Analysis of Soil, Water and Plant. Wildl. Inst. India. Dehradun 97.

Chen, A., He, H., Wang, J., Li, M., Guan, Q., Hao, J., 2019. A study on the arable land demand for food security in China. Sustain. Times 11, 1–15.

Coulibaly, B., Li, S., 2020. Impact of agricultural land loss on rural livelihoods in peri-urban areas: empirical evidence from sebougou, Mali. Land 9, 1–20.

Doos, B.R., 2002. Population growth and loss of arable land. Global Environ. Change 12, 303–311.

Ebrahimi, M., Souri, M.K., Mousavi, A., Sahebani, N., 2021. Biochar and vermicompost improve growth and physiological traits of eggplant (Solanum melongena L.) under deficit irrigation. Chem. Biol. Technol. Agric. 8, 1–14.

FAO, 2014. World reference base for soil resources 2014. In: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, 106. World Soil Resource.

Fox, B., 2004. An Overview of the Usangu Catchment , Ihefu Wetland , & Great Ruaha River Ecosystem Environmental Disaster, pp. 1–15.

Funakawa, S., Yoshida, H., Watanabe, T., Sugihara, S., Kilasara, M., Kosaki, T., 2012. Soil fertility status and its determining factors in Tanzania. Soil Heal. L. Use Manag.

Gomiero, T., 2016. Soil degradation, land scarcity and food security: reviewing a complex challenge. Sustain. Times 8, 1–41.

Halbac-Cotoara-zamfir, R., Smiraglia, D., Quaranta, G., Salvia, R., Salvati, L., Giménez-Morera, A., 2020. Land degradation and mitigation policies in the mediterranean region: a brief commentary. Sustain. Times 12, 1–17.

Hatamian, M., Nejad, A.R., Kafi, M., Souri, M.K., Shahbazi, K., 2020a. Nitrate improves hackberry seedling growth under cadmium application. Heliyon 6.

Hatamian, M., Rezaei Nejad, A., Kafi, M., Souri, M.K., Shahbazi, K., 2020b. Interaction of lead and cadmium on growth and leaf morphophysiological characteristics of European hackberry (Celtis australis) seedlings. Chem. Biol. Technol. Agric. 7, 1–8.

Havlin, J., Heiniger, R., 2020. Soil fertility management for better crop production. Agronomy 10, 1–5.

Henryson, K., Sundberg, C., Kätterer, T., Hansson, P.A., 2018. Accounting for long-term soil fertility effects when assessing the climate impact of crop cultivation. Agric. Syst. 164, 185–192.

Horneck, D., Sullivan, D., Owen, J., Hart, J., 1999. Soil test interpretation guide. Commun. Exp. Stn. State Oregon Rehab. 1–8.

Hossain, A., Krupnik, T.J., Timsina, J., Mahboob, M.G., 2020. Environment, Climate, Plant and Vegetation Growth, Environment, Climate, Plant and Vegetation Growth.

Kadigi, R.M.J., Kashaigili, J.J., Mdoe, N.S., 2004. The economics of irrigated paddy in Usangu Basin in Tanzania: water utilization, productivity, income and livelihood implications. Phys. Chem. Earth 29, 1091–1100.

Kamprath, E.J., 1970. Exchangeable aluminum as a criterion for liming leached mineral soils. Soil Sci. Soc. Am. J. 34, 252–254.

Karlsson, I., Messing, I., 1980. A Reconnaissance Soil Survey in Parts of Mbeya Region in Tanzania.

Kashaigili, J., Matthew, P., Henry, M., Mahoo, F., A, B., Mbilinyi, B., Tumbo, S.I., 2006. Use of a hydrological model for environmental management of the Usangu Wetlands, Tanzania. IWMI Res. Rep.

Kharal, S., Khanal, B.R., Panday, D., 2018. Assessment of soil fertility under different land-use systems in Dhading District of Nepal. Soil Syst. 2, 1–8.

Kleinman, P.J.A., Sharpley, A.N., 2002. Estimating soil phosphorus sorption saturation from Mehlich-3 data. Commun. Soil Sci. Plant Anal. 33, 1825–1839.

Lankford, B., 2004. Irrigation improvement projects in Tanzania; scale impacts and policy implications. Water Pol. 6, 89–102.

Lead, C., Lennart, A., Brazil, H.B., 2019. Chapter 4 : land degradation. IPCC 2, 1–186.

Lema, M.W., Ijumba, J.N., Njau, K.N., Ndakidemi, P.A., 2014. Environmental contamination by radionuclides and heavy metals through the application of phosphate RocksDuring farming and mathematical modeling of their impacts to the ecosystem. Int. J. Eng. Res. Gen. Sci. 2, 852–863.

Lema, M.W., Mseli, Z.H., 2017. Assessment of soil pollution (heavy metal) from small scale gold mining activities, 4, pp. 1–5. A Case of.

Lindsay, W.L., Norvell, W.A., 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42, 421–428.

Machibya, M., Mdemu, M., 2005. Comparison assessment of water use and damage between modern and traditional rice irrigation schemes: case of Usangu basin, Tanzania. Int. J. Environ. Res. Publ. Health 2, 335–342.

McLeod, S., 1973. Studies on wet oxidation procedures for the determination of organic carbon in soils. Note Soil Tech. 73–79.

Mehlich, A., 1984. Mehlich 3 soil test extractant : a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 37–41.

Mhoro, L., Anthony, J., 2015. Growth and yield responses of rice , wheat and beans to Zn and Cu fertilizers in soils of Mbeya region , Tanzania. Int. J. Agric. Pol. Res. 3, 402–411.

Mng'ong'o, M., Munishi, L.K., Ndakidemi, P.A., Blake, W., Comber, S., Hutchinson, T.H., 2021. Toxic metals in East African agro-ecosystems : key risks for sustainable food production. J. Environ. Manag. 294, 112973.

Mowo, J., Floor, J., Kaihura, F.B.S., Magoggo, J.P., 1993. Review of Fertilizer Recommendations in Tanzania. Part 2, Revised Fertiliser Recommendations for Tanzania. Soil Fertility Report No. F6.

Mowo, J., Janssen, B.H., Oenema, O., German, L.A., Mrema, J.P., Shemdoe, R.S., 2006. Soil fertility evaluation and management by smallholder farmer communities in northern Tanzania. Agric. Ecosyst. Environ. 116, 47–59.

Muchena, F.N., Kiome, R.M., 1995. The role of soil science in agricultural development in East Africa. Geoderma 67, 141–157.

Mwaseba, D.L., Kaarhus, R., Johnsen, F.H., Mattee, A.Z., Mvena, Z.S.K., 2007. Rice for food and income: assessing the impact of rice research on food security in the Kyela and Kilombero districts of Tanzania. Outlook Agric. 36, 231–236.

Nahar, N., Khan, Z., 2021. Vertical distribution of soil properties and organic carbon under different land use systems in saline soils of Bangladesh. Environ. Chall. 4, 100097.

Najarian, A., Souri, M.K., 2020. Influence of sugar cane compost as potting media on vegetative growth, and some biochemical parameters of Pelargonium × hortorum. J. Plant Nutr. 43, 2680–2684.

Nájera, F., Tapia, Y., Baginsky, C., Figueroa, V., Cabeza, R., Salazar, O., 2015. Evaluation of soil fertility and fertilisation practices for irrigated maize (Zea mays L.) under mediterranean conditions in central Chile. J. Soil Sci. Plant Nutr. 15, 84–97.

Ndakidemi, P.A., Semoka, J.M.R., 2006. Soil fertility survey in western Usambara mountains, northern Tanzania. Pedosphere 16, 237–244.

Nelson, D.W., Sommers, L.E., 1980. Total nitrogen analysis of soil and plant tissues. J. AOAC Int. 63, 770–778.

Ngailo, J.A., Mwakasendo, J.A., Kisandu, D.B., Tippe, D.E., 2016. Rice farming in the Southern Highlands of Tanzania: management practices, socio-economic roles and production constraints. Eur. J. Res. Soc. Sci. 4.

Ngoc, B., Ngoc, V., Thanh, M., Thi, T., Loan, H., 2021. Analysis of the soil to food crops transfer factor and risk assessment of multi-elements at the suburban area of Ho Chi Minh City, Vietnam using instrumental neutron activation analysis (INAA). J. Environ. Manag. 291, 112637.

Noroozlo, Y.A., Souri, M.K., Delshad, M., 2019. Stimulation effects of foliar applied Glycine and glutamine amino acids on lettuce growth. Open Agric. 4, 164–172.

Pathak, H., 2010. Trend of fertility status of Indian soils. Curr. Adv. Agric. Sci. 2, 10–12.

Schwartz, H.F., Corrales, M.A.P., 1989. Bean production problems in the tropics. CIAT.

Senkoro, C.J., George, L.J., Atanasio, M.E., Charles, W., Mzimbiri, M., Msaky, J., Rose, U., Lyimo, S.D., 2017. Optimizing fertilizer use within the context of integrated soil fertility management in Zambia. In: Fertil. Use Optim. Sub-saharan Africa 210–219.

Sillanpää, M., 1982. Micronutrients and the Nutrient Status of Soils: A Global Study: Food and Agriculture Organization of the United Nation, Boletín de suelos de la FAO. Food and Agriculture Organization of the United Nations.

Sims, J.T., Maguire, R.O., Leytem, A.B., Gartley, K.L., Pautler, M.C., 2002. Evaluation of Mehlich 3 as an agri-environmental soil phosphorus test for the mid-Atlantic United States of America. Soil Sci. Soc. Am. J. 66, 2016–2032.

Souahi, H., Chebout, A., Akrout, K., Massaoud, N., Gacem, R., 2021. Physiological responses to lead exposure in wheat, barley and oat. Environ. Chall. 4, 100079.

Souri, M.K., Alipanahi, N., Hatamian, M., Ahmadi, M., Tesfamariam, T., 2018a. Elemental profile of heavy metals in garden cress, coriander, lettuce and Spinach, commonly cultivated in Kahrizak, South of Tehran-Iran. Open Agric. 3, 32–37.

Souri, M.K., Dehnavard, S., 2017. Characterization of tomato growth and fruit quality under foliar ammonium sprays. Open Agric. 2, 531–536.

Souri, M.K., Hatamian, M., 2019. Aminochelates in plant nutrition: a review. J. Plant Nutr. 42, 67–78.

Souri, M.K., Naiji, M., Aslani, M., 2018b. Effect of Fe-Glycine aminochelate on pod quality and iron concentrations of bean (Phaseolus vulgaris L.) under lime soil conditions. Commun. Soil Sci. Plant Anal. 49, 215–224.

Souri, M.K., Naiji, M., Kianmehr, M.H., 2019. Nitrogen release dynamics of a slow release urea pellet and its effect on growth, yield, and nutrient uptake of sweet basil (Ocimum basilicum L.). J. Plant Nutr. 42, 604–614.

Souri, M.K., Rashidi, M., Kianmehr, M.H., 2018c. Effects of manure-based urea pellets on growth, yield, and nitrate content in coriander, garden cress, and parsley plants. J. Plant Nutr. 41, 1405–1413.

Stewart, Z.P., Pierzynski, G.M., Middendorf, B.J., Vara Prasad, P.V., 2020. Approaches to improve soil fertility in sub-Saharan Africa. J. Exp. Bot. 71, 632–641.

Tekulu, K., Taye, G., Assefa, D., 2020. Effect of starter nitrogen and phosphorus fertilizer rates on yield and yield components, grain protein content of groundnut (Arachis Hypogaea L.) and residual soil nitrogen content in a semiarid north Ethiopia. Heliyon 6, e05101.

Vanlauwe, B., Descheemaeker, K., Giller, K., 2014. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil 1, 1239–1286.

Wasonga, C., Sigunga, D., Musandu, A., 2010. Phosphorus requirements by maize varieties in different soil types of Western Kenya. Afr. Crop Sci. J. 16.

Wickama, J.M., Mowo, J.G., 2001. Using local resources to improve soil fertility in Tanzania. Manag. Afr. Soils 14.