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Characterization of soil phosphate status, sorption and saturation in paddy wetlands in usangu basin-Tanzania

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HIGHLIGHTS

- Phosphorus (P) is a vital plant macronutrient but in excess amount have detrimental effect to environment.
- Sorption capacity (PSC) and saturation degree (PSD) determines P availability for agricultural uptakes and environment.
- P loss to the water sources observed in Usangu basin leading low productivity and eutrophication.
- Immediate precautionary actions for sustainable P management are vital to increase productivity and environmental safety.

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ABSTRACT

Phosphorus (P) is a vital plant macronutrient required for plant growth which usually available in limited amount. P availability for plant uptake in highly weathered soil is controlled by soil erosion and high fixation. The availability of P applied from fertilizers depend on the soil pH, soil sorption capacity (PSC) and P saturation status (PSD), which determines P storage, losses, fixation, and additional P to be added with minimal loss to the environment. PSC and PSD are agro-environmental indicators used to estimate P availability and P loss to the environment. However, PSC and PSD of agricultural soils had been never studied in Tanzanian soils. This study was conducted to assess and estimate P availability, PSC and PSD and the risks of P losses in tropical soils from Usangu basin popular for paddy farming. In total, 198 soil samples from 10 paddy irrigation schemes were collected (November–December 2019) and analyzed for inherent P (P_{M3}), metal oxides of Aluminium (Al $_{M3}$), iron (Fe $_{M3}$), and calcium (Ca $_{M3}$) as main PSC and PSD determinant. The determined concentrations were in range of; P $_{M3}$ 014.9–974.69 mg/kg, Al $_{M3}$ 234.56–3789.36 mg/kg, Fe $_{M3}$ 456.78–2980.23 mg/kg, and Ca $_{M3}$ 234.67–973.34 mg/kg. Estimated PSC_{M3} ranged 5.62–34.85 mmol/kg with a mean value of 14.14 mmol/kg corresponding to high status, ensuring high P holding capacity for plant uptake. However, some soils had very low PSC_{M3} creating a risk of P loss to environment. Among soils, the estimated PSD $_{M3}$ ranged from 0.01 to 17.57% and was below (<24%), indicating low P loss risks to surface and groundwater, however, some soils were observed to have PSD_{M3} above 15% which correspond to a critical degree of phosphate saturation of 25% in a watershed using oxalate extraction method. Therefore some sites were associated with high P loss to the environment, immediate and precautionary actions for sustainable P management to increase productivity, environmental safety and sustainability are needed to be in place.

1. Introduction

Phosphorus (P) is a vital plant element required for plants growth and soil fertility limiting element in tropical soils because of high soil erosion, losses and fixation due to high clay content and metal oxides as a result of high weathering activity (Guppy et al., 2005). Availability of P for agricultural uptakes in agricultural

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soils from organic and inorganic fertilizer depends on the sorption capacity (PSC) of the soil to hold P and protect it from losses, soil pH, metal cations (Barrow, 2017, 2020; Barrow et al, 2020, 2021), and P saturation degree (PSD) of the soils; which determines additional P which can be added to the soils and held safely with minimum losses to the environment (De Bolle, 2013; Van Der Zee and Van Riemsdijk, 1986). The PSC determines the capacity of soil to hold added P from fertilizers materials but also is an estimator of P available for plant uptakes, runoffs and leachates (De Campos et al., 2018; Schoumans and Chardon, 2014). On the other hand, phosphate saturation degree (PSD) measures the amount of P fixed in the soil and the capacity of the soil to hold additional P to a particular soil depth (De Smet et al., 1996). To increase fertilizer use efficiency and less environmental impacts, it is advised to consider PSC and PSD in planning and estimating P fertilizer requirements and recommendations (Schoumans, 2015; Schoumans and Chardon, 2014). Both PSC and PSD have been proposed to be used as one of the P management criteria in agricultural soils and as environmental indicators to estimate P loss risks from agricultural soils to runoffs and surface water (Sato, 2003; Uriyo et al., 1977). Traditionally, PSC and PSD of agricultural soils are determined by data obtained from ammonium oxalate analyses where the concentration of extractable P, Al, Fe and Ca are determined (De Bolle, 2013; Guppy et al., 2005; Kleinman and Sharpley, 2002). However, the ammonium oxalate analysis is not commonly conducted as routine procedures in most soil laboratories, therefore its application is of limited use (Kleinman, 2017; Kleinman and Sharpley, 2002). Mehlich 3 method developed in 1984 in the United States (Mehlich, 1984) is commonly used as routine and standard procedures in most soil laboratories to estimate soil fertility parameters; hence Mehlich 3 data are readily available in most laboratories (Mehlich, 1984; Pittman et al., 2005). A study conducted by Kleinman and Sharpley (2002) found that the PSC and PSD determined by ammonium oxalate and Mehlich 3 method (M3) in different agricultural soil types were highly correlated (R^2 >95%). Therefore, concluded that to reduce environmental waste, time and cost which most soil laboratory can not afford PSC and PSD should be estimated from Mehlich 3 data which are usually available in most soil laboratory (Kleinman and Sharpley, 2002). Henceforth the M3 data which are readily available can be used to estimate PSC_{M3} and PSD_{M3} for agriculture and environmental conservation purposes (De Bolle, 2013; De Campos et al., 2018). The PSC_{M3} and PSD_{M3} (Fe + Al + Ca) are more useful as Mehlich-3 extraction is widely used in soil testing laboratories to predict plant-available P, Al, Fe, and other elements, but also used to predict the risk of P loss from agricultural fields (Mehlich, 1984).

The PSC is estimated based on the concentration of inherent P, Al, Fe, and Ca, which are the main determinant of soil P sorption capacity, while PSD is calculated based on inherent P and PSC of the soils (De Bolle, 2013; Gonzalez-Rodriguez and Fernandez-Marcos, 2018; Uriyo et al., 1977). In acidic soils, non-crystalline Al and Fe minerals control PSC (Equation (1)), while in calcareous soils, Ca is a key determinant (Equation (2)) (Schoumans and Chardon, 2014).

$$PSC_{M3(Fe+Al)} = (Fe_{M3} + Al_{M3}) \tag{1}$$

$$PSC_{M3(Ca)} = (Ca_{M3}) \tag{2}$$

Where PSC = soil P sorption capacity (in mmol/kg), $Fe_{M3,}$ Ca_{M3} and Al_{M3} = Mehlich 3 extractable Fe, and Al (in mmol/kg) (Kleinman and Sharpley, 2002).

Total PSD in the soil profile can be determined based on the mean P_{M3} and mean PSC (Al $_{M3,}$ Fe $_{M3,}$ and Ca $_{M3}$) up to the 90 cm depth or the groundwater table. In non-calcareous soils (soil pH below 8), the PSD is determined by Fe_{M3} and Al_{M3}. In acidic soils pH 1–5, PSD is estimated from Mehlich-3 P (P_{M3}), iron (Fe_{M3}), and aluminium (Al_{M3}) (Equation (3)) and in alkaline soils pH greater than 8, PSD is estimated by Mehlich-3 P (P $_{M3}$) and calcium (Ca $_{M3}$) (Equation (4)).

$$PSD_{M3}(Fe + Al) = \frac{P_{M3}}{[Fe_{M3} + Al_{M3}]} x100 \tag{3}$$

$$PSD_{M3}(Ca) = \frac{P_{M3}}{[Ca_{M3}]} x100 \tag{4}$$

Higher PSD values indicate soil has a low capacity to hold more P safely and is associated with increased P in soil solution, surface water runoff and leaching (Sharpley and Mcdowell, 2016). Despite the importance of PSC and PSD had never been estimated and studied in the agricultural soil of Usangu agro-ecosystem and Tanzania in general. The present study was conducted to determine soil phosphate status, P sorption capacity (PSC), soil properties that are the determinants of P sorption and the phosphate saturation degree (PSD) to evaluate the possibility of P availability and leaching to the surface and groundwater in Usangu basin-Southern highland Tanzania to improve P management strategies for increased land productivity and sustainability, which currently is lacking in Tanzanian soils.

2. Methodology and experimental section

2.1. Study area and sample collection

The study was conducted in Usangu Basin (USB) Mbeya-Tanzania, located between latitudes 7°41′and 9°25′ South and longitudes 33°40′ and 35°40′ East. Usangu has an area of 20,800 km^2 with two distinctive parts. The mountainous South, dominated by trees and annual precipitation of 1000–1600 mm; the northern part is dominated by a wide flat plain with alluvial fans that support both irrigated and dryland farming and settlements. The area has an average annual precipitation of 700–1000 mm. In general, USB has unimodal rainfall from December to March and six months of dryness. From the southern part, many rivers flow to the northern flat land where its water is used in paddy irrigation farming and flow down to form the Great Ruaha River, to Ruaha National Park, Mtera and Kidatu dams. The area is popular for irrigated paddy farming (Kashaigili et al., 2006) and the major soil types in the study area are Eutric Fluvisols, Eutric Leptosols, Haplic Acrisols, Haplic Lixisols and Umbric Nitisols (FAO, 2014; Wickama and Mowo, 2001).

To accomplish this study, 198 soil samples were collected from 10 paddy irrigation schemes in 68 sampling sites in the Usangu basin (Figs. 1and 2), at a depth of 0–30 cm, a common plough layer in farming areas in the study area. Samples were taken from three different land-use, i.e., paddy farms, maize farms and conserved areas from November–December 2019. Three soil samples were collected at each sampling point at 3 m from each selected point centre. Approximately 500 g of soil were collected at a depth of 0–30 cm using a hand auger; the collected soil samples were stored in a plastic bag and sent to the lab. In the lab, soil samples were air-dried in a cool, dry place until constant weight, then were ground to pass a 2 mm plastic sieve to obtain fine earth for analysis.

2.2. Sample extraction and quality assurance of the applied methodology

From collected soil samples, about 100 g were stored in the plastic container, ready for P_{M3}, Al $_{M3}$, Fe $_{M3}$, Ca $_{M3}$, pH, clay content

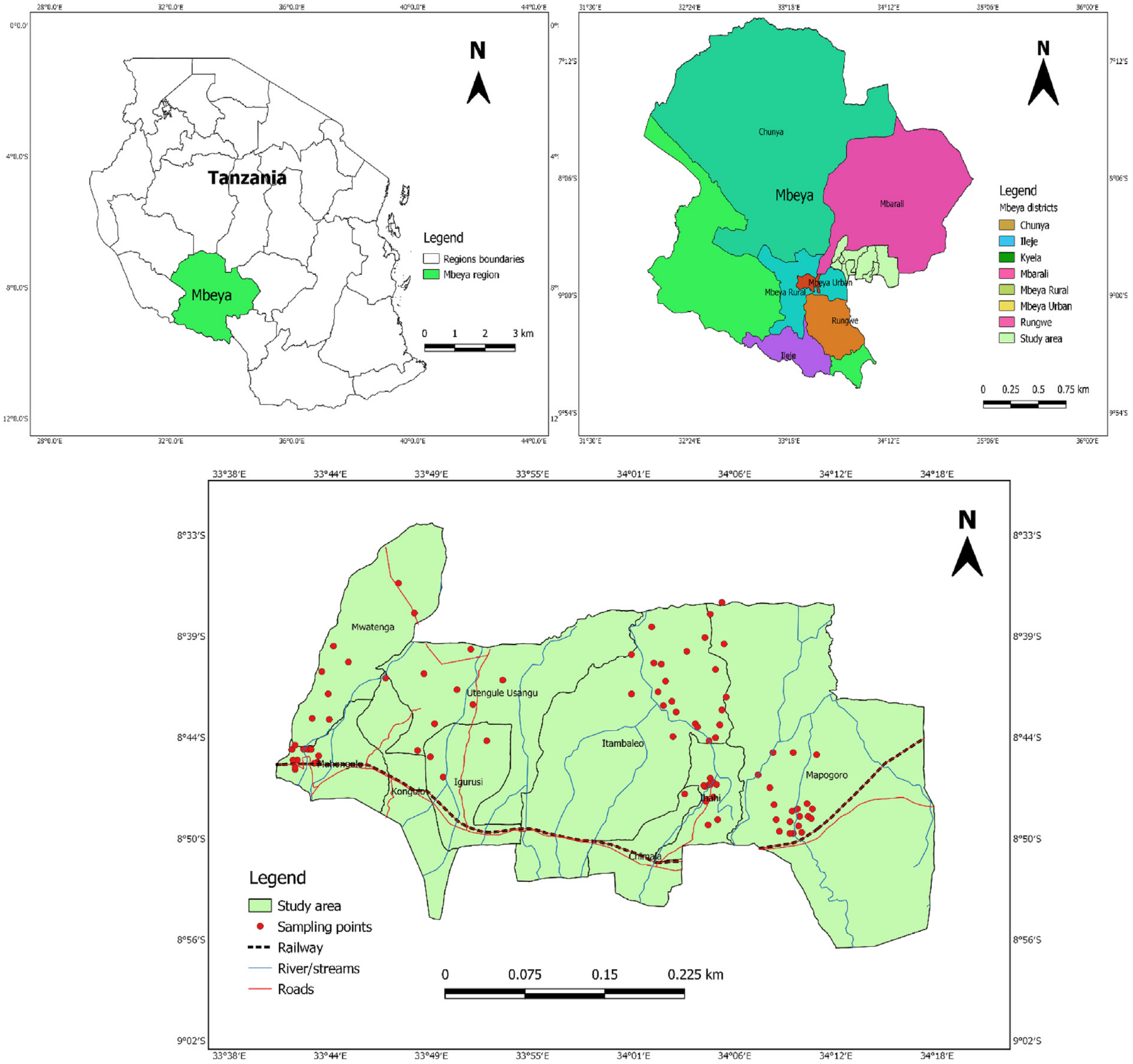
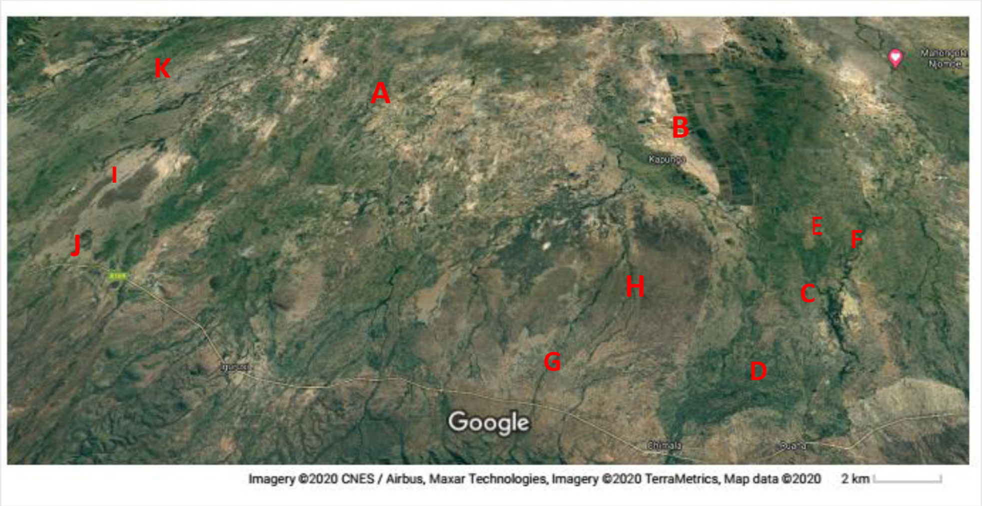


Fig. 1. Distribution of soil sampling sites in the Usangu basin-Mbeya Tanzania, November—December 2019.

and other soil property analyses. From soils samples, extractable P_{M3}, Al_{M3}, Fe_{M3}, and Ca_{M3}, were determined using Mehlich 3 extraction method (M3), a mixture of acetic acid (0.2 M CH_3COOH), nitric acid (0.013 M HNO_3), ammonium nitrate (0.25 M NH_4NO_3), ammonium fluoride (0.015 M NH_4F) and ethylenediaminetetra-acetic acid (0.001M EDTA) (Mehlich, 1984). In summary, two (2) grams of air-dried soils were weighed and placed in 50 ml centrifuge tubes, 20 ml of Mehlich 3 extraction solution were added and tied, shaken in a mechanical shaker at 180 rpm for 5 min. The mixture was centrifuged at 1200 rpm for 5 min and filtered to a 15 ml volumetric flask through an acid-resistant filter (Whatman No. 42) with 0.42 μm pore size to obtain clear filtrates. The soil extracts were made to the mark with Mehlich 3 extraction solution and all samples were extracted and measured in triplicate. The standards were prepared from a stock solution of 1000 mg/L by successive dilutions. The concentration of P, Al, Fe, Ca, Mg, and other micronutrients in M3 soil extracts were determined by ICP-OES (Thermo Scientific iCAP 7400 ICP-OES Pickles) and ICP-MS (Thermo Scientific iCAP TQ MS Ermentrude). Soil pH was measured using the glass electrode method of Chaturvedi and Sankar. (2006), with a water to soil ratio of 2.5:1. Soil organic carbon (SOC) content was determined by the chromic acid titration method Walkley and Black (1934). The recovery of samples spiked with standards ranged from 86% to 104.1%. The instrumental and method detection limits (LOD) for Mehlich 3 extractable elements are shown in Table 1.

Quality assurance: Reagent blanks and certified standard reference soil sample SCP (S150123029) EnvironMAT obtained from SCP Science-Qmx laboratories, Thaxted-United Kingdom, were used to monitor the determination quality of the soil to ensure the reliability of data. Analytical grade chemicals were used throughout the study without any further purification. To prepare all the reagents and calibration standards, Milli-Q water (>18.2 mΩ cm^{-1}) was used and all glasswares were acid washed with dilute 10%



Imagery ©2020 CNES / Airbus, Maxar Technologies, Imagery ©2020 TerraMetrics, Map data ©2020 2 km

Fig. 2. The google map showing the schemes covered in this study A:Utengule usangu, B: Kapunga, C: Mubuyuni, D: Uturo, E: Isenyela, F:Mabadaga, G: Chimala, H: Ihahi, I: Mahongole, J: Igalako, K: Mwatenga.

Table 1
Instrument and method detection limits (LODs) for selected elements in certified SCP EnviroMAT (S150123029) standard samples using Mehlich 3 method (M3).

S/N	Element	Instrumental LOD (mg/L)	Method LOD (mg/L)	Experimental Values-SCP (mg/L)	Reference Values- SCP (mg/L)
1	Ca	0.031	0.032	0.402	0.407
2	Al	0.001	0.021	0.069	0.102
3	Fe	0.050	0.050	0.026	0.031
4	Mg	0.005	0.006	0.039	0.045
5	Mn	0.002	0.003	0.0049	0.006
6	P	0.106	0.120	0.020	0.026
7	Zn	0.010	0.010	0.042	0.044

HNO_2 and 10% HCl followed by four times washing with distilled water and finally were rinsed thrice with Milli-Q water to avoid possible contamination.

3. Results and discussion

The general soil properties from the study area are presented in Table 2, where the electric conductivity of soil paste was observed to range from 6970 to 12800 dS/m with a mean value of 10223 dS/m, which correspond to medium to high, which might affect the availability of other plant nutrients. While soil pH ranged 6.4–7.6, which correspond to slight acidic to slight alkaline condition in the study area, which likely to influence the availability and sorption of P in the soil surfaces. The total nitrogen was observed to be in the range of 0.02–0.17% amount which shows total N concentration was low, organic carbon (OC) as important parameters in soil fertility and availability of other plant nutrients were observed to range 0.37–2.37% where most sites had OC below 2% which is recommended for agricultural soils. These parameters might influence the availability and dynamics of P in agricultural soils hence influencing the P sorption and saturation.

Table 2
Essential Physico-chemical properties of soil samples collected from the Usangu Basin, Tanzania (November–December 2019, values as mean, n = 3).

Site	EC (dS/m)	pH	N (%)	OC (%)
Chimala	8800	7.1	0.05	0.60
Igalako	12800	6.9	0.06	0.68
Ihahi	6970	6.9	0.07	0.80
Ilaji	19600	7.2	0.17	2.37
Isenyela	7140	6.6	0.06	0.75
Kapunga	8900	7.4	0.04	0.45
Mabadaga	7850	7.4	0.11	1.33
Mahangole	9170	6.4	0.11	1.37
Mubuyuni	8300	7.5	0.03	0.37
Uturo	10090	6.7	0.16	1.99
Mean	**10223**	**6.4**	**0.11**	**1.51**

3.1. Soil P status and availability

The concentration of phosphorus (P_{M3}) in agricultural soils was observed to vary across irrigation schemes; ranging from 0.52 to 49.87 mg/kg (Table 4), which were observed to be lower in other sites and higher in other sites (Tables 2 and 3). Among irrigation schemes P_{M3} concentration were observed to be higher in Ihahi (49.87 mg/kg), Mahongole (40.32 mg/kg), Igalako (22.10 mg/kg), Kapunga (21.50 mg/kg), Uturo (18.02 mg/kg), and Mubuyuni (15.89 mg/kg) (Table 7). The study found that places/locations which observed to have a high concentration of Al_{M3} and Fe_{M3} were observed to have a low concentration of available P_{M3} due to high P fixation and sorption, which means a high concentration of Al and Fe had a significant negative correlation with available P_{M3} ($P < 0.05$), which could potentially affect the available P hence affecting plant growth and yields (Barrow, 2017; Barrow et al., 2020; Kleinman, 2017). The determination of P_{M3} in different land uses observed a higher concentration of P_{M3} in farming areas such as paddy farming (49.87 mg/kg) and maize farming area (40.32 mg/kg) than in conserved areas (35.79 mg/kg) (Table 6), which ranged optimum (26–35 mg/kg) to high (36–45 mg/kg) amount for P requirement for crop production (Mallarino et al.,

Table 3
Soil nutrient availability in paddy wetland soils and P_{M3} in different land use from the Usangu Basin, Tanzania (values as mean, n = 3, November–December 2019).

	Land Use	Al (mg/kg)	Ca (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	P (mg/kg)	Zn (mg/kg)
Mean	Conserved areas	214.91	919.65	174.83	300.97	13.49	3.53
	Maize farming	193.59	1362.55	107.03	286.87	25.73	3.64
	Paddy farming	294.10	806.89	214.81	238.59	7.70	2.14
Minimum	Conserved areas	125.36	194.82	97.9	115.99	0.99	1.61
	Maize farming	124.87	1318.56	91.64	253.49	15.2	3.20
	Paddy farming	93.21	95.10	81.14	42.18	0.52	0.34
Maximum	Conserved areas	337.51	2010.72	314.08	520.20	35.79	7.47
	Maize farming	278.21	1415.24	127.75	316.90	40.32	4.13
	Paddy farming	792.97	2494.35	470.59	1069.21	49.87	5.53

Table 4
Soil nutrient availability in paddy wetland soils and P_{M3} in different irrigation schemes from the Usangu Basin, Tanzania (values as mean, n = 3, November–December 2019).

	Irrigation Scheme	Al (mg/kg)	Ca (mg/kg)	Fe (mg/kg)	Mg (mg/kg)	P (mg/kg)	Zn (mg/kg)
Mean	Chimala	182.19	482.61	324.08	183.49	5.98	2.47
	Igalako	320.96	1420.45	182.79	253.8	10.94	1.97
	Ihahi	188.54	1060.09	158.31	215.31	17.56	3.38
	Ilaji	277.06	422.47	248.68	180.66	4.97	2.43
	Isenyela	210.72	755.58	107.89	101.30	6.35	1.46
	Kapunga	346.16	785.38	190.58	232.22	7.55	1.81
	Mabadaga	201.95	2387.82	155.81	1031.78	1.66	0.46
	Mahangole	287.42	1126.13	154.62	291.24	13.87	3.16
	Mubuyuni	285.44	452.71	288.81	196.03	4.44	2.02
	Uturo	199.15	811.53	245.48	339.29	6.57	2.94
Maximum	Chimala	184.3	495.60	326.97	188.39	6.22	2.79
	Igalako	563.72	2467.91	235.18	296.31	22.10	3.59
	Ihahi	367.55	1627.17	289.54	409.10	49.87	5.53
	Ilaji	337.51	654.66	314.08	245.43	8.39	2.97
	Isenyela	222.35	762.25	111.38	101.86	6.93	1.70
	Kapunga	662.23	1481.94	321.6	334.16	21.50	4.11
	Mabadaga	214.83	2494.35	165.35	1069.21	1.86	0.54
	Mahangole	739.25	2010.72	197.24	445.81	40.32	6.41
	Mubuyuni	792.97	1558.84	470.59	707.26	15.89	3.88
	Uturo	312.28	1274.94	332.93	520.2	18.02	7.47

2013; Sims et al., 2002). This might be exacerbated by farming practices conducted in the area like organic and inorganic fertilizer applications and use of other phosphate-based agro-chemical biocides such as glyphosate-based herbicides and pesticides (Romano-Armada et al., 2017). Based on the recommended level of P_{M3} in agricultural soils (Low:0–25 mg/kg, optimum:26–35 mg/kg, high: 36–45 mg/kg and very high: >46 mg/kg) (Mallarino et al., 2013), some sites were observed to have a low concentration of P_{M3} (<25 mg/kg) which affecting the crop growth and yield while other sites such as Mahaongole (40.32 mg/kg) and Ihahi (49.87 mg/kg) had very high $P_{M3;}$ which require no or little addition of P from fertilizer to reduce production cost and reduce P loss to surface runoffs and leaching. The concentration of P_{M3} were observed significantly ($P < 0.05$, $R^2 = 0.36$) to increase with the decrease of altitude. Lowland areas were observed to have high P_{M3} concentration than those in the upland, this might be due to surface runoffs and soil erosion in upland areas. Therefore, proper P management and monitoring in highland areas is important to avoid P loss in soils and accumulation in water reservoirs in lowland areas. Additionally, study found that, the concentration of Al_{M3} ($p < 0.001$, $r^2 = 0.36$) and Fe_{M3} ($p < 0.001$, $r^2 = 0.24$) were negatively correlated with concentration of P_{M3} in soils while the inverse scenario were observed with the concentration of Ca_{M3} ($p < 0.001$, $r^2 = 0.43$). This indicate that Al, Fe and Ca were key determinants of solubility and availability of P in agricultural soils (De Bolle, 2013; De Campos et al., 2018). The ratio of $P_{M3}/(Al_{M3}+Fe_{M3})$ (Table 5), which estimates the availability of P_{M3} for plant uptake were observed to be 0.004–0.16, ranging from below optimum ($P_{M3}/(Al_{M3}+Fe_{M3})<0.06$, optimum ($P_{M3}/(Al_{M3}+Fe_{M3})$) 0.06–0.11 and above optimum $P_{M3}/(Al_{M3}+Fe_{M3})>0.15$ (Sims et al., 2002) (see Table 4).

Table 5
The distribution of Al, Fe, Ca, P and estimated PSC, PSD and max sorption in soils of Usangu irrigation schemes, Tanzania. November–December 2019 (values as mean, n = 3).

Irrigation Scheme	Al (mmol/kg)	Ca (mmol/kg)	Fe (mmol/kg)	P (mmol/kg)	PSC (Al + Fe)	PSD (Al + Fe)	Al/Fe	Max sorption	M3 ($P_{M3}/(Al_{M3}+Fe_{M3})$)
Chimala	6.75	12.04	5.8	0.19	12.56	1.54	1.16	49.2	0.01
Igalako	11.9	35.44	3.27	0.35	15.17	2.72	3.83	101.22	0.05
Ihahi	6.99	26.45	2.83	0.57	9.82	6.77	2.48	72.55	0.16
Ilaji	10.27	10.54	4.45	0.16	14.72	1.00	2.37	50.53	0.01
Isenyela	7.81	18.85	1.93	0.21	9.74	2.1	4.04	57.19	0.02
Kapunga	12.83	19.6	3.41	0.24	16.24	1.8	4.52	71.68	0.06
Mabadaga	7.48	59.58	2.79	0.05	10.27	0.52	2.68	139.71	0.00
Mahangole	10.65	28.1	2.77	0.45	13.42	5.11	3.92	83.04	0.14
Mubuyuni	10.58	11.3	5.17	0.14	15.75	1.12	2.19	54.09	0.03
Uturo	7.38	20.25	4.4	0.21	11.78	2.05	1.67	64.05	0.05

3.2. P sorption and sorption capacity

The capacity of the soil to adsorb or fix P in different irrigation schemes and land use in the Usangu basin were estimated using the Mehlich 3 data (Guo, 2009; Kleinman and Sharpley, 2002). The study found that soils had a varying capacity of adsorbing P among different land uses and sites (Table 5). For example, the general PSC trend based on the concentration of Al_{M3} and $Fe_{M3,}$ the common P adsorbent in acidic soils was 5.62–34.85 mmol/kg with a mean value of 14.14 mmol/kg. Where higher PSC were observed in farming areas, i.e., paddy farming areas (5.62–34.85 mmol/kg) with a mean value of 14.75 mmol/kg, maize farming area (6.30–12.60 mmol/kg) with a mean value of 9.09 mmol/kg than PSC in the conserved area which had PSC of 7.92–18.10 mmol/kg and mean value of 11.10 mmol/kg. Based on the concentration of Ca_{M3} as a determinant of P sorption in neutral to alkaline soils PSC estimated ranged; paddy farming 2.37–62.24 mmol/kg and mean value of 22.95 mmol/kg, maize farming area 32.90-35-31 mmol/kg and mean value of 34.00 mmol/kg while in the conserved areas had PSC of 4.86–50.17 mmol/kg and mean value of 22.95 mmol/kg. The higher values of PSC based on Ca_{M3} are reflected by the higher calcium concentration determined in the study area (Table 6) (Kleinman and Sharpley, 2002). The perfect positive correlation ($p < 0.001$, $r^2 = 0.43$) between Ca_{M3} and PSC_{M3} were observed, indicating the importance of Ca_{M3} in P sorption and availability in studied soils, on the other hand, the negative correlation were observed between Al_{M3} ($p < 0.001$, $r^2 = 0.36$) and Fe_{M3} ($p < 0.001$, $r^2 = 0.24$) with PSC_{M3} in the study area. This indicates that Fe and Al can reduce the available P in the soils but also can be used as remediation measures to reduce P available in water resources to avoid eutrophication (Schoumans and Chardon, 2014).

The ratio of P_{M3} and Al_{M3} as another way to estimate the capacity of the soil to adsorb P in the soil was observed to be in the range of 3.32–12.35 mmol/kg with higher values in farming areas than in conserved areas (Tables 5 and 6). The spatial distribution of PSC (in mmol/kg) were observed to vary among irrigation schemes in the study area. The observed PSC values were Mubuyuni (15.75), Igalako (15.17), Ilaji (14.72), Mahongole (13.42), Chimala (12.56), Uturo (11.78) Ihahi (9.82), and Isenyela (9.74) (Table 5). This indicates the variability in the determinant of PSC in different locations which determine the availability and solubility of phosphorus (Gichangi et al., 2008; Gonzalez-Rodriguez and Fernandez-Marcos, 2018). The soils and locations with low PSC have a high risk of P loss to runoffs and soil erosion, hence limiting the availability of P for agricultural uptakes (De Bolle, 2013; Vanden Nest, 2015). Therefore, split fertilization is recommended to ensure high fertilizer use efficiency (P plant uptake) for high return and reduced P loss to the environment.

3.3. P saturation degree and P loss

The phosphate saturation degree (PSD) is the agro-environmental indicator. PSD can show the amount of soil P available and the amount of additional P which can be added to the soil for safe storage and availability to plants before excess P start leaching to the surface and ground waters (Schoumans and Chardon, 2014; Van Meirvenne et al., 2007). In agriculture, PSD is used to indicate the likelihood of P availability in soil solution and losses to the environment (water) via leaching and soil erosion (Hongthanat, 2010). In environmental conservation, PSD values are used to estimates the likelihood of P loss from soil to surface and groundwater via runoff, soil erosion and leaching (De Bolle, 2013; Renneson et al., 2016). The PSD estimated in the study area ranged from 0.01 to 17.57% with a mean value of 2.83% (Table 6). The P_{M3} to Al_{M3} ratio as an alternative measure for saturation was estimated and observed to be in the range of 0.01–25.00% with a mean of 4.01%. Generally based on all these, the soil in the study area had unsaturated status (mean PSD_{M3} was below 24%) with respect to P (De Bolle, 2013; Van Meirvenne et al., 2007). The ratio of Al/Fe and Fe/Al were observed to have a negative and positive correlation to PSD of the soil respectively. In addition, the concentration of Al and Fe had a significantly negative correlation ($p < 0.01$, $r^2 = 0.57$, and $p < 0.01$, $r^2 = 0.42$, respectively) with PSD of the soil in the study area, this is because Al and Fe positively enhance the P sorption capacity of the soil to adsorb P hence reduce P saturation (De Bolle, 2013; De Campos et al., 2018; Fischer et al., 2017; Kleinman, 2017; Schoumans and Chardon, 2014). Therefore soils with a high concentration of Al and Fe such as clayey soils are unlikely to get easily P saturated compared to sandy soils which have few binding sites (Asomaning et al., 2018; Schoumans and Chardon, 2014).

Additionally, the study observed variation of estimated PSD among land uses where paddy farming areas had PSD of 0.01–17.57%, maize farming area 5.53–15.48%, while the conserved area had PSD of 0.26–12.71% this might be exacerbated by the application of organic and inorganic fertilizers in farming areas compared to conserved areas. Furthermore, the study found that the PSD was slightly different among irrigation schemes in the Usangu basin, where higher values observed in Ihahi (17.57%), Mahongole (15.48%), Uturo (6.18%), Igalako (5.72%), Kapunga (5.80%), Mubuyuni (3.75%), Chimala (1.62%), Ilaji (1.52%), and Mabadaga (0.56%). This might be influenced by variation in concentration of Al_{M3}, Fe_{M3}, $Ca_{M3,}$ which determines the sorption capacity of the soil as results of agriculture intensification. Among ten studied irrigation schemes, five found to have high PSD values (i.e., Ihahi (17.57%), Mahongole (15.48%), Uturo (6.18%), Igalako (5.72%), Kapunga (5.80%)), which likely to have high P loss risk to water bodies through leaching, surface runoff and soil erosion. The maximum sorption was determined by considering the concentration of Al_{M3}, Ca_{M3} and Fe_{M3} in mmol/kg; the maximum P sorption ranged from 24.34 to 172.35 mmol/kg. All values were observed to be above the PSC; hence based on the current status; the soil has additional capacity to accumulate more P for agricultural uptakes without leading to serious P loss to the environment.

3.4. The correlation of PSCand PSD to crop productivity

The PSC and PSD influence crop productivity as it determines the P availability to plants and losses (Schoumans et al., 2014). PSC determines the capacity of the soil to sorb and hold P for a long time and release to the soil solution when needed based on the P equilibrium concentrations among the soil colloids and soil solution (Muindi et al., 2015). Therefore, soils with very low PSC are

Table 6
The distribution of soil Al, Fe, Ca, P (in mmol/kg) and estimated PSC, PSD and max sorption in different land use in the Usangu basin, Tanzania (as values mean,n = 3, November–December 2019).

Land Use	Al	Ca	Fe	P	PSC (Al + Fe)	PSD (Al + Fe)	PSD (P_{M3}/Al_{M3})	Al/Fe	Max sorption
Conserved areas	7.97	22.95	3.13	0.44	11.1	4.47	6.16	2.81	68.08
Maize farming	7.18	34.00	1.92	0.83	9.09	9.60	12.35	3.65	86.18
Paddy farming	10.9	20.13	3.85	0.25	14.75	2.28	3.32	3.32	69.76

Table 7
The estimated PSC (mmol/kg) and PSD (%) values on different land use in the Usangu basin, Tanzania (November–December 2019, values as mean, n = 3).

	Land Use	PSC_{M3} (Al + Fe)	PSC_{M3} (Ca)	PSD_{M3} (Al + Fe)	PSD_{M3} (Ca)	PSD_{M3} (P_{M3}/Al_{M3})	Max sorption
Mean	Conserved areas	11.1	22.95	4.47	2.18	6.16	68.08
	Maize farming	9.09	34.00	9.60	2.44	12.35	86.18
	Paddy farming	14.75	20.13	2.28	1.51	3.32	69.76
Minimum	Conserved areas	7.92	4.86	0.26	0.2	0.37	45.62
	Maize farming	6.30	32.9	5.53	1.4	6.73	78.5
	Paddy farming	5.62	2.37	0.01	0.01	0.01	24.34
Maximum	Conserved areas	18.10	50.17	12.71	5.56	15.92	118.43
	Maize farming	12.60	35.31	15.48	3.85	19.67	93.55
	Paddy farming	34.85	62.24	17.57	13.63	25.00	172.35

prone to P loss to the environment rendering P unavailable for plant uptake but also contaminating the water reservoirs (Asomaning et al., 2018). However extreme values of PSC can fix all added P and make it unavailable for plant uptake, as is complexed by Al and Fe (Barrow et al., 2020; Barrow and Debnath, 2020; Guppy et al., 2005). Agricultural soils in the study area with high PSC like those in Mubuyuni (17.75 mmol/kg), Kapunga (16.24 mmol/kg), Igalako (15.17 mmol/kg), Mahongole (13.42 mmol/kg), Uturo (11.78 mmol/kg) have been reported to be one of the irrigation schemes with high paddy productivity per unit area (Ngailo et al., 2016), compared to schemes like Ilaji, Ihahi and Mabadaga which associated with low PSC (Table 2). The higher PSC reduces the P loss to surface runoff and water bodies because P is bound to a solid phase and partially available to the soil solution through the pseudo-equilibrium processes of desorption, reducing P loss and leaching. Henceforth increases P available for agricultural uptakes for higher yields (Vanden Nest et al., 2016).

The ratio of P_{M3} to Al_{M3} and Fe_{M3} (M3) that estimates P available for plant uptake was determined in the study area. The ratio, according to Mallarino et al. (2013), are classified into three groups, where i) M3 below 0.06 indicates the availability of P for plant uptake is below optimum, ii) M3 0.06–0.11 is optimum and recommendation for P addition is rarely made, and iii) M3 greater than 0.11, the availability of P for plant uptake is above optimum, soil P will not limit crop yield, and no P addition is recommended in those areas (Mallarino et al., 2013; Penn et al., 2018; Sims et al., 2002). In the study area, M3 were observed to range from 0.00016 to 0.16 (Table 5), with most areas being in the M3 below optimum to the optimum group, while few soils from Ihahi and Mahongole irrigation scheme having M3 greater than 0.11, which correspond to above optimum, this indicates that any P addition in this site may accelerate P loss to the surface and groundwater resources and will be uneconomical for P fertilization but will just increase production cost.

3.5. PSC and PSD as agro-environmental indicator

Traditionally, agriculture is considered as partly good and partly bad to the environment (OECD, 2019). Where positively agriculture impacts the environment, for instance, by trapping greenhouse gases within crops and soils or mitigating flood risks through the adoption of certain farming practices. Agricultural activities add potential beneficial roles in the ecosystem and on the other hand agriculture can negatively and serious impact the environment through contamination, pollution and degradation of soil, water, and air (Moss, 2008). Agriculture can destroy natural independent systems as it clears natural vegetation and substitutes natural nutrient cycle and soil conservation mechanisms. Therefore, agriculture influence the ecosystem toward both degradation and sustainability (Vanni et al., 2005). Therefore, any assessment in the agroecosystem should have agricultural and environmental perspectives. The PSC and PSD parameters as agro-environmental indicators determine agriculture fertility management and environmental conservation and monitoring (De Bolle, 2013; Kleinman, 2017; Sharpley et al., 2001). The PSD determines how much additional P loading the soil can be expected to receive before P desorption/nutrient loss rises to an environmental concern (Schoumans and Chardon, 2014; Van Meirvenne et al., 2007). High PSD indicates the soil has little additional capacity to hold and store P safely. Therefore, that soil will be characterized by high P loss to the environment and low productivity (Wang et al., 2016). The estimated PSD has been used to characterize the concentration of P in runoffs in farming areas, and irrigation channels and a strong positive correlation had been reported between PSD and the concentration of P in runoffs and water reservoirs. This indicates that an increase in PSD is likely to increase P loss to water bodies leading to eutrophication. In the study area, the estimated PSD was observed to be less than 24%, indicating most areas had unsaturated P status; however, the PSD in Mahongole and Ihahi were observed to be high (12.71–17.57%), which could accelerate the P loss and eutrophication. PSC determines the capacity of the soil to hold P safely, soils with high PSC are environmentally friendly allowing low amount of P in soil solution and loss to the environment. In this study, soils were observed to have PSC from low to high PSC, i.e., 6.3–34.85 mmol/kg (Table 7), which correspond to high to low P loss to the environment (Bortoluzzi et al., 2015; Fortune et al., 2005; Hooda et al., 2000). Therefore, PSC and PSD together can be adapted for agricultural purposes to ensure increased fertilizer use efficiency but also as environmental indicators to estimate the risk of P loss to the environment and associated impacts (Gichangi et al., 2008; Kleinman, 2017). This study provides this PSC and PSD information which had never been established before in Tanzania agricultural soils to be included in agricultural land use management especially on the estimation of fertilizer requirements for increased land productivity and reduced nutrient environmental contamination.

4. Conclusion

As increasing agricultural intensification and increased phosphatic fertilization. it is important to have sustainable management strategies to ensure the availability of phosphorus (P) for plant uptakes and manage the P loss to the environment by controlling the use of phosphatic fertilizer in the agro-ecosystem. For sustainable management of P in agro-ecosystem it is important to establish the PSC and PSD of agricultural soils, to estimate the availability for plant uptake and risk of P loss to water reservoirs leading to water eutrophication and non-point source water pollution. From the study, the estimated PSD_{M3} (0.01–17.57%) were classified as low to high indicating a low risk of P loss to the environment. However, the estimated PSC_{M3} and PSD_{M3} indicated soils in the study area have sufficient capacity to stockpile additional P safely for increased crop productivity. Immediate precautionary actions are needed to be in place to ensure sustainable P management for increased productivity and reduced environmental contamination since some soils were observed to have very low PSC and PSD close to a critical level (25%) which above it may result in serious P loss to the environment leading to environmental contamination and ecosystem degradation. Determination of PSC and PSD as agro-environmental indicators in the Usangu agro-ecosystem provide a step toward establishing site-specific P management strategies for increased crop productivity and reduced environmental contaminations. Further studies are needed to monitor P concentration and its dynamics in farming areas to ensure environmental safety and sustainability.

Author contributions

M.M, P.A.N, T.H.H and L.K.M wrote conceptualization and methodology; M.M, L.K.M and T.H.H; wrote original draft preparation, M.M, P.A.N, L.K.M, W.B; S.C T.H.H reviewed and edited the manuscript, and P.A.N, L.K.M, T.H.H and S.C. Supervised research activity and writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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