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Case Report

Increasing agricultural soil phosphate (P) status influences water P levels in paddy farming areas: Their implication on environmental quality

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ABSTRACT

Intensive paddy farming activities involve higher use of irrigation water and agrochemicals to increase crop productivity per unit area. However, a practice may result in environmental challenges due to nutrient loss and agro-chemicals contamination from agricultural fields. The present study characterized the relationship between agricultural soil phosphate (P) status and P levels in water bodies in Usangu agro-ecosystem (UA), the area famous for paddy rice production in Southern Highland Tanzania. The studied soil pH ranged from 6.4 to 7.6, while water pH was 4.9–6.8, which varied among study sites and negatively correlated to each other. This study found a positive correlation between P concentration ($P < 0.001$, $R^2 = 0.78$) in agricultural soils and water samples in the study area, where P in soil were 1.66–17.56 mg/kg and 0.02–1.65 mg/L in water. This correlation pattern of P in soil and water indicates that increased P content in farming areas under poor management (flooding system of irrigation), as observed in the study area likely to influence increased levels of P in water bodies leading to water eutrophications, but also reducing the land productivity per unit area. The significant P enrichment (>1.65 mg/L) from agricultural fields to water bodies found in different water samples from irrigation schemes potentially leads to eutrophication. To sustainably manage P concentration in water bodies and increase land productivity per unit area, the hotspot for P loss to water bodies in the agro-ecosystem has to be identified and managed, but also flooding irrigation system standard in the study area has to be abandoned to reduce plant nutrient loss and contamination of water bodies.

1. Introduction

The increasing world population has increased food demand, while fertile arable land is decreasing. For that reason, crop productivity per unit area must be increased to meet food demand, especially when productive arable land is decreasing. To achieve increased and high crop yield per unit area, farmers have opted for agricultural intensification, mainly involving wide productivity crop varieties and increased use of agrochemicals, i.e., organic and inorganic fertilizer, pesticides, herbicides, crop growth regulators, and wastewaters. Intensive agriculture activities worldwide, especially paddy rice farming, use an enormous amount of irrigation water and agrochemical inputs, which increase crop productivity. However, it is associated with environmental challenges due to increased nutrient loss and agro-chemicals residuals from agricultural fields. Among farming activities that have raised severe environmental concerns include paddy farming in wetlands since they directly connected to hydrological networks; thus, nutrient loss from paddy fields is likely to influence water quality in connected ecosystems. In addition, increasing plant nutrients in agricultural soils above plant requirements and above soil capacity to hold them safely encourages the loss of these nutrients and metals to water reservoirs [1]. Despite the increasing environmental concern, the characterization of agricultural farming activities influence on phosphate concentration in water bodies has never been conducted in detail in most of Sub-Saharan Africa; thus, their evidence is in its infancy. A rapidly growing population in Southern Highland Tanzania and other nearby regions has increased rice demand [2–5]. To fulfil this demand, farmers need to sustain their production and increase paddy rice productivity per unit area [2,6]. Where the application of large quantities of fertilizers is the prominent option has been taken by both smallholder and large-scale farmers but also, high utilization of agrochemicals has become essential in paddy farming [7–9]. Despite the critical role of Phosphorus (P) in agro-ecosystem,

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excess P in agricultural soils can drive the P loss to the environment and water reservoirs. A high concentration of P in water reservoirs is risky because it can alter the aquatic ecosystem disrupting typical ecosystem functioning and making water resources unfit for humans, animals and other domestic and industrial uses.

A P concentration greater than 0.1 mg/L in the freshwater ecosystem can seriously create excessive development and growth of algal blooms and other aquatic plants as a result of eutrophication phenomenon, where reservoirs are characterized by high quantities of nutrients (Nitrogen (N) and P) [10,11]. In agro-ecosyem, P from agricultural soils can potentially influence P concentration in water reservoirs; thus, understanding the correlation between P in agricultural soils and P in water reservoirs such as rivers, ponds, and irrigation channels is essential in establishing management strategies to avoid P enrichment in water bodies. It might be water enriched with P, a potential resource in agricultural soils, as P is an essential plant macronutrient. However, it is very detrimental for water bodies to have elevated P levels above 0.1 mg/L [12].

Modern farming aimless utilize agrochemicals such as pesticides, herbicides, fertilizers and growth regulators; this increases P and other plant nutrients in agricultural soils [8,13–15]. Excessive use of chemical fertilizer, herbicides, and pesticides in paddy farming areas potentially influences P concentration in water bodies and eutrophication in paddy farming areas not only in the Usangu basin but worldwide [3,16,18,19]. In addition, paddy farming has been frequently reported to influence environmental and ecological concerns, especially water quality and eutrophication worldwide, as conentration of plant nutrients and agro-chemical residuals have observed to be increasing with agriculture modernization [20,21]. Despite the increasing environmental concern, the characterization of agricultural farming activities influence on phosphate concentration in water bodies has never been conducted in detail in most of Sub-Saharan Africa; thus, their evidence is in its infancy. Therefore, Characterization of the influence and correlation between agricultural soil P status and P concentration in water in rivers and irrigation channels in paddy farming areas in Usangu agro-ecosystem (UA) is critical in understanding the necessary management strategies required to achieve environmental safety and reduced P loss to the environment to achieve long term land productivity. This study was designed to quantify the influence of agricultural soil P status on phosphate concentration in water in rivers and irrigation channels in paddy farming areas of UA-Tanzania.

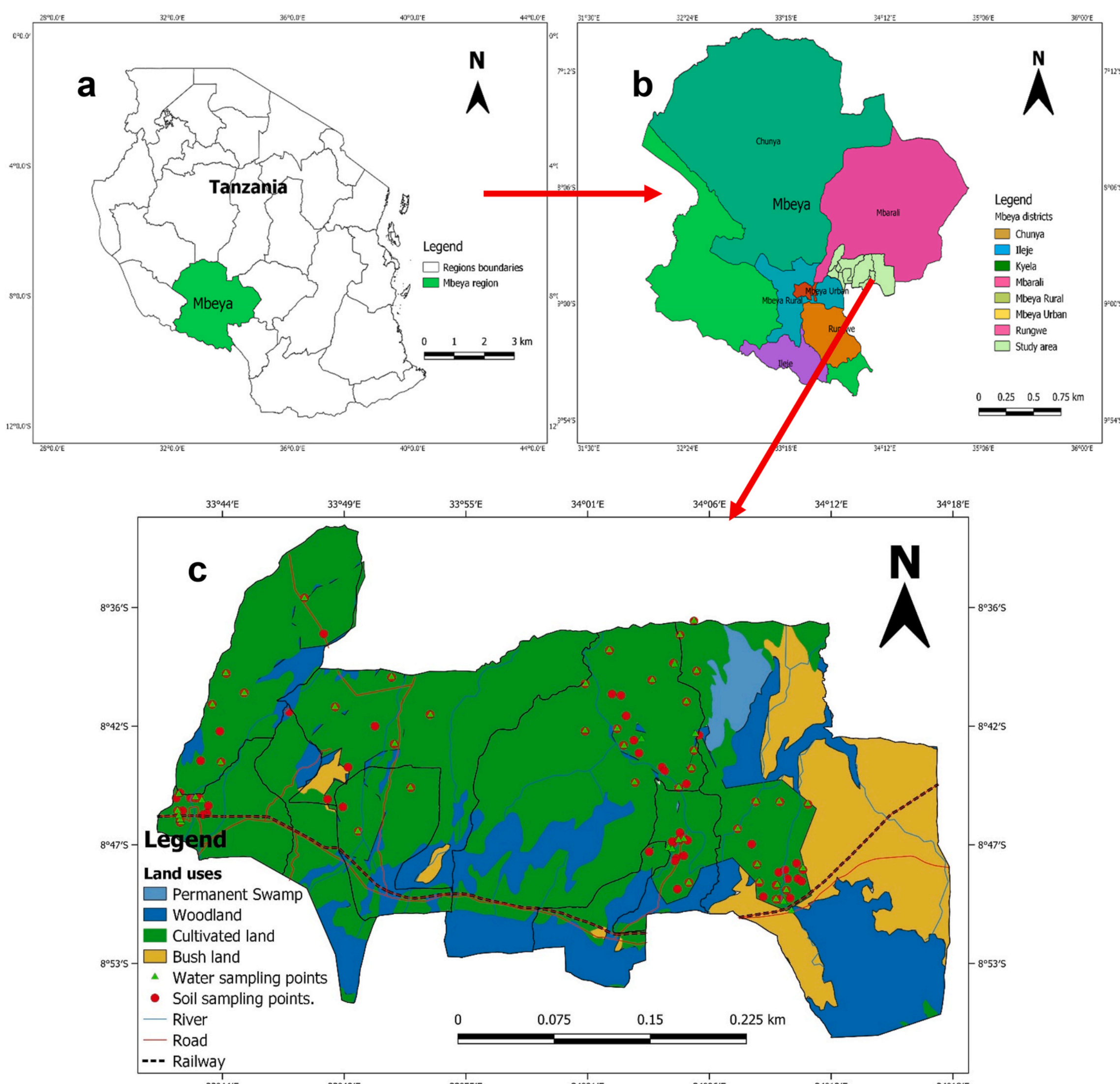

Fig. 1. Distribution of soil and water sampling sites in the Usangu basin-Mbeya Tanzania.

2. Material and methods

2.1. Study area, soil and water sampling

The study was conducted in Usangu Basin Mbeya-Tanzania, located between latitudes 7°41′and 9°25′ South and longitudes 33°40′ and 35°40′ East. The basin has an area of more than 20,000km^2 with two distinctive parts dominated by paddy rice farming producing more than 30% of the rice used in Southern Highland-Tanzania and 10–14% of rice consumed in Tanzania [2,6,22,23]. From the Usangu basin, many rivers flow to northern flat land where water is utilized in irrigated paddy farming and flow down to form the Great Ruaha River network, then to Ruaha National Park, Mtera and Kidatu dams. To accomplish this study, 42 soil and water samples from ten paddy irrigation schemes in the Usangu basin (Figs. 1 and 2) were sampled from November to December 2019. Where about 500 g of soil and 500 ml of water were collected from selected points. The studied irrigation schemes or locations involved in this study were selected based on the paddy rice production records and the rate of agricultural intensifications.

2.2. Determination of P from soil and water samples

From collected soil and water samples, phosphate was determined as follows;

Extractable P in soil samples: From soil samples, extractable P was determined using the Mehlich 3 extraction method (M3) [24]. Where 2 g of soil samples were weighed into 50 ml centrifuge tubes, and 20 ml extraction solution was added and shaken in a mechanical shaker at 180 rpm for 5 minutes, followed by centrifugation for 5 minutes at 1200 rpm. The suspension was then filtered using 0.42 μm filter paper into a 15 ml volumetric flask. The soil extracts were made to the mark with Mehlich 3 extraction solution and all samples were extracted and measured in triplicate.

The concentration of P in soil extracts was determined by ICP-OES (Thermo Scientific iCAP 7400 ICP-OES Pickles). The soil pH was measured using the glass electrode method of Chaturvedi and Sankar. [25], with a water-to-soil ratio of 2.5:1.

Determination of Total P in Water samples; Total P in water samples was determined as described by Pierzynski [26], where 50 ml of water samples were added in a volumetric flask, and 0.05 ml of phenolphthalein (POP) indicator were added and mixed well, 1 ml of H_2SO_4 solution and 0.4 g of solid $(NH_4)_2S_2O_8$ were added and mixed well followed by 30 minutes heating in the hot plate until water samples reduced to 10 ml, cooled, then 0.05 ml of the POP indicator were added and diluted to 30 ml with distilled. The total P concentration in digested water samples was determined spectrophotometrically by the method of Murphy and Riley [27] at 880 nm.

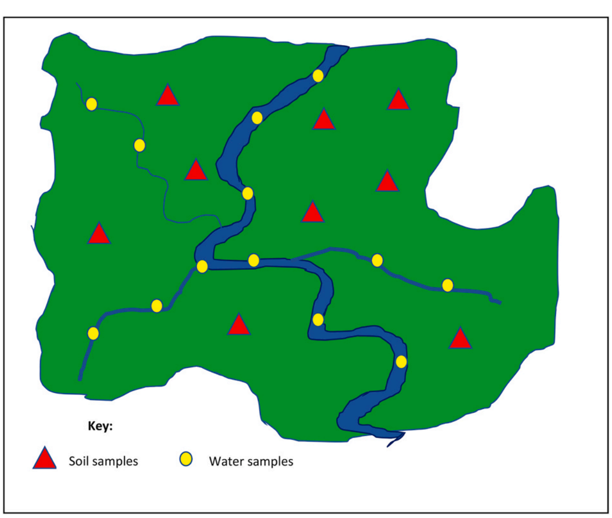

Fig. 2. Schematic portrayal of soil and water sampling plant used in Usangu basin for total P analyses.

3. Results and discussion

3.1. Soil and water pH

The determining soil and water pH from the study area are presented in Table 1. Where soil pH ranged from 6.4 (slightly acidic) to 7.6 (slightly alkaline), a condition which likely to influence P availability and sorption on the soil surfaces. Water pH is an important indicator of acidity and alkalinity of water [7,28,29]. The general trend of water pH in UA ranged from 4.9 to 6.8, and a mean of 5.5 (Table 1), where some of the determined pH values were outside FAO recommended water pH range (6.5–8.4) for irrigation water (FAO, 1985). Soil and water pH have the potential to influence the concentration of P in soil and water, limiting crop production but also posing environmental challenges due to P loss to the environment [2,6,7,17,28]. Comparing soil and water pH in different schemes helps provide evidence of pH on the availability of P in agricultural soils and water reservoirs and their implication for water quality management in the agro-ecosystem. These parameters might influence the availability and dynamics of P in agricultural soils, which consequently affect or influence the P concentration in water reservoirs.

3.2. Phosphate (P) status in agricultural soils

The P status in agricultural soils determined in soil samples collected in different paddy farming areas in Usangu agro-ecosystem was found to be in a range of 1.66–17.56 mg/kg, which was observed to be lower (<15 mg/kg) in most of the studied sites and higher (>15 mg/kg) in a few studied sites (Tables 1 and 2). Higher concentrations of P in agricultural soils among schemes were in the order of Ihahi > Mahongole > Igalako > Kapunga > Uturo > Mubuyuni (Table 2), hence influencing plant-available P and P that are likely to be lost to the environment [30–32]. The concentration of P in paddy irrigation schemes is influenced by farming practices such as organic and inorganic fertilizer applications [33]. Most sites studied had low concentrations of P (<25 mg/kg), affecting crop productivity [34]. Therefore, proper P management and monitoring are important to avoid P loss in soils to ensure high land productivity and reduce and accumulation of P in water reservoirs in lowland areas.

3.3. Total phosphate concentration in water samples

Phosphorus has a severely detrimental effect when available in excess amount ($P > 0.1$ mg/L) in irrigation water [12], leading to eutrophication [35]. Eutrophication leads to excessive growth of phytoplankton, algae blooms, aquatic plants, and water quality degradation, making water unfit for animal and human users and domestic and industrial uses [35,36]. The concentration of phosphorus (P) in motionless superficial water (ponds and lakes) and moving water (rivers and channels) in the natural ecosystem is usually low ($P < 0.01$ mg/L), which helps keep freshwater ecosystems stable [37–40]. The total P

Table 1
Overall summary of chemical characteristics of soil and water samples collected from Usangu Basin-Tanzania during November–December 2019 (n = 42).

Parameter	Soil pH (−)	Water-PH (−)	Soil-P (mg/kg)	water-total P (mg/L)
Mean	7.01	5.47	7.99	0.34
Median	7.00	5.50	6.46	0.14
SD	0.36	0.23	4.59	0.51
Minimum	6.40	5.12	1.66	0.02
Maximum	7.50	5.81	17.56	1.65

Note: SD refer to standard deviation.

Table 2
Summary of soil and water chemical composition in different irrigation schemes of Usangu Basin-Tanzania from November–December 2019.

Site	Soil pH (–)	Water-PH (–)	Soil-P (mg/kg)	Water-total P (mg/L)
Chimala	7.10	5.48	5.98	0.16
Igalako	6.90	5.51	10.94	0.37
Ihahi	6.90	5.70	17.56	1.65
Ilaji	7.20	5.81	4.97	0.12
Isenyela	6.60	5.91	6.35	0.23
Kapunga	7.40	5.26	7.55	0.22
Mabadaga	7.40	5.67	1.66	0.23
Mahangole	6.40	5.62	13.87	0.11
Mubuyuni	7.50	5.23	4.44	0.11
Uturo	6.70	5.12	6.57	0.02
Mean	**7.01**	**5.47**	**7.99**	**0.35**
STD	**0.37**	**0.24**	**4.78**	**0.54**

concentration in water samples from Usangu agro-ecosystem was observed to range from 0.01 to 1.65 mg/L. Where some sites had a total P above the acceptable limit of 0. 1 mg/L, thus posing a eutrophication threat in agro-ecosystem water resources. The spatial distribution of P in water in the UA was observed to vary among schemes where water samples from Ilaji, Igalako, Kapunga and Chimala recorded high P concentrations in sampled water samples (Table 2). On the other hand, water samples from Ruaha and Uturo were observed to have P concentrations below 0.1 mg/L; hence they were less polluted and were within the acceptable natural state. The concentration of P in stream waters has increased since the 1980s due to increased industrial and agricultural intensification and mining activities in both East African agro-ecosystems [12,41]. Studies in irrigation water quality in Kapunga rice farm in Tanzania observed more than 1.65 mg/L of P in some drainages, channels and paddy fields, indicating P enrichment from paddy farming areas indicating eutrophication status and appreciable loss of P from agricultural fields [14,15,42,43]. This study's results align

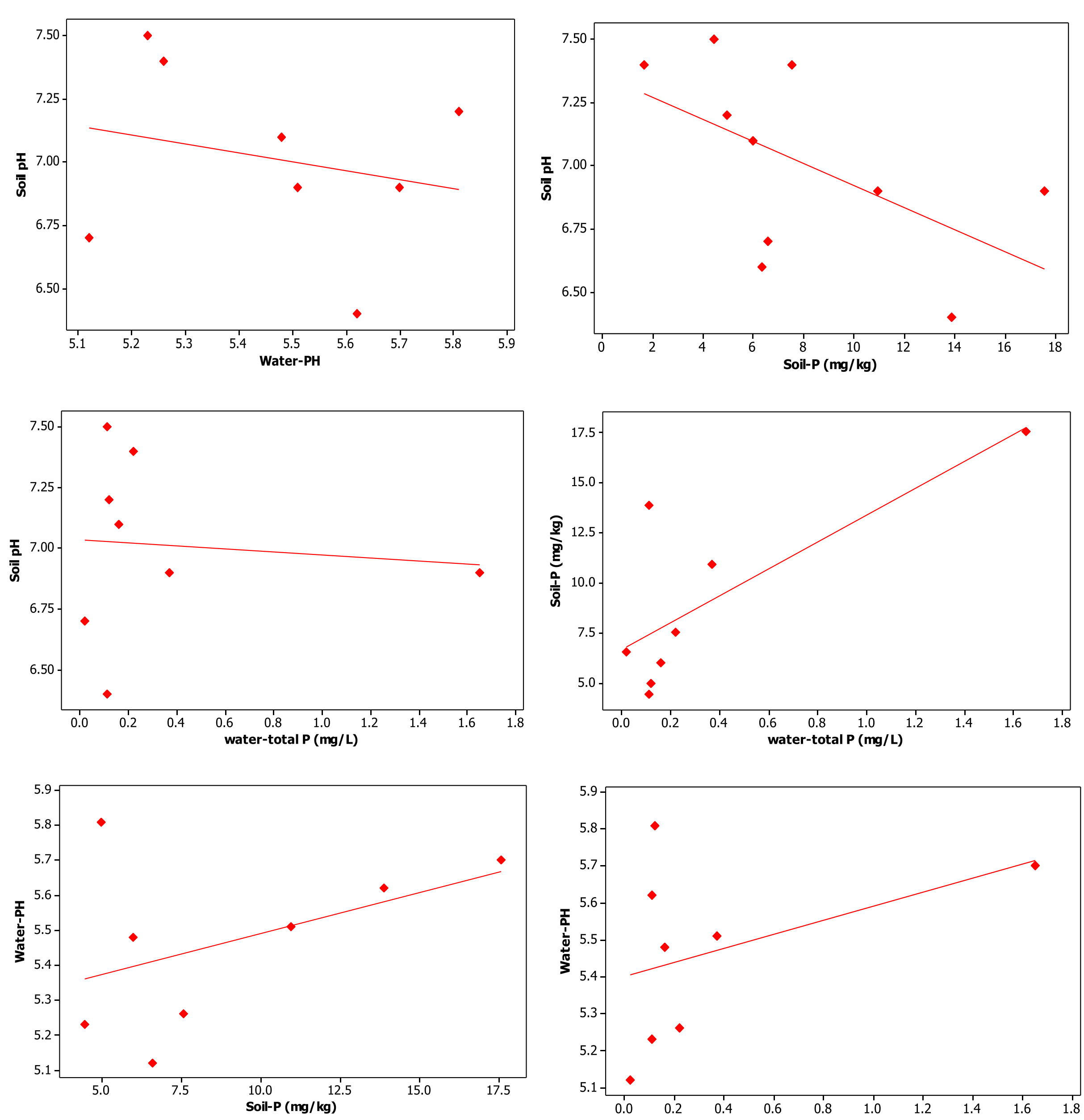

Fig. 3. The scatter plot showing the correlation of soil pH, soil P, and water pH on the P concentration in water reservoirs.

Table 3
Correlation matrix between pH and P concentration in soil and water samples in Usangu agro-ecosystem during November–December 2019.

Parameters	Soil pH (−)	Water-PH (−)	Soil-P (mg/kg)	Water-total P (mg/L)
Soil pH	1			
Water-PH	−0.24	1		
Soil-P (mg/kg)	−0.56**	0.45**	1	
water-total P	−0.09	0.42*	0.77***	1

Mean values with asterisk are statistically significant at $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

with Mshana (2015) results, who reported an appreciable amount of P in Lake Rukwa as influenced by agricultural intensification, the same scenario recorded in Lake Victoria by Gikuma-Njuru et al. [44], who reported 39.6–92 μg/L P. Despite the importance of this information in water quality management, this information is in its infancy in most East-African agro-ecosystem.

3.4. The influence of soil P and soil P to water P concentration

The influence of agricultural soil P concentration on water P concentration in rivers and irrigation channels was determined by comparing the concentration of P in soils and water. The study observed that the concentration of P in agricultural soils had a strong correlation ($P < 0.05$, $R^2 = 0.81$) to P concentration in water bodies (rivers and channels) (Fig. 3). This indicates that the increasing P concentration in agricultural soils increases tP concentration in water bodies; this might be exacerbated by the loss of P from agricultural soils via runoff, leaching, and soil erosion. Furthermore, the soil pH was highly correlated with the P concentration in water reservoirs (Table 3 and Fig. 3). The study found that soil-P had a positive correlation ($P < 0.01$, $R = 0.77$) with P concentration in water (Table 3). The soil P and water pH were observed to influence the available P in water, which means an increase in soil P and soil pH are likely to increase the level of P available in water bodies from agricultural fields. This might be exacerbated by sorption by Ca ions at higher pH [1].

The prediction of P concentration in water samples in water bodies in Usangu basin using soil pH, soil-P, and water pH was observed to provide the best fit (Table 4). All factors were observed to significantly positively influence the concentration of P ($P < 0.01$, $R^2 = 0.81$) in water samples (Eqn (1)).

$$\text{Water total P (mg / L)} = -7.50 + 0.85\text{soil pH} + 0.12\text{soil P (mg / kg)} + 0.14\text{Water pH} \quad \text{(Eqn 1)}$$

That means the concentration of P in water bodies will likely increase by 0.85 units by every unit increase of soil pH, 0.12 increase by every unit increase of soil-P whilst the water pH will increase water P concentration by 0.14 by every unit increase in water pH. Thus, water P management could depend on different factors belonging to agricultural soils. The determined relationship of positive correlation of P concentration in soil and water in agro-ecosystem implies that at the current state, any advancement of farming fields that increases P will negatively influence agricultural productivity and water quality in the agro-ecosystem. Therefore, any agricultural intensification should take into consideration of increased land productivity and environmental quality of the agro-ecosystem.

Table 4
Model coefficients used to predict water total P (mg/L) using soil pH, Soil-P, and water pH in the Usangu agro-ecosystem.

Predictor	Estimate	Standard error (SE)	t-value	*P*-value
Intercept	−7.5	1.53	−4.89	<0.001
Soil pH	0.85	0.15	5.53	<0.001
Soil-P (mg/kg)	0.12	0.01	9.58	<0.001
Water-PH	0.14	0.21	0.7	0.493

4. Conclusions

This study established and provided evidence that increasing P concentration through agricultural intensification in farming areas may likely increase P concentration in water bodies in Usangu agro-ecosystem. This is due to the presence of substantial P loss and enrichment from agricultural fields to water bodies which disrupt the water quality and potentially the entire aquatic ecosystem in the area. The scenario will decrease the available P for plant uptake for increased plant productivity. Furthermore, the enriching P amount will contribute to water eutrophication and aquatic ecosystem degradation. The P concentration of more than 1.65 mg/L P found in some water samples in the agro-ecosystem indicates the eutrophic status of aquatic ecosystems. Thus, farmers and regulatory authorities have to take all necessary initiatives to monitor and maintain irrigation water quality in agro-ecosystem for increased land productivity, environmental quality and sustainability; This can be achieved through enforcement of good agronomic practices, which reduce P losses from agricultural fields, the introduction of mandatory riparian buffers and utilization of slow releasing fertilizers in areas with high hydrological networks.

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Availability of data and material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on request.

Author contributions

M.M, L.K.M, and P.A.N; Conceptualization and methodology, M.M; writing—original draft preparation, M.M, L.K.M, and P.A.N; writing—review and editing, L.K.M, and P.A.N; Supervision.

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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