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Soil fertility status for potato production in the central highlands of Malawi

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The potato is one of the most important food and cash crops in Malawi, but current yields are low and the fertilizer recommendations rely on outdated soil fertility information. To understand the influence of soil factors in limiting current potato production, the mineralogical and physicochemical soil characteristics of 26 farms in the central highlands of Malawi were evaluated. Cluster analysis with clay, crystalline iron oxide, and total carbon content revealed three clusters with two corresponding to Ferralsols and one to Regosols, which are known to exist in the area. In the three clusters, the soil was generally acidic with low exchangeable acidity and aluminium (Al; $< 0.7 \text{ cmol}_c \text{ kg}^{-1}$); thus, Al toxicity was not a concern because the soil solution Al would be very low to negatively affect plant growth. Inorganic nitrogen was adequate, while available phosphate and exchangeable potassium (K) were variable within each cluster. However, a deficiency in exchangeable calcium (Ca; $< 3.6 \text{ cmol}_c \text{ kg}^{-1}$) and magnesium (Mg; $< 1.2 \text{ cmol}_c \text{ kg}^{-1}$) indicated that low base cation concentration was the problem and the potential yield-limiting factor. Soil management, not soil type, appeared to determine soil nutrient conditions based on the current soil Ca and Mg deficiencies and variable K nutrient status. There is a need for updating the current fertilizer recommendations by incorporating K, Ca, and Mg and promoting soil amendment interventions using locally available animal manure and plant ash.

Key words: acid soil; fertilizer; Ferralsols, Regosols, *Solanum tuberosum* L., aluminium toxicity, calcium; magnesium.

INTRODUCTION

Sub-Saharan Africa is challenged by persistent food insecurity: almost 218 million out of 950 million people

are undernourished (OECD/FAO, 2016). Alleviating hunger and poverty requires a strong agricultural sector

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Glossary: Al, aluminium; C, carbon; Ca, calcium; Fe, iron; K, potassium; Mg, magnesium; N, nitrogen; Na, sodium; P, phosphorus; S, sulphur; Zn, zinc.

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(Clover, 2003) because farming accounts for 15% of the regional gross domestic product (GDP) and employs 50% of its total labour force.

In Malawi, with a population of more than 16 million, agricultural production systems contribute with the 30% of GDP and 80% of national employment (FAO, 2015). The country has 58,000 km² of arable land (World Bank Group, 2021), and small-scale farmers produce over 80% of the country's food (FAO, 2003). Maize (*Zea mays* L.) is the dominant staple crop, occupying 75% of cultivated land (Kabambe and Kadyampakeni, 2008). However, between 2008 and 2017 average maize yields fell to 1.99 t ha⁻¹ (FAO, 2017), due to erratic rainfall as well as suboptimal management against pests, diseases, and nutrient deficiency (Mueller et al., 2012; WFP, 2018). This has led to annual food shortages, leaving more than 20% of the population food insecure (WFP, 2018). In recent years, the potato (*Solanum tuberosum* L.) has become an important food and cash crop, as demand for fresh consumption and processing tubers has steadily increased (Khonje, 2013; Mudege et al., 2015). Due to its nutritive value, market value, and low risk of price volatility, potato farming can strengthen food security and the finance stability of small-scale farmers during food shortages (Devaux et al., 2014). Potatoes are cultivated on only 2.8% of Malawi's agricultural land, mainly by small-scale farmers in the central highlands where weather conditions are favourable (Demo et al., 2009; FAO, 2017). The average yield between 2008 and 2017 was estimated at 17 t ha⁻¹ (FAO, 2017). Soil fertility and acidity issues are thought to be potential yield-limiting factors, along with the low availability of quality seed potatoes and wide-spread infestations, including late blight, bacterial wilt, and viral diseases (Demo et al., 2009; Kateta et al., 2015). Currently, there is no official fertilizer recommendation for potatoes in the country and many potato farmers modify the official recommendations set for maize (Mutegi et al., 2015). The rate of maize fertilizer recommendations is the same anywhere in the country (92 kg N ha⁻¹, 21 kg P₂O₅ ha⁻¹, and 4 kg S ha⁻¹) and fail to account for Malawi's diverse geographical and soil characteristics (Brown, 1958; Brown and Young, 1962; Mutegi et al., 2015). The recommendations are based on soil information produced in the 1960s, which found that nitrogen (N) and phosphorus (P) were primary yield-limiting nutrients for crop production, while potassium (K) was adequate (Brown, 1958). Some recent soil studies identified N, K, sulphur (S), and zinc (Zn) deficiencies as the reason for the lack of a potato yield increase (Chilimba and Liwimbi, 2008; Lakudzala, 2013; Liu and Basso, 2017), while research trials pointed to applications of N and P (Demo et al., 2008). Low soil pH and aluminium (Al) toxicity were also suggested (Chilimba, 1994; Kabambe et al., 2012).

To update fertilizer recommendations for potato production in the central highlands, soil profile evaluations were conducted in three representative locations, and

distinctly different soil types (Ferralsols and Regosols) within a potato growing region in Dedza district were discovered (Kinoshita et al., 2019). This previous study identified a different nutrient balance in each soil type according to the soil-forming factors. The objectives of this study were to investigate the current soil nutrient status of multiple potato fields within the central highlands of Malawi and determine the factors affecting their nutrient status. This paper summarizes the current soil fertility and acidity status for major soil types under the regional potato cropping systems.

MATERIALS AND METHODS

Location and soil sample collection

The field survey was conducted from late October to early November 2015, in the central highlands of Malawi in the Bembeke Extension Planning Area (EPA) of Dedza district (Figure 1). The topography and landscape are characterized by hills, river valleys, and flat-topped interfluvies (Thatcher, 1969). Elevation ranges from 1200 to 2200 m above sea level. The climate in the Bembeke EPA is defined as humid subtropical (Cwa) with hot summers and dry winters (Peel et al., 2007). The mean annual air temperature was 17.4°C and the mean annual rainfall was 1110 mm between 1961 and 1990 (World Meteorological Organization, 2010). Farmers in the study area cultivate potato, maize, beans, soybeans, groundnuts, and sweet potatoes on a small scale under a rain-fed system. Potatoes are grown during the rainy season (November–April).

Within the Bembeke EPA, 26 spatially well-distributed villages were identified (Figure 1). In each village, potatoes were grown in two topographical areas: on slopes and on a floodplain. In this study, one field on the slope was selected, and soil samples were collected before potato planting and fertilization. Ten subsamples were collected from each field at a depth of 0–10 cm and composited to create representative samples, which were sent to the Obihiro University of Agriculture and Veterinary Medicine under an appropriate permit. The samples were air dried, passed through a 2 mm sieve and cleaned of all visible plant roots and debris before further analysis. Crop management information from interviews with the landowners and extension agents was also collected. The most common fertilizer rate used by the local farmers was 69 kg N ha⁻¹, 21 kg P₂O₅ ha⁻¹, and 4 kg S ha⁻¹.

Soil analysis

The following soil analytical methods generally followed the Japanese methods of soil environment analysis (Editorial Committee for Methods of Soil Environment Analysis, 1997). A particle size assessment was conducted using the pipette method. Crystalline iron (Fe) oxide content was determined by the difference between total Fe oxide and non-crystalline Fe oxide. Total Fe oxide was extracted by the dithionite-citrate method (Blakemore et al., 1987), and non-crystalline Fe oxide was extracted by the acid ammonium oxalate method (Editorial Committee for Methods of Soil Environment Analysis, 1997). The Fe concentrations in the extracts were measured by an inductively coupled plasma emission spectrometer (ICPS-8100, Shimadzu Corporation, Kyoto, Japan). The pH (H₂O) and pH (KCl) were measured using a pH electrode in a 1:2.5 soil/water and soil/1 mol L⁻¹ KCl solution ratio. Exchangeable soil acidity (also known as Y₁) was extracted by 1 mol L⁻¹ KCl solution to a solution ratio of 1:2.5, and the extract was

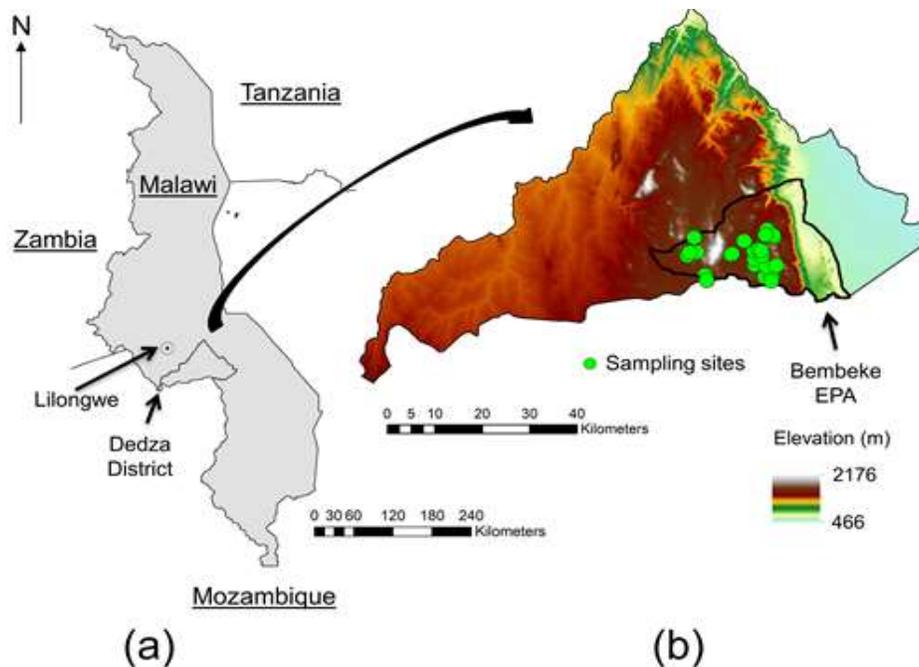


Figure 1. Maps of (a) Malawi and (b) Bembeke Extension Planning Area (EPA) within Dedza district showing soil sampling sites.

titrated with 0.1 mol L^{-1} NaOH (Mizuno and Yoshida, 1993). The same extract was used for exchangeable Al measurements using the ICPS-8100. Total carbon (TC) was measured using a dry combustion method by a CHN automated elemental analyser (Vario EL III, Elemental Analysensysteme, Hanau, Germany). Inorganic N ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) was extracted using 2 mol L^{-1} KCl and measured colorimetrically by a flow injection analyser (FIAstar 5000, FOSS, Hilleroed, Denmark). Phosphate absorption coefficient (PAC) is a Japanese method for determining a soil's capacity to fix phosphate. It was determined by reacting a soil sample with a phosphate reaction solution ($13.44 \text{ mg P}_2\text{O}_5 \text{ ml}^{-1}$) for 24 h. After the reaction, the remaining concentration of phosphate in the solution was measured using the molybdate yellow method using a spectrophotometer (UVmini-1240, Shimadzu Corporation, Kyoto, Japan). The available phosphate was measured using Truog and Bray II methods. The concentration of phosphate in the extract was measured colorimetrically using the molybdate blue method with the UVmini-1240. Cation exchange capacity (CEC) and exchangeable cations were measured by the Schollenberger method using 1 mol L^{-1} NH_4OAc and 10% KCl solutions at pH 7.0. The CEC was determined using the formal titration method. Calcium, Mg, K, and sodium (Na) in the extract were measured by an atomic absorption spectrometer (Z-5010, Hitachi High-Tech Corporation, Tokyo, Japan). Base saturation is the percent of the sum of exchangeable cations relative to the CEC, and Ca saturation is the percent of exchangeable Ca relative to the CEC.

Statistical analysis

The soil samples were grouped according to their clay, crystalline Fe oxide, and TC content that likely reflect the natural soil formation processes using Ward's hierarchical cluster analysis in JMP Pro 14 statistical software (SAS Institute Inc., 2018). The mean differences in the measured soil properties between groups were tested using the Tukey–Kramer HSD test.

RESULTS AND DISCUSSION

Soil characteristics of the clusters

The three clusters, A ($n = 8$), B ($n = 13$), and C ($n = 5$), showed significantly different clay and crystalline Fe oxide contents. Each cluster's soil characteristics reflected the previously identified Ferralsols and Regosols (Kinoshita et al., 2019). Cluster A soils had the highest clay and crystalline Fe oxide content and resembled the characteristics of Ferralsols (Table 1). The soils in this cluster had a heavy clay texture and the majority of the sites were located on stable land in relatively flat areas (Figure 2). A small texture variation in this cluster was likely the result of the minimal input of new parent materials from the surrounding areas and prolonged soil weathering. Cluster B soils had a predominantly light clay and sandy clay texture and also resembled the characteristics of Ferralsols. The majority of the sites were located on the edges of hill slopes but some were also located in river valleys and interfluves (Figure 2). The textural differences could be the result of the erosion or sedimentation of colluvial materials because many of the sites were located on slopes.

Additionally, Cluster B had the largest sample size and a wide variation in topography. Cluster C soils had either a sandy clay loam or a sandy loam texture. They were the least weathered soils among the clusters and resembled the characteristics of Regosols. These soils were found either in river valleys or on the western side of Dedza Mountain (Figure 2). In the river valleys, the

Table 1. Soil texture, total carbon, and crystalline Fe oxide content in three clusters found in the study area.

Cluster	ID	Sand				Textural class	TC	Fe _d -Fe _o
		Coarse	Fine	Silt	Clay			
		(%)						(g kg ⁻¹)
A	1	11.7	17.6	8.18	62.5	Heavy clay	10.6	55.4
A	2	20.7	17.4	8.11	53.8	Heavy clay	12.4	22.8
A	3	19.2	17.9	9.42	53.5	Heavy clay	11.3	38.3
A	4	21.8	21.8	4.98	51.3	Heavy clay	10.7	28.5
A	5	18.2	23.4	8.15	50.3	Heavy clay	12.2	44.6
A	6	26.6	19.5	5.20	48.7	Heavy clay	8.50	28.1
A	7	16.4	23.7	11.2	48.7	Heavy clay	11.2	32.8
A	8	29.2	20.1	2.91	47.8	Heavy clay	11.9	35.9
B	9	30.5	19.1	5.01	45.5	Heavy clay	20.3	27.0
B	10	20.4	24.3	12.2	43.2	Light clay	9.17	23.8
B	11	26.7	21.2	11.4	40.7	Light clay	10.5	18.4
B	12	25.3	23.2	10.8	40.7	Light clay	11.5	29.0
B	13	31.2	22.1	7.92	38.8	Light clay	17.8	26.1
B	14	32.1	24.6	4.75	38.5	Sandy clay	17.9	23.8
B	15	18.8	31.0	11.8	38.4	Light clay	11.7	34.7
B	16	31.2	22.7	7.96	38.2	Light clay	12.7	27.2
B	17	41.6	18.9	1.61	37.9	Sandy clay	10.4	14.7
B	18	27.1	28.9	8.16	35.8	Sandy clay	8.11	25.3
B	19	25.5	32.3	8.39	33.9	Sandy clay	7.32	29.6
B	20	26.7	30.4	11.1	31.8	Sandy clay	6.43	15.8
B	21	38.7	18.8	11.9	30.6	Sandy clay	11.3	29.9
C	22	20.8	42.3	15.1	21.7	Sandy clay loam	9.22	14.4
C	23	29.7	38.7	10.0	21.7	Sandy clay loam	14.9	16.8
C	24	31.9	34.2	14.4	19.5	Sandy clay loam	6.76	12.2
C	25	41.4	30.7	9.42	18.4	Sandy clay loam	9.21	7.02
C	26	27.2	48.8	12.4	11.6	Sandy loam	5.39	9.58

TC (total carbon); Fe_d (Fe extracted by the dithionite-citrate method); Fe_o (Fe extracted by the acid ammonium oxalate method).

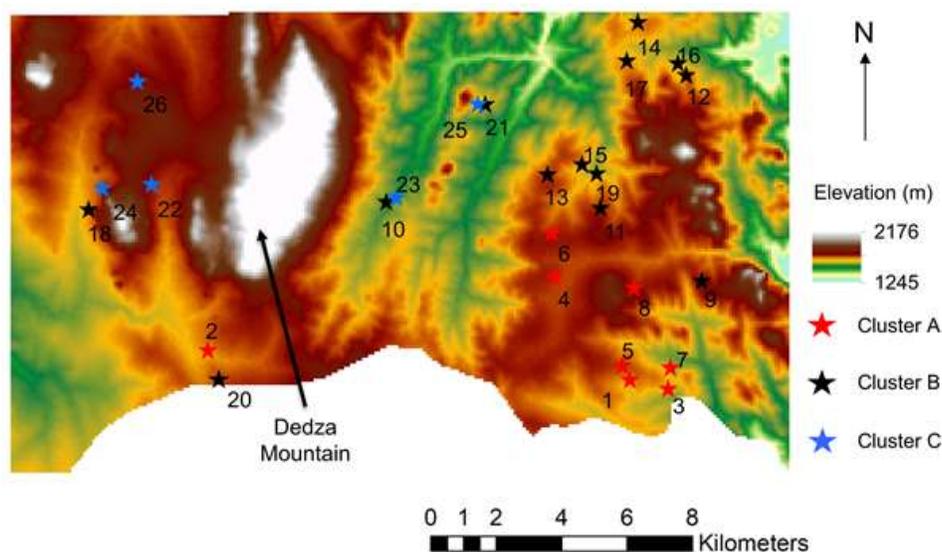


Figure 2. Locations of three clusters of soil samples in the Bembeke Extension Planning Area in relation to topography.

Table 2. Soil pH and acidity in three clusters found in the study area.

Soil properties		Cluster A (n = 8)	Cluster B (n = 15)	Cluster C (n = 5)
pH (H ₂ O)	-	5.3±0.2	5.2±0.4	5.3±0.2
pH (KCl)	-	4.5±0.1	4.5±0.3	4.5±0.2
Exchangeable acidity (Y ₁)	-	2.8±0.8	3.7±1.5	1.7±0.7
Exchangeable Al	(cmol _c kg ⁻¹)	0.196±0.102	0.305±0.240	0.104±0.114

Presented as mean ± standard deviation.

soils could be affected by alluvial and colluvial deposits from the surrounding hills. Our previous soil survey identified Regosols on the western side of Dedza Mountain, and indicated the presence of illite from biotite and muscovite minerals, which is different from the eastern side of the mountain (Kinoshita et al., 2019). The mineralogical characteristics of the parent materials could be different on either side of the mountain, but they require further study. Our results agreed well with the previously reported heavy clay, sandy clay, and sandy clay loam soils in the study area (Brown, 1958).

The TC content within each cluster was variable, especially in Cluster B (Table 1), probably because of the differences in topography but also soil management, such as using organic fertilizers. A variation in organic matter management in the study area (where some farmers applied manure) was previously documented (Kabambe et al., 2012). In this study, inputs of goat manure, fishpond slurry, or plant ash were identified.

Soil acidity and Al toxicity status

The soils in the study area were generally acidic but did not contain a high amount of Al, which means no cluster caused Al toxicity to plants (Table 2). The mean pH (H₂O) in each cluster was 5.2-5.3 with a minimum pH (H₂O) of 4.6. The low soil pH values were in accordance with a previous report (Kabambe et al., 2012). The difference between pH (H₂O) and pH (KCl), known as ΔpH, indicated the amount of exchangeable acidity. The ΔpH ranged from 0.49 to 1.05, which indicated low exchangeable acidity in the majority of the soils. This was confirmed by measuring the exchangeable acidity and exchangeable Al. The values for exchangeable acidity and Al were slightly higher for Cluster B soils, but they were less than 6.0 and 0.7 cmol_c kg⁻¹, respectively. These were considered low and Al was not likely to be problematic for plant growth (Manrique, 1986). The dominant clay mineral in the region is kaolinite and gibbsite with a low CEC (Kinoshita et al., 2019). The major source of exchangeable Al is the Al in the clay lattice, which is released when a high concentration of H⁺ on the permanent exchange site is present, but the clay of the study site was not expected to produce a large amount of exchangeable Al. Our previous study showed

that soils associated with Cluster C contained illite with a higher CEC (Kinoshita et al., 2019). However, the overall clay content of these soils was low; therefore, exchangeable Al was not high (Table 1). This contradicted with previous claims of Al toxicity's being a problem in the study area (Kabambe et al., 2012), but that study did not measure exchangeable Al content. Often, Al toxicity is claimed from low pH (H₂O) values, but the actual measurement of exchangeable acidity or Al is crucial for determining the existence of Al toxicity issues.

Soil NPK status

The soil test data showed relatively high levels of N, while P and K levels were highly variable among the clusters and fields (Table 3). Inorganic N (NO₃-N and NH₄-N) ranged from 17.7 to 55.2 mg kg⁻¹, 28.0 to 69.5 mg kg⁻¹, and 12.0 to 62.0 mg kg⁻¹ for clusters A, B, and C, respectively. A potato yield of 30 t ha⁻¹ would require about 102 kg N ha⁻¹ for the Russet Burbank cultivar as it is grown in the U.S. (Stark et al., 2004). Using a standard soil bulk density of 1.39 Mg m⁻³ (Batjes et al., 2019) at a 10 cm soil depth, 30 mg N kg⁻¹ would supply about 41.7 kg N ha⁻¹. Considering that farmers usually apply 69 kg ha⁻¹ of N fertilizers, the soil test data showed sufficient N for potato production, even compared with the U.S. information. In some fields, regardless of cluster, there was the potential for excessive N availability, which, during the growing season, can reduce tuber yield, increase susceptibility to brown centre and hollow heart, and reduce specific gravity and skin set (Stark et al., 2004).

Soil-available phosphate in Clusters A and C was optimal or slightly deficient overall; only one site in each cluster showed deficiency, even compared to the Japanese standards (Table 4). In Cluster B, phosphate levels were highly variable with five and two sites showing deficiency and slightly excessive levels, respectively. Even the soils associated with Ferralsols had a low phosphate fixation capacity: PAC values ranges from 0 to 2690; if they exceed 1500, the soils show a high phosphate fixation capacity, while values less than 1000 represent a low capacity. The PAC of this study was less than 800 for all the sites: 600-800 in Cluster A, 330-790 in Cluster B, and 170-550 in Cluster C

Table 3. Soil nutrient status in three clusters found in the study area.

Soil properties		Cluster A (n = 8)	Cluster B (n = 13)	Cluster C (n = 5)
Cation exchange capacity	(cmol _c kg ⁻¹)	10.0±1.38	10.6±2.87	8.59±4.99
Phosphate absorption coefficient	-	665±70.1	505±115	316±143
Inorganic N	(mg kg ⁻¹)	33.2±13.7	38.1±10.7	34.2±18.9
Truog phosphate	(mg P ₂ O ₅ kg ⁻¹)	79.8±33.7	109±151	104±49.9
Bray II phosphate	(mg P ₂ O ₅ kg ⁻¹)	343±170	298±320	326±138
Exchangeable Ca	(cmol _c kg ⁻¹)	1.74±0.554	2.64±2.46	2.53±2.14
Exchangeable Mg	(cmol _c kg ⁻¹)	0.677±0.199	0.740±0.343	0.747±0.609
Exchangeable K	(cmol _c kg ⁻¹)	0.302±0.123	0.328±0.122	0.347±0.206
Base saturation	(%)	27.0±6.65	32.1±15.7	38.2±11.6
Ca saturation	(%)	17.1±4.34	21.9±14.8	25.9±8.97

Presented as mean ± standard deviation. Inorganic N as sum of soil NH₄-N and NO₃-N.

Table 4. Number of sites in each soil fertility status according to Japanese Fertilizer Recommendations.

	Range	Cluster A (n = 8)	Cluster B (n = 13)	Cluster C (n = 5)
	mg kg ⁻¹	Available phosphate (P ₂ O ₅)		
Deficient	0-50	1	5	1
Slightly deficient	50-100	5	6	1
Optimum	100-300	2		3
Slightly excessive	300-600		2	
Excessive	>600			
	cmol _c kg ⁻¹	Exchangeable K		
Deficient	0-0.17	1	1	2
Slightly deficient	0.17-0.32	3	7	1
Optimum	0.32-0.64	4	5	2
Slightly excessive	0.64-1.1			
Excessive	1.1-1.5			
Highly excessive	>1.5			
	cmol _c kg ⁻¹	Exchangeable Mg		
Deficient	0-0.50	2	4	2
Slightly deficient	0.50-1.2	6	9	2
Optimum	1.2-2.2			1
Excessive	>2.2			

Department of Agriculture, Hokkaido Government, 2015. Available phosphate according to Truog method.

(Table 3). Detailed information for the actual phosphate fertilizer application rate was not available; thus, P input and output dynamics were not yet understood in this study. Several farmers in Cluster B used alternative soil management to raise the soil-P levels, such as goat manure, fishpond slurry, or plant ash. The organic fertilizer inputs were also reflected in the high TC levels in some Cluster B sites (Table 1).

Overall, P deficiency for crop production was becoming

less significant in the study area, while the inherent phosphate fixation capacity was low. Since several fields still have a P deficiency, coming up with an expeditious phosphate fertilizer recommendation will require soil testing of each field in combination with fertilizer response trials in different soil types and the soil-available phosphate levels from this study (Rosen et al., 2014).

Soil exchangeable K ranged from optimum to deficient

across the clusters using the Japanese standards (Table 4). The upper boundary of slight deficiency ($0.32 \text{ cmol}_c \text{ kg}^{-1}$) is similar to other studies where they found K fertilizer response when the exchangeable K levels were between 0.20 and $0.30 \text{ cmol}_c \text{ kg}^{-1}$ (Allison et al., 2001). Potato has a relatively high requirement for K (Hopkins et al., 2020), and the continued potato cropping with fertilizer containing only N, P, and S is likely causing K mining from the soils. A previous study indicated a higher K content in Regosols associated with Cluster C because biotite and muscovite could be supplying it (Kinoshita et al., 2019). In this study, the potential K input from clay minerals or fertilizer was not sufficient to maintain adequate levels of K even in Cluster C. The application of organic fertilizer or plant ash appeared to maintain optimum soil exchangeable K levels, but K fertilization would be necessary in deficient sites.

Soil Ca and Mg status

Soil-exchangeable Ca was deficient in 23 out of 26 sites when compared to the recommended range ($3.6\text{-}6.1 \text{ cmol}_c \text{ kg}^{-1}$) for potato production (Table 3). The occurrence of low Ca levels in the study area was previously reported (Sakala et al., 2003), but it had not been ameliorated. Two sites in Cluster B and one in Cluster C had a much higher amount of Ca compared to other sites, owing to alternative soil management with the application of goat manure, fishpond slurry, or plant ash. This indicated the possibility low soil Ca content could be ameliorated by alternative soil management. Calcium is important for improving potato tuber yield and quality (Palta, 2010). In particular, the maintenance of healthy plant cell membranes and rigid cell walls depends on the presence of sufficient concentrations of Ca (Palta, 1996; Hirschi, 2004), which is also important for reducing internal defects such as brown spot and blackspot bruise (Karlson and Palta, 2006). Calcium is also known to play a key role in reducing heat stress-related potato plant growth and tuber yield reduction (Palta, 2010). This can be critical in this environment since high temperature restricts the production area to high elevations, so heat stress may be a significant factor in yield reduction.

The exchangeable Mg levels in the majority of the soils across the clusters were slightly deficient or deficient compared to the recommended range (Table 4). Soil Mg deficiencies in the study area had not previously been reported, so this study revealed the problem in this regard. Cluster C soils had relatively higher exchangeable Mg, thought to be related to the fresh input of Mg-containing clay minerals (Kinoshita et al., 2019). Magnesium deficiency affects the translocation of carbohydrates from leaves to tubers (Cakmak and Yazici, 2010) in the potato, and negatively affects tuber yield and quality. Unlike Ca, the use of alternative soil management appears insufficient for maintaining optimal exchangeable Mg levels, so the application of Mg-containing inorganic

fertilizer will be necessary.

The base saturation for the majority of the soils across the clusters was lower than the ideal range (60-80%) recommended for potato production, except for one site in Cluster B (Department of Agriculture-Hokkaido Government, 2015). Overall, the results suggested the need to include Ca and Mg as well as K supplements for improved soil nutrient management in potatoes.

Conclusion

The current status of soil nutrients in the potato-growing region of the central highlands of Malawi revealed adequate N, moderate amounts of P and K, and insufficient amounts of Ca and Mg. The current soil nutrient status is very different from that in the 1960s, when the current fertilizer recommendations, which include only N, P, and S fertilizers, were produced. Contrary to past research in the region, this study also revealed low-exchangeable Al, which showed that Al toxicity is not an issue. These results emphasized that low base saturation, not Al toxicity, is the primary candidate for potato-growing soil constraints in these acidic soils. The low soil pH values suggest many of the micronutrients being available but they need to be measured in the future since Zn has been identified as a potential yield-limiting factor. Differences in soil types affected the availability of some nutrients, as expected from our previous survey, especially Mg, but soil management appeared to be the dominant factor affecting soil nutrients. The ongoing application of only N-, P-, and S-containing inorganic fertilizer is suspected to be the cause of the current deficiency of Mg and Ca as well as K in some fields. The application of organic fertilizers and plant ash appeared to maintain P, K, and Ca at optimal levels, but an evaluation of the nutrient composition of these materials will be necessary before they can be appropriately integrated into soil nutrient management. The application of inorganic fertilizers will be necessary in combination with these locally available sources to supply K, Mg, and Ca depending on the soil test results. Rapid and low-cost soil testing will be useful and will allow local farmers to understand their soil nutrient status. Further field trials will be necessary to assess the potato yield response to suggested soil nutrient management strategies in order to produce updated fertilizer recommendations.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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