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SHORT REPORT

Analyzing soil-available phosphorus by the Mehlich-3 extraction method to recommend a phosphorus fertilizer application rate for maize production in northern Mozambique

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ABSTRACT

The available phosphorus (P) in soil is a major limiting factor for maize productivity in the Nacala corridor, Mozambique. In this study, soils were collected from three representative sites, Ribaue, Nampula, and Nacala, in the area, and each was used for maize pot experiment with five P fertilizer levels. The soil-available P content was determined by the Mehlich-3 method at 30 days after P fertilization. The shoot biomass and P concentration at the tasseling stage increased as the P fertilizer level increased and were significantly expressed as a function of soil-available P. Based on the function, the available P that attains 90% of the maximum shoot biomass was estimated as 79 mg P_2O_5 kg^{-1}. Consequently, the results in this study suggest a recommendation of 32–74 kg P_2O_5 ha^{-1} fertilizer for maize production in the Nacala corridor although a field evaluation and economical evaluation are necessary.

Abbreviations: Ex-: exchangeable cations; M-3: Mehlich-3; T-N: total nitrogen; T-C: total carbon

Introduction

Mozambique, a country in southeast Africa, has an advantage in agricultural production, which occupies 25% of the gross domestic product, because its natural ecosystem is more suitable for agriculture than that of other African countries. In particular, the northern part of Mozambique, which is called the 'Nacala corridor', is one of the areas expected to contribute to the development of the national economy because the area connects the inland countries to the Nacala harbor. The agricultural production in this area, which is transported to inland countries besides domestic consumption (Weng et al., 2013), would be important for a reduction in poverty and for economic growth (Chilonda et al., 2011). Therefore, Mozambique has managed to improve agricultural production in the Nacala corridor.

Diagnostic testing for soil fertility is recommended first because it would be an effective guide for fertilizer management to improve agricultural production and maintain soil fertility (e.g. Roy et al., 2006; Sanchez, 2002). However, the properties of soils have rarely been evaluated in terms of crop production in Mozambique (Maria & Yost, 2006), although a few studies have mentioned the need to assess soil chemical properties for fertilizer recommendations (Geurts & Van Den Berg, 1998).

In this situation, Tsujimoto et al. (2015) quantified the effect of the nitrogen on soil fertility for crop production in the Nacala corridor. Based on the results, the agriculture research centers in Mozambique (Instituto de Investigação Agrária de Moçambique (IIAM)) recommended the use of nitrogen fertilizers to farmers in this area. The N application demonstrated profitable yield increases with agronomic nitrogen-use efficiencies (kg grain yield per kg N input) of 20.6–35.3 kg kg^{-1} (Tsujimoto et al., 2017). However, almost all farmers, especially small-scale farmers, do not recognize the importance of the other soil components, such as phosphorus (P). Rusinamhodzi et al. (2012) reported that the maize yield increased with P fertilizer, although available P in the soil was not evaluated.

The available P in soil is one of major factors for crop productivity, especially under acidic soil conditions in Africa (Jibrin et al., 2002). Mostly, available P has been evaluated by the Bray-1 and Olsen P methods. The Bray-1 method is applicable for acid soils, while the Olsen method is applicable for basic soils because the extraction of P from the soil is hindered by adverse soil conditions (Sims, 2009). The soil

pH in the Nacala corridor ranges from pH 4.4 to 7.8 because this area encompasses acidic soil in the west inland region and calcareous soil in the east coastal region (Maria & Yost, 2006). Therefore, it is necessary to evaluate available P with a method that is less affected by soil pH, such as the Mehlich-3 (M-3) method (Mehlich, 1984). The authors reported on the effectiveness of the M-3 method in this area (Fukuda et al., 2017).

In this study, soils were collected from three representative sites in the Nacala corridor in northern Mozambique, and maize, a major staple crop in the country, was grown in the soils with five P fertilizer levels. The biomass and P concentration of maize were analyzed in relation to soil-available P determined by the M-3 method to recommend P fertilizer application in the area.

Materials and methods

Mozambique is divided into 10 agroecological zones (AEZs) based on climate, soil type, elevation, and farming system (Maria & Yost, 2006). The Nacala corridor has three AEZs (R7, R8, and R10). All three AEZs have (i) a high potential for food production, (ii) the existence of potential users, (iii) the presence of excellent agricultural support services, and (iv) high access via main roads (Maria & Yost, 2006). The soils were collected from Ribaue (AEZ: R10, 14°58′49.04″S, 38° 15′18.72″E), Nampula (AEZ: R7, 15° 8′53.10″S, 39°18′33.52″E), and Nacala (AEZ: R8, 14°31′44.81″S, 40°43′24.52″E).

The soils were air-dried and ground through a 2-mm sieve; chemical soil analyses were performed (see Table 1) before maize cultivation. A mixture of soil and distilled water at a ratio of 1:2.5 was used to measure soil pH and EC using a pH/ION/COND meter (models F-72 and ES-51, Horiba, Kyoto, Japan). Soil texture was determined by hydrometer analysis (Bouyoucos, 1962). Available P and exchangeable cations (Ex-Ca, Ex-Mg, Ex-K, and Ex-Na) were determined using the M-3 solution (0.2 M CH_3COOH, 0.25 M NH_4NO_3, 0015 M NH_4F, 0.013 M HNO_3, and 0.001 M ethylene diamine tetra-acetic acid (EDTA)), according to Mehlich (1984). Using the filtered M-3 solution, available P was determined by molybdenum blue method with a UV-visible spectrophotometer (T60 UV/VIS, PG Instruments Ltd, Wibtoft, Leicestershire, UK), and the cation determination was conducted by microwave plasma atomic emission spectroscopy (MP-AES; Agilent 4200 MP-AES, Agilent, Santa Clara, CA, USA).

The maize was grown in pots with the three soils (Ribaue, Nampula, and Nacala) and five P fertilizer levels (0.00, 0.25, 0.50, 1.00, 2.00 g P_2O_5 pot^{-1}) with three replicates per treatment. Each pot contained 10 kg of soil. The P fertilizer was applied by mixing single superphosphate with the soil, 30 days before planting, and the fertilizer levels corresponded to 0, 25, 50, 100, 200 kg P_2O_5 ha^{-1} on 16 January 2017. Available P in soil was analyzed 30 days after P fertilizer application by the M-3 method as mentioned above to react with P fertilizer and soil. Three maize seeds (*Zea mays* L. cv. ZM309) were planted on 15 February 2017 in each pot, thinned to one plant per pot on 7 March 2017 and grown until the tasseling stage. The soil moisture content was maintained at 50–60% of the maximum volume of water in the pots. Urea and potassium chloride were applied to the pot at 1.00 g N pot^{-1} and 1.00 g K_2O pot^{-1}, corresponding to 100 kg N ha^{-1} and 100 kg K_2O ha^{-1}, respectively, at the same time as sowing the maize seed.

At the tasseling stage, the shoot was harvested. Its biomass was determined after oven drying at 70°C for 72 h. The dried sample was ground and digested in H_2SO_4–H_2O_2 to measure the P concentration by the molybdenum blue colorimetric method.

The shoot biomass and the P concentration were statistically analyzed by one-way ANOVA combined with Tukey's multiple comparisons test ($p < 0.05$). The relationships between the biomass and available P and between the P concentration and available P were examined by a nonlinear response model. The statistical analyses were performed using R 3.3.3 software (R Core Team, 2017).

Results and discussion

The soil pH in Ribaue, Nampula, and Nacala were 5.59, 6.17, and 7.05, respectively (Table 1), which are included in the range as previously mentioned in another study (Maria & Yost, 2006). Therefore, Bray 1 and Olsen which are affected by soil pH should not be suitable for evaluating available P in the Nacala corridor. The other soil properties except available P were also presented in Table 1. Total nitrogen (T-N) and total carbon (T-C) were similar in Ribaue and Nampula, and these concentrations were higher than those in Nacala. Conversely, Ex-Ca, Mg, and Na in Nacala were higher than those in Ribaue and Nampula because Nacala is located on the seaside. The soil included plenty of

Table 1. Chemical properties of the soils collected from Nampula, Ribaue, and Nacala, northern Mozambique.

	pH(H$_2$O) (1:2.5)	EC (mS m^{-1})	Soil texture	T-N	T-C	Ex-Ca	Ex-Mg	Ex-K	Ex-Na
				(g kg^{-1})		(cmol$_c$ kg^{-1})			
Ribaue	5.59	26.18	Loamy Sand	0.41	5.4	1.02	0.49	0.01	0.02
Nampula	6.17	150.30	Loamy Sand	0.45	5.2	1.77	0.66	0.21	0.02
Nacala	7.05	85.85	Sand	0.21	3.3	8.34	0.88	0.06	0.10

sand more than 85% and soil textures were loamy sand in Ribaue and Nampula, and sand in Nacala.

The soil-available P content determined by the M-3 method before fertilizer application was the highest in Nampula (30.86 mg P_2O_5 kg^{-1}), followed by Ribaue (25.96 mg P_2O_5 kg^{-1}) and Nacala (16.40 mg P_2O_5 kg^{-1}). The difference in available P before fertilizer application caused a response in maize biomass and P concentration according to the fertilizer treatment (Table 2). The shoot biomass and P concentration increased as the application of P fertilizer increased. However, the effect of P fertilizer on shoot biomass was not significant in Nampula, probably due to higher available P before fertilizer application. In addition, the other soil physical and chemical properties might affect the maize growth in Nampula. The effect of P fertilizer was more obvious for shoot P concentration than shoot biomass. Even in Nampula, the P concentration from the application of more than 1.00 g P_2O_5 pot^{-1} was significantly higher than that from the application of 0.00 g P_2O_5 pot^{-1}.

The shoot biomass and P concentration against available P after fertilizer application are shown in Figure 1. The following equations were obtained by curve fitting:

$$SB = 54.9 \times (1 - e^{-0.0291 \times AP}) \tag{1}$$

$$PC = 2.64 \times (1 - e^{-0.0226 \times AP}) \tag{2}$$

where SB is the shoot biomass (g pot^{-1}), PC is the shoot P concentration (mg g^{-1}), and AP is the available P in the soil after fertilizer application (mg P_2O_5 kg^{-1}). Based on the equations, the value of available P that attains 90% of the maximum shoot biomass and P concentration were 79 and 102 mg P_2O_5 kg^{-1}, respectively. Mallarino et al. (2013) divides soils in the USA into five classes based on the available P levels by the M-3 method (very low,
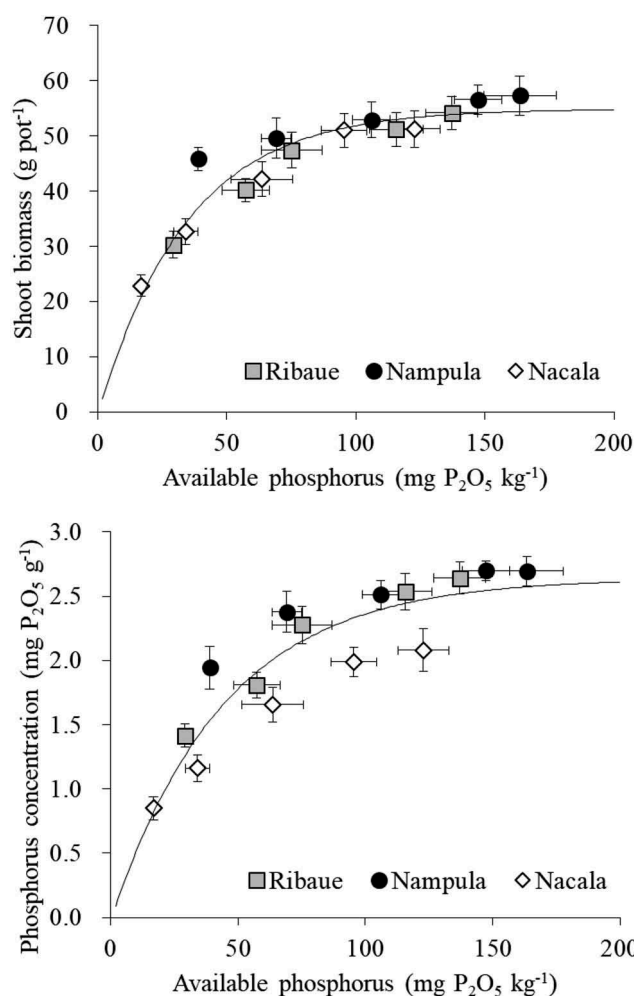

Figure 1. The relationship between maize shoot biomass and available phosphorus (above) and phosphorus concentration and available phosphorus (below). The error bars indicate the standard error of the replicates ($n = 3$). Available phosphorus was determined 30 days after the fertilizer application.

0–34 mg P_2O_5 kg^{-1}; low 37–57, mg P_2O_5 kg^{-1}; optimum, 60–80 mg P_2O_5 kg^{-1}; high, 82–103 mg P_2O_5 kg^{-1}; and very high, 105+ mg P_2O_5 kg^{-1}) and recommend no application of P fertilizer when the soil is in high and very high classes. The results in northern Mozambique in this study almost agree with the recommendation by Mallarino et al. (2013). The slightly lower available P to attain 90% of the maximum shoot biomass (79 mg P_2O_5 kg^{-1}) may be associated with the N fertilizer rate (100 kg ha^{-1}) in this study.

The amount of P fertilizer to improve available P to attain 90% of the maximum shoot biomass was different among the three sites in the Nacala corridor. P from fertilizer usually reacts in the soil and becomes fixed P or available P within 30 days (Ito et al., 2011; Fox & Kamprath, 1970). In this study, after P fertilizer application, the available P in the soil exponentially decreased (data not shown) and then reached an equilibrium after 30 days. The relationship between the shoot biomass and available P shown in Table 2 with

Table 2. Maize shoot biomass and phosphorus concentration at the tasselling stage for each treatment.

Location	Treatment (g P_2O_5 pot^{-1})	Shoot biomass (g pot^{-1})	Phosphorus concentration (mg P_2O_5 g^{-1})
Ribaue	0.00	30.30 ± 2.47 a	1.42 ± 0.09 a
	0.25	40.20 ± 2.10 ab	1.81 ± 0.10 ab
	0.50	47.43 ± 3.25 bc	2.28 ± 0.15 bc
	1.00	51.23 ± 3.07 bc	2.54 ± 0.14 c
	2.00	54.17 ± 3.05 c	2.64 ± 0.12 c
Nampula	0.00	45.83 ± 2.17 a	1.95 ± 0.16 a
	0.25	49.60 ± 3.61 a	2.38 ± 0.16 ab
	0.50	52.93 ± 3.20 a	2.51 ± 0.11 ab
	1.00	56.60 ± 2.65 a	2.70 ± 0.08 b
	2.00	57.33 ± 3.60 a	2.70 ± 0.11 b
Nacala	0.00	22.83 ± 1.95 a	0.85 ± 0.09 a
	0.25	32.67 ± 2.36 ab	1.16 ± 0.10 ab
	0.50	42.17 ± 3.13 bc	1.66 ± 0.13 bc
	1.00	51.00 ± 3.04 c	1.99 ± 0.11 c
	2.00	51.27 ± 3.29 c	2.08 ± 0.17 c

Within each column, values with the same letter were not significantly different ($p < 0.05$).

Equation (1) suggests that 0.55, 0.32, and 0.74 g P_2O_5 pot^{-1} fertilizer, corresponding to 55, 32, 74 kg P_2O_5 ha^{-1} fertilizer under 1.0 g N and 1.0 gK_2O per pot application, corresponding to 100 kg N and 100 kg K_2O ha^{-1}, are recommended for Ribaue, Nampula, and Nacala, respectively, to attain 90% of the maximum shoot biomass.

In this experiment, soil moisture condition was always kept at the optimum level for maize growth. In actual fields, it does not stay optimum and low soil moisture condition can inhibit P uptake of maize. In addition, Nacala corridor area may have a risk of leaching of P fertilizer because tested soils were sandy soil. Onasanya et al. (2009) suggested a 40 kg P ha^{-1} (91.6 kg P_2O_5 ha^{-1}) application to obtain the maximum maize yield in southern Nigeria but reported that small-scale farmers could not purchase sufficient P fertilizer in addition to N fertilizer. To recommend an optimum amount of fertilizer, a field evaluation and an economical evaluation of the relationship between fertilizer application and maize production are necessary.

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