Maize Yield Response and Nutrient Uptake after Micronutrient Application on a Volcanic Soil

Jacob B. Lisuma,* J. M. R. Semoka, and E. Semu

ABSTRACT

Micronutrients, which are often deficient in volcanic soils, together with macronutrients may lead to higher yields in these soils. A study was conducted under pot and field conditions to identify and correct some micronutrient constraints in a volcanic soil at Mpangala, Tanzania, for optimization of maize (*Zea mays* L.) yields. Dry matter (DM) yields, plant B, Cu, and Zn concentrations, plant B, Cu, and Zn uptake, and grain yields were used to assess the effects of micronutrient treatments. In pots, B, Cu, and Zn fertilizers were applied separately to the soil at two levels, 0 and 2 mg B kg^{-1}, 0 and 5 mg Cu kg^{-1}, and 0 and 10 mg Zn kg^{-1}, in combination with constant rates of 240 mg N kg^{-1} or 160 mg P kg^{-1} fertilizers. A higher rate of 320 mg P kg^{-1} was also included to assess the adequacy of the basal P rate used. A second pot study attempted to establish an optimum rate of Cu under glasshouse conditions; rates ranging from 0 to 20 mg kg^{-1} Cu were tested. Copper significantly ($P = 0.05$) increased both maize DM and grain yields; the estimated optimum rate was 20 mg Cu kg^{-1} under glasshouse conditions. This high rate is thought to be due to the high Cu-fixation capacity of volcanic soils. Boron and Zn were sufficient for normal plant growth. We conclude that maize production can be increased considerably in Mpangala and other similar soils in the same agroecological zone by applying N, P, and Cu at rates of 120, 80, and 10 kg ha^{-1}, respectively.

After N, P is the next most limiting nutrient in many tropical soils (Smith, 2000). Phosphorus-deficient soils generally do not support optimum crop yields because plant growth becomes retarded by the deficiency, leading to low yields. The approaches that have been used to replenish P in Mpangala soils include crop rotation, manure application, and the use of crop residues; however, such methods and materials do not optimize crop yields due to the insufficient P supplied by these materials. Triple super phosphate (TSP) is another source of P that is used but, due to high fertilizer prices and low agriculture-based incomes, only a few farmers use TSP and in most cases they use very low rates.

Currently, there it is possible for most small-scale farmers to use Minjingu phosphate rock (MPR), which is less expensive and locally available. Field experiments conducted in Mpangala, Makete District, since 1998 using MPR on low-P soils have shown some crop response, but yield levels obtained to date are still relatively low. For example, Semoka (2000) reported a yield of only 4.3 Mg ha^{-1} from a treatment of 100 kg N ha^{-1} and 120 kg P ha^{-1}; however, the Mpangala environment could support yields in excess of 6 Mg ha^{-1} once the limiting nutrients are corrected (Semoka, personal communication, 2000).

In addition to N and P, other nutrients suspected to be limiting in the Mpangala soil include B, Cu, and Zn. Kamasho (1980) found low levels of Cu and Zn in soils derived from volcanic ash in Mbeya district. Mpangala soils have a similar geologic origin as those of Mbeya (Harris, 1961) and could have low levels of these nutrients. Very little work has been done on micronutrients in Mpangala soils and the status of B, Cu, and Zn in these soils are not known. Otherwise, the area has a favorable climate and the soils have good physical properties such as good tilth, high water-holding capacity, and good aeration. Such conditions are favorable for high yields once any limiting nutrients are corrected. The main objectives of this study were: (i) to evaluate the levels of B, Cu, and Zn in the Mpangala soil, and (ii) to assess whether the addition of these micronutrients would increase maize yields in this soil and, possibly, in other soils with similar characteristics.

MATERIALS AND METHODS

A site that had not been treated with P, B, Cu or Zn fertilizers for the past 10 yr was selected for pot and field experiments. The soil was classified as a Pachic Haplustand (Semoka, 2000). The site was selected as representative of volcanic ash soils found at high altitudes in the southern highlands of Tanzania, which, according to de Pauw (1984), cover an area of approximately 790 km^2, and have high potential for maize production. The soils are also suitable for production of wheat (*Triticum aestivum* L.) and round potato (*Solanum tuberosum* L.), and recently some temperate fruit trees, e.g., peach [*Prunus persica* (L.) Batsch var. *persica*] and pear (*Pyrus communis* L.), have been introduced into the area.

Soil Properties of the Experimental Site

Some of the physical and chemical properties of Mpangala volcanic soil are shown in Table 1. The pH of the soil is 5.93 and is rated as medium (Landon, 1991). The optimum soil pH range for maize production is between 6 and 7 (Purseglove, 1988). The pH of 5.93 could be considered suitable for crop production when other soil and plant factors are not limiting. Organic C in Mpangala volcanic soil was found to be 2.23%. This value is rated as high (Landon, 1991). The high organic C could be explained by the fact that volcanic ash soils normally have a high organic C content.

Nitrogen content in the soil was 1.3 g kg^{-1}. Landon (1991) categorized soil total N values of 1.0 to 2.0 g kg^{-1} as low. Therefore, total N in Mpangala volcanic soil is rated as low.

J.B. Lisuma, Social Responsibility Program (SRP) National Office, P.O. Box 1382, Tabora, Tanzania; J.M.R. Semoka and E. Semu, Dep. of Soil Science, Sokoine Univ. of Agriculture, P.O. Box 3008, Chuo Kikuu Morogoro, Tanzania. Received 24 June 2005. *Corresponding author (jbulenga@yahoo.co.uk).

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Abbreviations: DM, dry matter; TSP, triple superphosphate.

Table 1. Some physical and chemical characteristics of the experimental soil.

Parameter	Value	Rating	Reference
pH in water	5.93	medium	Landon (1991)
Organic C, %	2.23	high	Landon (1991)
Bray 1 P, mg kg^{-1}	4.41	deficient	Landon (1991)
Total N, %	0.13	low	Landon (1991)
Cation exchange capacity, cmol$_c$ kg^{-1}	19.8	medium	Landon (1991)
Exchangeable Ca, cmol$_c$ kg^{-1}	4.09	medium	Landon (1991)
Exchangeable Mg, cmol$_c$ kg^{-1}	1.69	medium	Landon (1991)
Exchangeable K, cmol$_c$ kg^{-1}	1.13	high	Landon (1991)
Exchangeable Na, cmol$_c$ kg^{-1}	0.66	low	Landon (1991)
Exchangeable Al, cmol$_c$ kg^{-1}	1.00	–	–
Exchangeable H, cmol$_c$ kg^{-1}	0.35	–	–
Al saturation, %	5.05	–	–
Ca saturation, %	20.7	–	–
Hot-water-soluble B, mg kg^{-1}	0.52	medium	Golov and Bakhova (1996)
DTPA-extractable Cu, mg kg^{-1}	0.14	deficient	Lindsay and Norvell (1978)
DTPA-extractable Zn, mg kg^{-1}	0.86	marginal	Lindsay and Norvell (1978)
DTPA-extractable Fe, mg kg^{-1}	50.54	very high	Lindsay and Norvell (1978)
DTPA-extractable Mn, mg kg^{-1}	17.32	very high	Tandon (1995a)
Particle size analysis			
Sand, %	49	–	–
Silt, %	15	–	–
Clay, %	36	–	–
Textural class	sandy clay	–	FAO (1977)

The Bray 1 (available) P content of the soil was 4.41 mg kg^{-1}. Landon (1991) categorized extractable P (Bray 1 method) in soils as follows: high (>50); medium (15–50) and low (<15). Therefore, an available P of 4.41 mg kg^{-1} by the Bray 1 method is very low, implying that the soil is deficient in P.

The DTPA (diethylene triamine pentaacetic acid) extractable Cu was found to be 0.14 mg kg^{-1}. According to Lindsay and Norvell (1978) and Tandon (1995b), the critical level of DTPA-extractable Cu in the soil is 0.2 mg kg^{-1}; therefore, a DTPA-extractable Cu level of 0.14 mg kg^{-1} in the soil is low since it is below the soil critical level. The DTPA-extractable Zn in the soil was 0.86 mg kg^{-1}. Lindsay and Norvell (1978) suggested levels of 0.5 to 1.0 mg kg^{-1} to be the critical levels for Zn; therefore, the concentration of 0.86 mg Zn kg^{-1} is rated as marginal. The B concentration found in Mpangala soil was 0.52 mg B kg^{-1} as determined by hot water extraction. Cox and Kamprath (1972) proposed the B critical range to be between 0.2 and 1.0 mg kg^{-1}. Golov and Bakhova (1996), using the hot-water-soluble B method, gave the following scale: <0.33 mg B kg^{-1} is low, 0.34 to 0.70 mg B kg^{-1} is medium, and >0.71 mg B kg^{-1} is high. On the basis of these categories, the level of 0.52 mg B kg^{-1} for Mpangala soil falls in the medium range.

Pot Experiments

Triple superphosphate (20% P), $(NH_4)_2SO_4$ (21% N), $Na_2B_{10}O_{16}\cdot 10H_2O$ (17.5% B), $CuSO_4\cdot 5H_2O$ (25.4% Cu), and $ZnSO_4\cdot H_2O$ (36.4% Zn) were used as sources of plant nutrients in these experiments.

In the first pot experiment (Table 2), pots were arranged in a randomized complete block design with three replications. The total number of treatments was 10 and the total number of pots was 30. Two rates of P, 160 and 320 mg kg^{-1}, were applied, while a rate of 240 mg kg^{-1} was used for N, applied in two equal splits at the second and fourth week after planting. Rates of 2, 5, and 10 mg kg^{-1} were applied for B, Cu and Zn, respectively. Four maize seeds of hybrid UH 615 were planted per pot and thinned to two after 1 wk following emergence. The soils in the pots were maintained at approximately field capacity during the experimental period by watering with deionized water. Plant shoots were harvested at 42 d after planting by cutting the stems at ~1 cm above the soil surface. Plants were dried at 65°C to a constant weight. The dried plant samples were cut into small pieces and ground to pass through a 0.5-mm sieve for analysis.

Table 2. Treatments used in the pot experiment.

Treatment combination†	Micronutrients used
$P_0N_0B_0Cu_0Zn_0$	absolute control
$P_{160}N_{240}B_0Cu_0Zn_0$	micronutrient control
$P_{160}N_{240}B_0Cu_0Zn_{10}$	Zn alone
$P_{160}N_{240}B_2Cu_0Zn_0$	B alone
$P_{160}N_{240}B_0Cu_5Zn_{10}$	Cu and Zn
$P_{160}N_{240}B_0Cu_5Zn_0$	Cu alone
$P_{160}N_{240}B_2Cu_5Zn_0$	B and Cu
$P_{160}N_{240}B_2Cu_0Zn_{10}$	B and Zn
$P_{160}N_{240}B_2Cu_5Zn_{10}$	all micronutrients with low P rate
$P_{320}N_{240}B_2Cu_5Zn_{10}$	all micronutrients with high P rate

† Subscript values are nutrient rates in milligrams per kilogram.

The second pot study was conducted to determine the optimum rate of Cu to maximize yields, having in the preceding experiment observed Cu to be the most limiting micronutrient. Rates of 320 mg P kg^{-1}, 240 mg N kg^{-1}, and different levels of Cu (5, 7.5, 10, 15, or 20 mg Cu kg^{-1}) were used. Pots were arranged in a randomized complete block design with three replications. The total number of treatments was five, and the total number of pots was 15. The same procedures used in the preceding pot experiment were followed in the second pot experiment.

Field Experiment

Location of the Study Site

The experimental area was located between 8°59′ and 9°00′ S and 33°57′ and 33°58′ E, at an elevation of 2250 m above sea level. The annual mean rainfall ranges from 1000 to 1400 mm. The rainfall is well distributed during the first 6 mo of the season, November to April. Thus, an early planted crop of maize does not suffer moisture stress (Szilas, 2002). there is very little rainfall after the end of April, however, and thus early planting is important for a good maize crop. The mean air temperature during the growing season is 15.3°C, which is low for maize, thereby leading to a long growing season for this crop at this site.

Table 3. Treatments used in the field experiment.

Treatment combination†	Micronutrients used
$P_0N_0B_0Cu_0Zn_0$	absolute control
$P_{80}N_{120}B_0Cu_0Zn_0$	micronutrient control
$P_{80}N_{120}B_0Cu_0Zn_5$	Zn alone
$P_{80}N_{120}B_1Cu_0Zn_0$	B alone
$P_{80}N_{120}B_0Cu_{2.5}Zn_5$	Cu and Zn
$P_{80}N_{120}B_0Cu_{2.5}Zn_0$	Cu alone
$P_{80}N_{120}B_1Cu_{2.5}Zn_0$	B and Cu
$P_{80}N_{120}B_1Cu_0Zn_5$	B and Zn
$P_{80}N_{120}B_1Cu_{2.5}Zn_5$	all micronutrients with low P rate
$P_{160}N_{120}B_1Cu_{2.5}Zn_5$	all micronutrients with high P rate

† Subscript values are nutrient rates in kilograms per hectare.

Experimental Design, Field Plan, and Treatments

A randomized complete block design was used in this experiment, with 10 treatments as shown in Table 3, and the treatments were replicated four times. The dimensions of each plot were 5.1 by 4.5 m, with interblock and interplot spacing of 1 and 0.5 m, respectively. A 2-m-wide pathway was maintained around the entire experimental area. Seeds were sown at the spacing of 75 by 30 cm.

Triple superphosphate, sulphate of ammonia, B, Cu, and Zn fertilizers at the rates of 80 kg P ha^{-1}, 120 kg N ha^{-1}, 1 kg B ha^{-1}, 2.5 kg Cu ha^{-1}, and 5 kg Zn ha^{-1}, respectively, was applied by hand by spreading the fertilizers evenly on the soil surface and then plowing them under. The UH 615 maize (three seeds) was planted together with the application of the first split of 30 kg N ha^{-1}. Seedlings were then thinned to one plant per hill 2 wk after emergence. The second split of 40 kg N ha^{-1} was applied 4 wk after planting. The third split of 30 kg N ha^{-1} was applied 9 wk after planting and the fourth split of 20 kg N ha^{-1} at 15 wk after planting when maize was about to flower. Frequent weeding was done so that the experimental plots were almost free of weeds for most of the plant growth period. Plants were sampled at 20 wk after sowing by taking three ear leaves per row from each of the inner four out of six rows, giving a total of 12 leaves per plot. These plants were sampled when almost 50% of maize plants had tasseled. The samples were oven dried at 65°C to constant weight, cut into small pieces, and ground to pass a 0.5-mm sieve for chemical analysis.

Maize grain was harvested at 286 d after planting. A guard row was left around each plot so that only the inner four rows were harvested. Cobs were shelled, grain weighed, and the moisture content of the grain determined using a moisture meter. The grain yields are reported in tonnes ha^{-1} at 12.5% moisture.

The experimental data were analyzed as a randomized complete block design. Analysis of variance was used to evaluate the effects of the treatments on dry matter (DM) yield, contents of P, N, B, Cu, and Zn in plant samples, and maize grain yield. Duncan's new multiple-range test was used for the separation of means. The statistical model used for data analysis was as described by Snedecor and Cochran (1989):

$$Y_{ij} = \mu + T_i + \beta_j + E_{ij} \text{ for } i = 1,2,\ldots b$$
$$j = 1,2,\ldots t$$

where

Y_{ij} = observation for each of the treatments
μ = overall mean
T_i = effects due to treatments
β_j = effects due to the block
E_{ij} = variation within treatments and blocks (i.e., error term)

RESULTS AND DISCUSSION

Glasshouse Pot Experiments

Response of Maize to Boron, Copper, and Zinc

A dramatic effect on DM yields was observed in the Cu treatment, which significantly increased DM yields from 7.9 to 57.8 g pot^{-1} (Table 4). The very dramatic effect of Cu in increasing the DM yields suggests that Cu is a limiting nutrient in the Mpangala soil, and hence the significant ($P = 0.05$) increase in yields following its use.

The still higher ($P = 0.05$) DM yields when P was used at the rate of 320 mg kg^{-1} (in combination with the micronutrients) implies that the rate of 160 mg P kg^{-1} was not adequate in the Mpangala soil, probably due to high P fixation (Table 4). Szilas (2002) found the Mpangala soil to have a P adsorption maximum of 1017 mg P kg^{-1}, which is much higher than the P rate used in our studies.

Concentration and Uptake of Boron, Copper, and Zinc in Maize Shoots

The concentrations of B, Cu, Zn, and their uptake by the maize shoots are shown in Table 4. Boron concentrations ranged from 12.7 to 25.1 mg kg^{-1}, which were above the critical range of 8 to 10 mg B kg^{-1} reported by Melsted et al. (1969) and Lockman (1972). Therefore, Mpangala soil has adequate B content. Uptake of B was found to be significantly higher for the treatment that received 320 mg P kg^{-1} than for the other treatments, indicating that the high rate of P increased the uptake of B.

Copper concentrations in maize shoots ranged from 1.2 to 4.5 mg kg^{-1} and were below the critical levels established by Jones and Eck (1973). Copper application increased Cu uptake significantly compared with the control, signifying that Cu was one of the limiting nutrients in this soil and it was in this treatment where significantly higher DM yields were obtained.

Zinc concentrations in maize shoots ranged from 10.8 to 18.9 mg kg^{-1} and were below the critical range of 25 to 60 mg kg^{-1} established by Tisdale et al. (1993). Similarly, soil analysis data for Zn indicated that Mpangala soil had a marginal level of Zn. Addition of N and P in the soil did not increase Zn concentrations in maize shoots significantly, probably due to a dilution effect as a result of the increase in DM. The higher and significant Zn

Table 4. Concentrations and uptake of N, P, B, Cu, and Zn on maize dry matter (DM) yield in a pot experiment.

Treatment†	DM yield	N	N uptake	P	P uptake	B	B uptake	Cu	Cu uptake	Zn	Zn uptake
	g pot^{-1}	g kg^{-1}	mg pot^{-1}	g kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}
$P_0N_0B_0Cu_0Zn_0$	7.93d‡	0.079d	6.3d	0.012b	1.0e	18.1bc	145.3e	1.2e	9.8e	10.8d	85.7c
$P_{160}N_{240}B_0Cu_0Zn_0$	49.77c	0.156ab	77.6bc	0.014ab	7.1bcd	15.5cd	770.6d	1.5e	76.0d	11.7cd	581.9b
$P_{160}N_{240}B_0Cu_0Zn_{10}$	53.30bc	0.152abc	81.1bc	0.015ab	8.0bcd	14.4cd	772.6d	1.7e	91.2d	18.7a	998.7a
$P_{160}N_{240}B_2Cu_0Zn_0$	51.67c	0.153abc	79.2bc	0.012ab	6.3d	25.1a	1296ab	1.6e	81.3d	10.8d	557.8b
$P_{160}N_{240}B_0Cu_5Zn_0$	57.90b	0.142c	82.0bc	0.014ab	8.3bc	12.7d	747.7d	3.4bc	197.2b	11.0d	634.7b
$P_{160}N_{240}B_2Cu_0Zn_{10}$	51.37c	0.160a	82.3bc	0.015ab	7.3bcd	21.4ab	1091bc	3.9b	200.5b	18.9a	974.0a
$P_{160}N_{240}B_0Cu_5Zn_{10}$	50.73c	0.145bc	73.9c	0.014ab	6.8cd	14.6cd	739.2d	2.9cd	144.9c	14.3bc	724.5b
$P_{160}N_{240}B_2Cu_5Zn_0$	51.27c	0.156abc	79.7bc	0.013ab	6.7cd	17.9bc	917.8cd	3.7b	191.8b	12.8cd	653.6b
$P_{160}N_{240}B_2Cu_5Zn_{10}$	57.83b	0.152bc	87.9b	0.015a	8.7b	20.9b	1241ab	4.5a	257.7a	16.6ab	965.1a
$P_{320}N_{240}B_2Cu_5Zn_{10}$	68.50a	0.145bc	99.5a	0.016a	10.7a	20.0b	1369a	2.5d	169.0bc	14.5bc	993.3a
CV, %	6.66	4.91	7.6	10.67	13.5	12.0	15.2	11.9	13.4	10.8	13.8

† Subscript values are nutrient rates in milligrams per kilogram.
‡ Means in a column followed by the same letter(s) are not significantly ($P = 0.05$) different according to the Duncan's new multiple-range test.

uptake for the treatments with 160 and 320 mg P kg^{-1} could be related to the large increase in DM yield.

Estimation of Optimum Copper Level for Maize Production in Mpangala Soil

Response of Maize Dry Matter Yield to Different Levels of Copper

The greater increase in DM yields in the P treatments over those in the N treatments indicated that P was the most limiting macronutrient (Table 5). Dry matter yields did not differ significantly ($P = 0.05$) between the levels of 5 and 15 mg Cu kg^{-1}. The treatment that received 20 mg Cu kg^{-1} gave significantly higher DM yield than treatments with lower Cu rates, suggesting that this treatment improved Cu supply further, thereby leading to better Cu nutrition.

Concentration and Uptake of Copper in Maize Shoots

Most of the Cu concentrations in maize shoots were above the critical level of 7 mg kg^{-1} (Table 5), which is the lower value of the sufficiency range for maize at 30 to 45 d of age (Jones and Eck, 1973). The rate of 20 mg Cu kg^{-1} was required for optimizing maize yields in Mpangala soil — it gave significantly higher DM yields than did lower Cu rates. This rate of Cu is relatively high, suggesting that this soil has high Cu fixation.

Field Experiment

Maize Grain Yields

Maize grain yields (Table 6) ranged between 1.76 and 5.84 Mg ha^{-1}. The grain yield of 5.84 Mg ha^{-1} from the Cu treatment was significantly higher ($P < 0.05$) than that from the control and the rest of the treatments. The highest, and significant, grain yield across all treatments was obtained in the Cu-alone treatment. The results obtained from this study suggest that Cu, followed by P, influenced maize grain yields the most. The grain yield results obtained from the field experiment are in agreement with those obtained from the pot experiments. Higher maize yields beyond the 5.84 Mg ha^{-1} may be obtained at Mpangala if the Cu supply and other agronomic conditions are optimized. A Cu level of at least 10 kg ha^{-1} is suggested, on the basis of the second pot experiment, as the level that can optimize maize yields under the currently used nutrient application rates.

Table 5. Dry matter (DM) yields, Cu concentrations and uptake by maize, and soil DTPA-extractable Cu as a result of varying Cu levels.

Treatment†	DM yield	Plant Cu	Plant Cu uptake	DTPA-extractable Cu in soil
	g pot^{-1}	mg kg^{-1}	μg pot^{-1}	mg kg^{-1}
P_0N_{240} Cu_0	6.7d‡	2.9c	19.2c	0.12d
$P_{320}N_0$ Cu_0	13.6c	3.3c	44.5c	0.18d
$P_{320}N_{240}Cu_5$	38.9b	5.2b	204.7b	1.24c
$P_{320}N_{240}$ $Cu_{7.5}$	36.7b	7.3a	268.2b	1.65c
$P_{320}N_{240}$ Cu_{10}	39.4b	7.5a	294.9b	3.79b
$P_{320}N_{240}$ Cu_{15}	40.0b	7.5a	303.1b	3.92b
P_{320} N_{240} Cu_{20}	48.4a	9.2a	448.0a	4.85a
CV, %	10.8	17.4	25.3	18.5

† Subscript values are nutrient rates in milligrams per kilogram.
‡ Means in a column followed by the same letter are not significantly ($P = 0.05$) different according to the Duncan's new multiple-range test.

Table 6. Effects of added B, Cu, and Zn on maize grain yields and plant Cu concentration.

Treatment†	Grain yield	Cu conc.
	Mg ha^{-1}	mg kg^{-1}
P_0 N_0 B_0 Cu_0 Zn_0 (absolute control)	1.76d‡	0.45d
P_{80} N_{120} B_0 Cu_0 Zn_0 (micronutrient control)	4.06c	0.52cd
P_{80} N_{120} B_0 Cu_0 Zn_5	4.47bc	0.77cd
P_{80} N_{120} B_1 Cu_0 Zn_0	4.33c	0.74cd
P_{80} N_{120} B_0 $Cu_{2.5}$ Zn_0	5.84a	1.01abc
P_{80} N_{120} B_1 Cu_0 Zn_5	4.40c	1.06abc
P_{80} N_{120} B_0 $Cu_{2.5}$ Zn_5	4.17c	0.89bcd
P_{80} N_{120} B_1 $Cu_{2.5}$ Zn_0	5.35ab	1.41ab
P_{80} N_{120} B_1 $Cu_{2.5}$ Zn_5	4.87bc	1.43a
P_{160} N_{120} B_2 $Cu_{2.5}$ Zn_5	5.35ab	1.44a
CV, %	12.84	34.5

† Subscript values are nutrient rates in kilograms per hectare.
‡ Means in a column followed by the same letter(s) are not significantly ($P = 0.05$) different according to the Duncan's new multiple-range test.

Concentrations of Copper

The concentrations of Cu (Table 6) ranged from 0.45 to 1. 44 mg kg^{-1} and were below the critical value of 5 mg kg^{-1} given by Jones and Eck (1973). Maize plants treated with Cu showed concentrations of Cu lower than critical values while the grain yield was significantly increased, indicating that the Cu requirement for grain formation is higher than that for maize shoot growth.

CONCLUSIONS

The study clearly demonstrated that the Mpangala volcanic soil has severe Cu deficiency, probably due to strong Cu fixation capacity, and therefore the low yields of maize grown in Mpangala soil were partly attributed to the Cu deficiency. The use of Cu fertilizer improved maize yields appreciably. A pot experiment estimated the rate of 20 mg Cu kg^{-1} to be optimum in Mpangala soil. Research on the chemistry and adsorption of Cu, Zn, and B in Mpangala volcanic soil should also be performed to identify the adsorption or retention characteristics of this soil, because management of nutrients seems to be very challenging under these circumstances.

The rate of 160 kg P ha^{-1} is recommended for the immediate objective of increasing yields; however, higher rates of P are still required in Mpangala soil. Also, further research should be undertaken to evaluate N rates greater than the currently recommended rate of 120 kg ha^{-1} to ensure that the yield potential is reached after optimization of Cu and Zn.

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