Cassava Yield and Economic Response to Fertilizer in Tanzania, Kenya and Ghana

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ABSTRACT
Cassava (Manihot esculenta Crantz) is a major food crop in Africa with little information of response to applied nutrients. Our objectives were to: determine cassava yield response to macronutrients for production areas in Ghana, Kenya and Tanzania; evaluate the effect Mg, S, Zn and B application; and determine agronomic efficiency (AE) and value cost ratio (VCR) for nutrient application. Fresh storage root yield with no fertilizer averaged 14.4 Mg ha$^{-1}$ and mean yield increases due to 80 kg ha$^{-1}$ N applied were 8.1, 6.5 and 9.0 Mg ha$^{-1}$ in Ghana, Kenya and Tanzania. Storage root yield was increased 93% with P application for Aduma in Ghana and there was a curvilinear to plateau response to K at Wenchi Ghana. No other responses to P and K rates occurred, but an N × P synergism occurred in Tanzania. There were no responses to applied Mg, S, Zn, and B. The VCR for N at all sites was >2 indicating sufficient profit opportunity to make N application attractive to many financially constrained farmers. The mean soil organic C (SOC) was 8 g kg$^{-1}$; the results may lose applicability with much higher SOC soils. Over all trials, application of 80 kg ha$^{-1}$ N had, on average 8.44 Mg ha$^{-1}$ increased yield with 105 kg kg$^{-1}$ agronomic efficiency and 7.8 $\$^{-1}$ profit to cost ratio. The results indicate that cassava is efficient in P and K uptake with restricted and little profit potential for P and K application in these countries, respectively.

Core Ideas
- Cassava is a major food crop in tropical Africa
- Cassava is efficient in uptake of immobile nutrients.
- Cassava is highly responsive to applied N.

Cassava (Manihot esculenta Crantz) is an important crop of smallholder farmers in Tanzania, Kenya and Ghana (Harvest Choice, 2011). In Ghana, cassava is second to maize in terms of production area and an important cash crop (MOFA, 2010; FAO, 2015). In Tanzania and in Western and Coastal Kenya, cassava is second to maize in importance as a food crop (Mwango’imbe et al., 2013). However, mean cassava fresh storage root yield was estimated to be 13.5, 6.2 and 14.4 Mg ha$^{-1}$ for Kenya, Tanzania and Ghana, respectively (FAOSTAT, 2017) while cassava yield has reached 80 Mg ha$^{-1}$ (FAO, 2013). Pests and diseases, the use of poor cultural practices, and low soil fertility status are among causal factors for low cassava yields (Harvest Choice, 2011; Ezui et al., 2016). Several studies have shown that the soil nutrient balance is negative due to nutrient removal at harvest, minimal or no use of fertilizers, and soil erosion (Asadu and Nweke, 1999; Shekiffu, 2011; Fermont 2009). Few soil fertility studies have been conducted in cassava production in Tanzania, Kenya and Ghana and very few farmers apply fertilizer to cassava (Asadu and Nweke, 1999; Howeler, 2002; Fermont et al., 2009; Adjei-Nsiah, 2010). Responses of cassava to N, P, and K fertilizers has been reported in western Kenya, central-eastern Uganda, Ghana, and Coastal Tanzania (Fermont et al., 2009; Adjei-Nsiah, 2010; Shekiffu, 2011; Boateng, 2015), but response functions were not determined (Fermont et al., 2009). Application of 15 kg ha$^{-1}$ P and 30 kg ha$^{-1}$ K has been recommended for cassava sole crop and cassava-cowpea (Vigna unguiculata L.) intercropping in Coastal Tanzania (Shekiffu, 2011). Boateng (2015) recommended 60, 26, and 50 kg ha$^{-1}$ of N, P, and K for cassava production in Ghana. These fertilizer recommendations are, however, intended for farmers with the financial ability to apply fertilizer to maximize crop yield or profit per hectare. Smallholder farmers use little or no fertilizer for cassava production due to their low financial ability. Often, financial constraints allow fertilizer application for farmers with the financial ability to apply fertilizer to maximize crop yield or profit per hectare. Smallholder farmers use little or no fertilizer for cassava production due to their low financial ability. Often, financial constraints allow fertilizer application.
application on only a small part of the farm, and farmers need to make choices that maximize the net returns for their investment (Jansen et al., 2013). Crop nutrient response functions are needed to optimize fertilizer use choices for maximization of net returns on investment. Therefore, research was needed to determine cassava nutrient response functions.

Limited information is available on the fertility status of secondary and micronutrients in cassava production, and their effect on cassava yields (Shekiffu, 2011). Establishing recommendations for such nutrients will allow formulation of balanced fertilizers use for cassava production.

The objectives of this research were to: assess cassava storage root yield response to N, P, and K in major cassava producing areas in Tanzania, Kenya and Ghana; evaluate the effect of S, Zn, Mg, and B applied to cassava; calculate the agronomic efficiency (AE) of fertilizer N, P and K in cassava production; and determine the economically optimum rates (EOR) and VCR of N, P and K for cassava production.

**MATERIALS AND METHODS**

**Site Characteristics**

Field trials were conducted in 2014 and 2015 at:

(i) Vundemanyinyi, referred to as Mkinga, in Mkinga District and Chambezi in Bagamoyo District of eastern Tanzania;

(ii) Oyani in Migori County and Alupe in Busia County of western Kenya; and

(iii) Akuma, Wenchi, Dandwan and Adidwan in the Transition and southern Guinea Savanna agroecological zones of Ghana (Table 1). The selected sites were representative of land used for cassava production in the study areas and atypically serious edaphic constraints such as shallow soil depth were avoided.

Composite soil samples were collected by block for the 0- to 20-cm depth. These were air dried, sieved through a 2-mm sieve, and sent to the World Agroforestry Center Soil-Plant Spectral Diagnostic Laboratory in Nairobi, Kenya for analysis. Nutrient availability was determined using mid-infrared spectral analysis following validation or calibration using data from wet chemistry analysis for about 10% of the samples (Shepherd and Walsh, 2007; Terhoeven-Urselmans et al., 2010; Towett et al., 2015; https://www.worldagroforestry.org/sd/landhealth/soil-plant-spectral-diagnostics-laboratory/sops). Organic C and N were analyzed with a Thermal Scientific Flash 2000. Soil pH was determined with a 1:2.5 soil/water slurry. The Mehlich-3 extraction was used for available P, exchangeable bases and available micronutrients (Mehlich, 1984). Particle size distribution was determined using the Horiba LA 950 Laser Scattering Particle Size Distribution Analyzer.

In Tanzania, the soils were slightly acidic loamy sand and sandy clay loam with <10 kg kg⁻¹ soil organic C (SOC), low to adequate Mehlich-3 P, medium exchangeable K, and very low B at Chambezi (Horneck et al., 2015; Howeler, 2002) (Table 1). The soil at Oyani was clay with 17 g kg⁻¹ SOC and medium or adequate nutrient availability. The soils in Ghana were sandy clay with <10 g kg⁻¹ SOC, medium Mehlich-3 P availability at Wenchi but low at other locations although may be adequate for cassava (Howeler, 2002). Soil test K ranged from medium to high according to Howeler (2002).

The cassava growing season began in September to October in Kenya and Tanzania, and in May in Ghana (Fig. 1). In Tanzania and Kenya, the 2014 to 2015 growing season received less rainfall as compared with the 2015 to 2016 season. In Ghana, the first season received more rainfall than the second season. The Kenya sites received more rainfall than the sites in Tanzania and Ghana. Mean monthly maximum and minimum temperatures for the Ghana and Tanzania locations are about 30.5 and 21.5°C, respectively, but 28.5 and 15.5°C for the western Kenya sites.

**Treatments and Experimental Design**

Sixteen treatments were tested in an incomplete factorial design. It was assumed that N was the most limiting nutrient for cassava followed by P and then K. The N rates were 0, 20, 40, 60, and 80 kg ha⁻¹, applied alone and with a uniform application of 15 kg ha⁻¹ P. The P rates of 0, 7.5, 15, and 22.5 kg ha⁻¹ were evaluated with a uniform application of 60 kg ha⁻¹ N. The K rates of 0, 10, 20, and 30 kg ha⁻¹ were evaluated with constant levels of 60 kg N ha⁻¹ and 15 kg P ha⁻¹. A diagnostic treatment of 60 kg N ha⁻¹, 15 kg P ha⁻¹, 20 kg K ha⁻¹, 15 kg S ha⁻¹, 2.5 kg Zn ha⁻¹, 10 kg Mg ha⁻¹, 0.5 kg B ha⁻¹ for comparison with the 60 kg N ha⁻¹, 15 kg P ha⁻¹, 20 kg K ha⁻¹ treatment was also included to determine if application of one or more of the secondary or micronutrients could increase cassava yield.

The fertilizer nutrient sources were urea, triple super phosphate, potassium chloride, magnesium sulfate, zinc sulfate, and borax. All fertilizers except urea were applied during planting at points about 15 cm away from the planted cutting. The urea was applied in two splits with 50% each at 4 and 8 wk after sprouting of the cassava cuttings. The popular improved cassava varieties Kiroba, Minjera and Bankyehemaa were selected as test varieties in Tanzania, Kenya and Ghana, respectively.

The experimental design was a randomized complete block with three replications. The gross plot size was 4 m by 6 m and the net plot for yield determination was two rows of 4-m length.

**Trial Management and Data Collection**

For each site, fresh cassava cuttings of about 20 cm long were planted by placing one cutting per hole at about 45° angle relative to the soil surface. The plant spacing was 1 m by 1 m, giving 10,000 plant ha⁻¹. Cassava gap filling was performed at 2 to 3 wk after planting depending on the soil water availability. Weeding was undertaken four times using a hand hoe.

Cassava storage roots were harvested at 9 mo after planting in Tanzania and at 12 mo in Kenya and Ghana. All storage roots were rubbed free of soil and weighed immediately for fresh weight determination.

**Statistical Analysis**

Data were analyzed using Statistix 10.0 (Analytical Software, Tallahassee FL). The analyses of variance for fresh storage root yield were conducted by country across site-years (SY). The Ghana SY were analyzed as two groups of three sites to achieve homogeneity of variance within groups. Group “SY123” included on-station trials at Wenchi and Adidwan in 2014 to 2015 and an on-farm trial at Wenchi in 2015 to 2016. Group “SY456” included 2015 trials conducted on-station at Wenchi and on-farm trials at Akuma and Dandwa. When significant nutrient rate or interaction effects occurred, mean separation
was done by ANOVA-protected LSD 0.05. Contrast tests were done to test mean effects as well as linear and quadratic effects of applied P and K and the effect of the diagnostic treatment. The contrast tests were performed over SY combined, and when significant, by SY to test for interactions with SY. The N and N interaction effects were determined with only the 10 treatments that were relevant to the N × P interaction. Treatment effects were considered to be statistically significant at $P \leq 0.05$.

In cases of significant nutrient rate effects, fitting of asymptotic and linear models was attempted using appropriate non-linear and linear regression analyses. The asymptotic function representing curvilinear to plateau responses was given as yield (Mg ha$^{-1}$) = $a - bcx$, where $a$ is yield at the plateau in response to that nutrient, $b$ is the maximum gain in yield due to the application of that nutrient, $c$ is a curvature coefficient, and $x$ is the nutrient rate. Linear functions were given as yield = $a + bx$, where $a$ is the yield for the zero nutrient rate, $x$ is the nutrient application rate and $b$ is a slope or rate of change of the yield due to applied nutrient (kg kg$^{-1}$).

### Agronomic and Economic Analysis

Agronomic efficiency of N, P and K for cassava was calculated as a ratio of the increased cassava storage root yield relative to the amount of nutrient applied (kg kg$^{-1}$). The financial benefits of fertilizer use were determined by the value-cost ratio (VCR), that is, the ratio between the value of the additional cassava storage root yield and the cost of nutrient application. A VCR of 2 represents 100% return on the money invested in fertilizer and was considered to be sufficient to warrant financially constrained investment in fertilizer use (CIMMYT, 1988; Kihara et al., 2016). Cassava price of US$ 0.104 and fertilizer use costs of US$ 1.25, 2, and 1.25 for N, P and K kg$^{-1}$, respectively, were used to calculate VCR (1 US$ was equivalent to Tanzania Sh 2230, Kenya Sh 103.3 and Ghana cedi 4.241). The EOR of N application, or the rate to maximize net

### Table 1. Characteristics of cassava trial sites in Tanzania, Kenya, and Ghana†.

<table>
<thead>
<tr>
<th>Location</th>
<th>Tanzania</th>
<th>Kenya</th>
<th>Ghana</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chambezi</td>
<td>Mkinga</td>
<td>Oyani</td>
</tr>
<tr>
<td>Soil type</td>
<td>Ferralic Cambisol</td>
<td>Ferric Lixisol</td>
<td>Ferric Lixisol</td>
</tr>
<tr>
<td>Latitude‡</td>
<td>-6.547</td>
<td>-4.966</td>
<td>-8.993</td>
</tr>
<tr>
<td>Longitude‡</td>
<td>38.915</td>
<td>38.976</td>
<td>34.512</td>
</tr>
<tr>
<td>Altitude, m</td>
<td>39</td>
<td>121</td>
<td>1440</td>
</tr>
<tr>
<td>Year</td>
<td>2014</td>
<td>2014</td>
<td>2014</td>
</tr>
<tr>
<td>pH</td>
<td>6.10</td>
<td>6.19</td>
<td>5.63</td>
</tr>
<tr>
<td>SOC, g kg$^{-1}$</td>
<td>3.8</td>
<td>5.2</td>
<td>17.5</td>
</tr>
<tr>
<td>SON, g kg$^{-1}$</td>
<td>0.5</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Clay, g kg$^{-1}$</td>
<td>147</td>
<td>177</td>
<td>658</td>
</tr>
<tr>
<td>Silt, g kg$^{-1}$</td>
<td>124</td>
<td>93</td>
<td>212</td>
</tr>
<tr>
<td>Sand, g kg$^{-1}$</td>
<td>729</td>
<td>730</td>
<td>128</td>
</tr>
<tr>
<td>K, cmolc kg$^{-1}$</td>
<td>0.15</td>
<td>0.20</td>
<td>0.81</td>
</tr>
<tr>
<td>Ca, cmolc kg$^{-1}$</td>
<td>1.53</td>
<td>2.17</td>
<td>5.45</td>
</tr>
<tr>
<td>Mg, cmolc kg$^{-1}$</td>
<td>0.55</td>
<td>0.64</td>
<td>1.99</td>
</tr>
<tr>
<td>Mehlich–3 P, mg kg$^{-1}$</td>
<td>10.6</td>
<td>18.7</td>
<td>16.0</td>
</tr>
<tr>
<td>Mn, mg kg$^{-1}$</td>
<td>55</td>
<td>79</td>
<td>230</td>
</tr>
<tr>
<td>Zn, mg kg$^{-1}$</td>
<td>1.51</td>
<td>3.25</td>
<td>3.37</td>
</tr>
<tr>
<td>B, mg kg$^{-1}$</td>
<td>0.07</td>
<td>0.13</td>
<td>0.25</td>
</tr>
<tr>
<td>S, mg kg$^{-1}$</td>
<td>6.2</td>
<td>9.6</td>
<td>7.8</td>
</tr>
</tbody>
</table>

† Alupe in Kenya was at 0.993 latitude, 34.512 longitude and 1420 m asl elevation, but no soil test information was available. At Wenchi site in Ghana, three trials were conducted: Site year 1 (SY1): on-station 2014 to 2015; SY3: on-farm 2015 to 2016; SY4: on-station 2015 to 2016.‡ Latitude and longitude are in decimal degrees with WGS84 projection.

Fig. 1. Rainfall during the growing seasons at the trial sites in Ghana, Kenya and Tanzania. Rainfall for Wenchi in season 2014 to 2015 was for Wenchi on-station and on-farm trial.
returns per hectare to N application, was calculated with the N use cost being 12-fold the fresh cassava storage root value (kg kg\(^{-1}\)).

## RESULTS

In all countries, applied N increased cassava fresh storage root yields, but overall yield was not affected by P rate except for SY456 in Ghana (Table 2). The interactions of N × P rate and site × N × P rate were significant in Tanzania. The effects of P and K rate and the interactions of N × P rate, SY × N rate, SY × P rate, and SY × K rate were significant for SY456 in Ghana. Yield was affected by K rate for SY456 in Ghana. No significant yield increase due to the diagnostic treatment of applied Mg, S, Zn, and B occurred in any country with nonsignificant mean yield increases of 2.81, –4.85 and 1.36 Mg ha\(^{-1}\) in Tanzania, Kenya and Ghana, respectively (Table 2).

In Ghana for SY456, mean cassava storage root yield by SY with no fertilizer applied ranged from 4.55 to 8.46 Mg ha\(^{-1}\). The highest yields per SY ranged from 12.25 Mg ha\(^{-1}\) for 60 kg N ha\(^{-1}\) at Dandwa to 21.12 Mg ha\(^{-1}\) with 60 kg N ha\(^{-1}\), 15 kg P ha\(^{-1}\), plus 30 kg K ha\(^{-1}\) at Wenchi (Tables 3 and 4). Storage root yield was increased with N alone applied for SY456. The SY × N × P interaction was significant due to inconsistent N rate effects with 15 kg ha\(^{-1}\) P applied with no significant N effect at Wenchi and Dandwa but a significant yield increase at Akuma (Table 3). The yield response to N alone was linear for SY456 fit a linear model. The AE of applied N decreased with N rate when the yield response was curvilinear (Fig. 3). The AE of N was highest at Akuma and lowest at Dandwa as compared with other SY when N was applied alone. At 20 kg N ha\(^{-1}\), AE of N were 64, 458, 202, 196, and 167 kg kg\(^{-1}\), respectively, for: Dandwa, Akuma (N alone), Akuma (N with 15 kg P ha\(^{-1}\) ), and Wenchi and Adidwan (overall) in Ghana; and for Mkinga (N alone) in Tanzania. Similarly, AE at 80 kg N ha\(^{-1}\) were 51, 123, 108, 81, and 121, respectively, for Dandwa, Akuma (N alone), Akuma (N with 15 kg P ha\(^{-1}\) ), and Wenchi and Adidwan (overall) in Ghana and for Mkinga (N alone) in Tanzania. The AE of N for linear yield responses in Kenya and Tanzania ranged from 107 to 125 kg kg\(^{-1}\). Cassava responses to P at Akuma and K at SY456 were linear (Table 2) and the AE were constant and indicated by the \(b\) coefficient. The AE for P at Akuma was 21.7 kg kg\(^{-1}\).

While the P rate effect was not significant, the significant N × P interaction in Tanzania occurred with enhanced response to N with 15 kg P ha\(^{-1}\) applied of 4.71 and 0.70 Mg ha\(^{-1}\) at Chambezi and Mkinga with the respective AE of P equal to 314 and 47 kg kg\(^{-1}\).

The VCR for N applied to cassava were >2 at all sites and for P and K at Akuma (Fig. 4). The higher VCR were obtained at low N rates and decreased with increasing N rate when there was a curvilinear response. Akuma had the highest VCR and Dandwa had the lowest VCR relative to other sites. The VCR for 20 kg N ha\(^{-1}\), when the cost per kilogram of N use was equal to the value of 12 kg of fresh cassava storage roots, were 5.3, 38.1, 16.4 and 13.9 $ $\text{kg}^{-1}$ for Dandwa, Akuma, and Wenchi and Adidwan in Ghana, and for Mkinga in Tanzania, respectively. At 80 kg N ha\(^{-1}\), the VCR were 4.2, 9.0, 10.1, and 16.4 $ $\text{kg}^{-1}$ for Dandwa, Akuma, Wenchi and Adidwan in

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**Table 2. Nutrient application effects on cassava fresh storage root yield by site-year (SY) in the study areas of Tanzania, Kenya and Ghana.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Tanzania</th>
<th>Kenya</th>
<th>Ghana†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>N</td>
<td>4</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>N × P</td>
<td>4</td>
<td>*</td>
<td>ns‡</td>
</tr>
<tr>
<td>N × SY</td>
<td>4</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>N × P × SY</td>
<td>4</td>
<td>*</td>
<td>ns</td>
</tr>
<tr>
<td>CV (%)</td>
<td>18.11</td>
<td>21.39</td>
<td>35.02</td>
</tr>
<tr>
<td>P §</td>
<td>3</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>P × SY§</td>
<td>3</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>K §</td>
<td>3</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>K × SY§</td>
<td>3</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Diagnostic§</td>
<td>1</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

† Trials in Ghana were analyzed as two groups due to heterogeneity of variance.
‡ ns, no significance.
§ These effects were tested with contrast comparisons.

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and was obtained with 80 kg N ha\(^{-1}\) applied but this yield did not differ significantly with the yield with 60 kg N ha\(^{-1}\).

In Tanzania, the mean yield with no fertilizer was 16.4 Mg ha\(^{-1}\) for Mkinga and 18.3 Mg ha\(^{-1}\) for Chambezi. The highest yields were 24.76 and 28.09 Mg ha\(^{-1}\) at 80 and 60 kg N ha\(^{-1}\) for Chambezi and Mkinga, respectively. Application of N, without and with 15 kg ha\(^{-1}\) P, increased storage root yields at both sites in Tanzania but the site × N × P and N × P interactions were significant (Table 2). The 3-way interaction was due to an asymptotic response to N alone at Mkinga but other responses to N were linear (Table 2). The magnitude of yield response to N was greater with 15 kg P ha\(^{-1}\) applied compared with 0 kg P ha\(^{-1}\).

Often the highest N rate was too low to achieve a curvilinear effect on cassava storage root yield as illustrated by the overall linear responses for Kenya and Tanzania (Fig. 2). The response of storage root yield to applied N, without and with 15 kg ha\(^{-1}\) P, for SY123 and SY456 in Ghana fitted asymptotic functions which were slightly curvilinear with low and declining slope as N rate increased with little added yield increase at N rates >80 kg ha\(^{-1}\).

Yield was affected by P rate and the SY × P interaction for SY456 in Ghana (Table 2). The P rate effects on yield were linear at Akuma, inconsistent at Wenchi, and not significant for other SY. Cassava storage root yield was affected by K rate and the K × site interaction for SY456 in Ghana but was not affected by K for the other sets of trials (Table 2). The SY × K interaction was due to no K effect at Akuma and contrasting effects at Wenchi and Dandwa (Table 4). The effects of K rate for SY456 fit a linear model.

The AE of applied N decreased with N rate when the yield response was curvilinear (Fig. 3). The AE of N was highest at Akuma and lowest at Dandwa as compared with other SY when N was applied alone. At 20 kg N ha\(^{-1}\), AE of N were 64, 458, 202, 196, and 167 kg kg\(^{-1}\), respectively, for: Dandwa, Akuma (N alone), Akuma (N with 15 kg P ha\(^{-1}\)), and Wenchi and Adidwan (overall) in Ghana; and for Mkinga (N alone) in Tanzania. Similarly, AE at 80 kg N ha\(^{-1}\) were 51, 123, 108, 81, and 121, respectively, for Dandwa, Akuma (N alone), Akuma (N with 15 kg P ha\(^{-1}\) ), and Wenchi and Adidwan (overall) in Ghana and for Mkinga (N alone) in Tanzania. The AE of N for linear yield responses in Kenya and Tanzania ranged from 107 to 125 kg kg\(^{-1}\). Cassava responses to P at Akuma and K at SY456 were linear (Table 2) and the AE were constant and indicated by the \(b\) coefficient. The AE for P at Akuma was 21.7 kg kg\(^{-1}\).
The yield increases due to applied N were 3.18, 6.63 and 7.47 Mg ha\(^{-1}\) in Ghana, Kenya, and Tanzania, respectively, with AE of 53, 110, and 124 kg kg\(^{-1}\). Cassava N response was expected in the study areas. All SY except for Alupe had <10 g kg\(^{-1}\) SOC indicating low N availability for cassava production (Table 1), especially since most SOC was expected to be in recalcitrant forms due to low annual return of organic materials to the soil. Previous studies conducted in Tanzania, Ghana and Kenya also associated cassava production with low SOC soils and increased storage root yield with N application (Shekiffu, 2011; Boateng, 2015; Fermont et al., 2009). However, SOC level was not associated with yield without N application and with response to N in the current study. The EOR for N were 35, 73 and >80 kg ha\(^{-1}\) at Akuma with 0 kg P ha\(^{-1}\), Ghana SY123, and for all other sites when the N cost was 12-fold the cassava storage root value ($ kg\(^{-1}\) --1). Linear N response at the other sites indicated indicating low N availability for cassava production (Table 1), especially since most SOC was expected to be in recalcitrant forms due to low annual return of organic materials to the soil. Previous studies conducted in Tanzania, Ghana and Kenya also associated cassava production with low SOC soils and increased storage root yield with N application (Shekiffu, 2011; Boateng, 2015; Fermont et al., 2009). However, SOC level was not associated with yield without N application and with response to N in the current study. The EOR for N were 35, 73 and >80 kg ha\(^{-1}\) at Akuma with 0 kg P ha\(^{-1}\), Ghana SY123, and for all other sites when the N cost was 12-fold the cassava storage root value ($ kg\(^{-1}\) --1). Linear N response at the other sites indicated
that the economically optimal N rate was beyond the range of the N levels evaluated. The AE for N were 279, 88, and 106 kg kg\(^{-1}\) at Akuma with 0 kg ha\(^{-1}\) P at EOR, Ghana SY123 at EOR, and for all other sites with 80 kg N ha\(^{-1}\) implying generally low efficiency and the likelihood that much applied N was lost. Urea-N was split applied with 50% applied each at 4 and 8 wk after sprouting of the cuttings. However, considering the often high soil sand content, especially in Tanzania, and the substantial rainfall in some months, leaching loss of nitrate N may have contributed to low AE. Assuming 5 mg P uptake per kilogram of fresh storage root, the fertilizer N recovery would be 60%. Therefore, delaying application of some of the urea N to 12 wk after sprouting of cuttings may have improved AE and recovery efficiency with more curvilinear responses to N.

The yield increase due to applied P ranged from 0 to 93%. Application of N with 15 kg P ha\(^{-1}\) resulted in more cassava storage root yield as compared with N with 0 kg P ha\(^{-1}\) in Tanzania and Ghana. Response to applied P was not related to Mehlich-3 P which ranged from 7.6 to 18.7 mg kg\(^{-1}\) suggesting that cassava is efficient in soil P uptake (Howeler, 2002). Vascular arbuscular mycorrhizae associations with cassava roots may have enhanced soil P uptake (Howeler, 2002; Grant et al., 2005).

Mehlich-3 K for the Ghana SY was above 0.08 to 0.18 cmolc kg\(^{-1}\) and deemed adequate for cassava production (Howeler, 2002), yet applied K gave significant storage root yield increase at Wenchi and Dandwa with an overall yield increase of 23% for SY456 (Table 4). For SY of SY456, the yield increase due to applied K ranged from 14 to 144%.

The nonsignificant mean yield increases due to applied secondary and micronutrients (S, Zn, Mg, and B) were 6% for Wenchi in Ghana and 11% for Tanzania. The low soil test Zn in Ghana and the low soil test B at Chambezi in Tanzania suggests a need for further investigation for these potential deficiencies with cassava and other crops.

Both AE and VCR of N decreased with increased N rate in cases of asymptotic responses as was expected. The VCR for N at all sites, P at the Tanzania sites, and P and K at Akuma were >2 and high enough that fertilizer N applied to cassava was likely to be highly competitive with other fertilizer use applications for other crops in terms of profit potential (Shekiffu, 2011; Tetteh et al., 2017; Kibunja et al., 2017; Senkoro et al., 2017).

**CONCLUSION**

Most of the soils in the study areas are characterized by low SOC and low to medium Mehlich-3 P and exchangeable K. Low soil Zn and B were also observed at sites in Ghana and Tanzania, respectively. Fertilizer N should be routinely applied for cassava produced on soils with <10 g kg\(^{-1}\) SOC with high profit potential for 60 kg N ha\(^{-1}\) and in other cases with 80 kg N ha\(^{-1}\). The rate of N application can be determined with reasonable confidence for each production area given that SY × N interactions accounted for little variation in yield. However, any determination of response functions from past research conducted under homologous growing conditions for any of these production areas should also be considered in determination of response functions for a recommendation domain. The N application practice should definitely involve split application but N use efficiency might be improved by delaying the second application to 12 wk after sprouting of planted cuttings or even do a 3-way split.
especially for sites with high sand content. Fertilizer P application for cassava in Tanzania can be profitable due to the synergy of N with P application but has a low probability of profitable response for other production areas. Application of K for cassava with typical storage root yields of less than 30 Mg ha\(^{-1}\) will generally not be profitable as responses that did occur were nearly as likely to be negative as positive. Application of Mg, S, Zn, or B also has low if any profit potential. Prediction of responses to applied nutrients from soil test values was not validated for the agroecological zones represented by this research. Cassava appears to have potential for adequate P and K uptake at low soil test levels. It is likely to be more profitable to apply P, except for the production areas in Tanzania, and K to other more responsive crops with cassava in rotation benefiting from the residual effects of these P and K applications.

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