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Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa

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Abstracts

Insufficient and unbalanced fertiliser use widens cassava yield gaps. We assessed the spatial variability of optimal fertiliser requirements of cassava for enhanced nutrient use efficiency and increased yield using the balanced nutrition approach of the QUEFTS model. Two datasets comprised of five fertiliser experiments conducted at eight locations across Southern Togo, Southern Ghana and Northern Ghana from 2007 to 2012 were used. The ratio of storage roots dry matter yield over the sum of available N, P and K expressed in crop nutrient equivalent from the soil and nutrient inputs was used as a proxy to estimate nutrient use efficiency. Nutrient use efficiencies of 20.5 and 31.7 kg storage roots dry matter per kilo crop nutrient equivalent were achieved at balanced nutrition at harvest index (*HI*) values of 0.50 and 0.65, respectively. N, P and K supplies of 16.2, 2.7 and 11.5 kg at an *HI* of 0.50, and 10.5, 1.9 and 8.4 kg at an *HI* of 0.65 were required to produce 1000 kg of storage roots dry matter. The corresponding optimal NPK supply ratios are 6.0 – 1.0 – 4.2 and 5.3 – 1.0 – 4.2. Nutrient use efficiencies decreased above yields of 77-93% of the maximum. Evaluation of the performance of blanket fertiliser rates recommended by national research services for cassava production resulted in average benefit:cost ratios of 2.4±0.9, which will be unattractive to many farmers compared to 3.8±1.1 for the balanced fertiliser rates. The indigenous soil supply of nutrients revealed that, at balanced nutrition, K was the most limiting nutrient to achieve storage roots yields up to 8 Mg dry matter ha^{-1} at most sites, whereas N and P were needed at greater yields. Dry weight of storage roots measured on the control plots in our researcher managed experiment ranged from 5.6 to 12.2 Mg ha^{-1}, and were larger than the average weight in farmers' fields in West Africa of 4 Mg ha^{-1}. Substantial yield increase could be attained in the region with improved crop management and fertiliser requirements formulation on the basis of balanced nutrition.

Keywords: QUEFTS, nutrient use efficiency, crop nutrient equivalent, nitrogen, phosphorus, potassium, harvest index.

1. Introduction

Cassava (*Manihot esculenta* Crantz) has long been considered a subsistence crop, but is becoming increasingly commercialised. The world production of fresh cassava storage roots increased tremendously from 176 to 277 million Mg between 2000 and 2013 (FAOSTAT, 2014). West Africa produces 28% of the world's cassava and the rest of Africa a further 26% (FAOSTAT, 2014). The increase in production was achieved through both expansion of the cultivated area and enhanced yields of cassava. Although average yields in West Africa increased between 2000 and 2013 from 9.7 to 13 Mg ha^{-1} of fresh storage roots (FAOSTAT, 2014), a large yield gap remains, given that yields close to 60 Mg ha^{-1} have been attained in researcher-managed fields in the region (Odedina et al., 2009).

Plausible reasons for this yield gap are nutrient limitations due to poor soil fertility. In general, fertiliser use on roots and tuber crops in Sub-Saharan Africa is negligible. However, nutrient removal for cassava production is on average 4.5 kg nitrogen (N), 0.83 kg phosphorus (P) and 6.6 kg potassium (K) per 1000 kg dry matter of storage roots (Howeler, 1991). The insufficient use of external nutrients leads to soil nutrients depletion (Howeler, 2002). Application of external fertilisers is necessary to replenish the soil with nutrients removed through harvested products and exported crop residues. The fertiliser recommendations for cassava production found in most countries in West Africa and elsewhere in SSA are usually blanket recommendations, regardless of agro-ecological or soil diversity. The use of blanket fertiliser recommendations for cassava production is likely to generate unbalanced crop nutrition since cassava is cultivated on diverse soils in West Africa, and soils on farmers' fields are highly heterogeneous (Adjei-Nsiah et al., 2007). Unbalanced nutrition may lead to increased nutrient losses (Cassman et al., 2002), which can hamper the productivity and profitability of the farm (Angus et al., 2004), and cause environmental pollution. Appropriate fertiliser recommendations based on balanced nutrition may contribute to reduce cassava yield gaps.

Balanced nutrition of a given nutrient refers to supplying that nutrient to the plant in accordance with the plant's need while maximizing the use efficiency of this nutrient. When more than one nutrient is considered, e.g. N, P and K together, balanced nutrition refers to the optimization of the use efficiency of these nutrients together giving the strongest response to their supply in congruence with plant needs. The term optimising is used given the difficulty of maximising the use efficiency of several nutrients simultaneously. The method developed by Janssen (Janssen, 1998; Janssen, 2011) can handle several nutrients simultaneously by assuming that balanced nutrition is achieved when the supplies of all nutrients expressed in crop nutrient equivalent (CNE) units are equal. As a unit, 1 kilo CNE (kCNE) or 1000 CNE of a nutrient is defined as the quantity of that nutrient that has the same effect on yield as 1 kg of N under conditions of balanced nutrition. The concept of CNE allows summing up the total supply of N, P and K and quantitatively describing balanced nutrition as the situation where the supplies of each of the three nutrients are equal. Both CNE and balanced nutrition concepts were also applied by Maro et al. (2014) for coffee production in Tanzania using QUEFTS model.

The model for the quantitative evaluation of the fertility of tropical soils (QUEFTS) (Janssen et al., 1990) accounts for the interaction between N, P and K to derive the balanced nutrition, which explains its widespread use in tropical agro-ecologies where these nutrients can seriously hinder crop production. Originally developed for maize (Janssen et al., 1992), QUEFTS has been also adapted to rice (Witt et al., 1999; Xu et al., 2013), wheat (Pathak et al., 2003; Chuan et al., 2013), highland banana (Nyombi et al., 2010) apart from coffee. Literature on the balanced nutrition of cassava is scarce, with only one case study from India (Byju et al., 2012). Site-specific fertiliser requirements for balanced nutrition of cassava in the region and their relative performance compared to existing blanket fertiliser rates have yet to be assessed. In this paper we assess the spatial variability in fertiliser requirements of cassava under balanced nutrition conditions in West Africa in order to increase nutrient use efficiency and yields.

2. Materials and methods

2.1 Field experiments

Two datasets, referred to as Set 1 and Set 2, were used in this study. Set 1 was collected in three field experiments at three locations in southern Togo (Davié), southern Ghana (Kumasi) and northern Ghana (Nyankpala, Table 1). The trials were laid out in a randomised complete block design (RCBD) with four blocks at each site containing 10 NPK fertiliser combinations (Table 2). N, P and K rates were defined in Set 1 to assess the indigenous supply of nutrients by the soil (S1, S3 and S5 in Table 2), as well as the response of the crop to different rates of fertilisers (other treatments). N was applied as urea (46%N, Davié and Kumasi) or sulphate of ammonia (21%N, Nyankpala), P as triple super phosphate (TSP: 20%P) and K as muriate of potash (MOP: 50%K). All TSP and one third of the urea and MOP were applied 4 weeks after planting, the remaining urea and MOP at 10 weeks after planting. Set 2 was collected in two other field experiments at five locations across southern Togo (Gbave, Davié Tekpo and Sevekpota) and northern Ghana (Gbanlahi and Savelugu) (Table 3) in agro-ecological zones that are similar to those in Set 1. Set 2 experiments comprised five NPK fertiliser combinations (Table 2). These fertiliser combinations were used to evaluate performance of the QUEFTS model in simulating yields in response to fertiliser applications. At each site, Set 2 experiments were laid out following a RCBD with four blocks in a single field, except for Sevekpota where seven farmers each harboured a single block (replication) of the full set of treatments. Fertilizer was applied in a similar way in both Set 1 and Set 2.

2.2 Description, parameterisation and verification of QUEFTS

The original QUEFTS model simulates crop yields in response to nutrient supplies following four steps (Janssen et al., 1990, Janssen and Guiking, 1990). In Step 1, QUEFTS estimates nutrient supplies from soil and inputs of organic materials or fertilizer. In Step 2, the actual uptake of a nutrient is calculated as a function of the total supply of that nutrient, and of the interaction with the two other macronutrients. In Step 3, two yields are calculated by the model for each nutrient uptake, one corresponding to a situation where the nutrient is maximally diluted in the crop, and another one corresponding to a situation of maximum accumulation of that nutrient. The relation between yield and nutrient uptake is indicated by the physiological nutrient use efficiency (*PhE*), which varies between *PhEmin* and *PhEmax*. *PhEmax* represents the situation where the nutrient is maximally diluted in the crop; *PhEmin* the situation of maximum nutrient accumulation. In Step 4, the yield is calculated for pairs of nutrients (*Y12*, yield in response to nutrient 1 with *PhEmin* and *PhEmax* of nutrient 2 as boundary conditions) denoted by *YNP*, *YNK*, *YPN*, *YPK*, *YKN* and *YKP* using the yield ranges defined in Step 3; the average yield of all pairs of nutrients is retained as the final yield estimate of the crop.

In this paper, the calculation of *Y12* was modified in two ways, as compared with the original QUEFTS version. Firstly, the value of the constant *r* representing the minimum nutrient uptake required to produce any grain yield in the equations relating yield (*Y*) to uptake (*U*) was assumed to be zero (Janssen et al., 1990). In our study, *U* was always large enough to produce a yield of cassava storage roots. The second modification refers to imposing a restriction that *Y12* does not exceed *YMAX* nor the minimum value of the yield at maximum dilution of N, P and K (*YdN*, *YdP*, *YdK*), as recently suggested by Sattari et al., (2014) and Maro et al. (2014). Thus, if *Y12* is greater than *YMAX*, or than *YdN*, *YdP or YdK*, the calculated *Y12* is replaced by the minimum value among *YMAX*, *YdN*, *YdP* and *YdK*. *YMAX* is the maximum yield dictated by radiation, water availability and genetic properties of the crop.

Data from Set 1 were used to derive *PhEmax* and *PhEmin* values for each nutrient (Table 4). *PhEmin* and *PhEmax* depend on harvest index (*HI*) (Sattari et al., 2014), which is the ratio of the weight of the economic plant component (grain for cereals, and storage roots in the case of cassava in this study) over the weight of the whole plant (total biomass including stems, leaves and storage roots). *PhEmax* and *PhEmin* were obtained using the following equations:

$$PhEmax = 1000 \text{ x } HI/(HI \times C_{min,roots} + (1 - HI) \times C_{min,tops}) \quad \text{(Equation 1)}$$

$$PhEmin = 1000 \text{ x } HI/(HI \times C_{max,roots} + (1 - HI) \times C_{max,tops}) \quad \text{(Equation 2)}$$

C_{min} and C_{max} are the minimum and maximum values of mass fractions (g kg^{-1}) in the roots ($C_{min,roots}$ *and* $C_{max,roots}$) and in the top biomass including stems and leaves ($C_{max,tops}$ and $C_{max,tops}$). C_{min} and C_{max} values of 2.5 and 6.6 for N, 0.8 and 1.5 for P and 2.8 and 11.0 g kg^{-1} for K in the storage roots, and 7.9 and 17.9 for N, 0.9 and 2.8 for P and 3.4 and 18.8 for K in the tops obtained from Set 1 were used.

Set 2 data were used to test the model's ability to estimate observed yields. Soil supplies of available N, P and K (*SAN*, *SAP* and *SAK*) used as input data for model testing are presented in Table 5. In Set 1 dataset, *SAN*, *SAP* and *SAK* were calculated as the intercept of the linear regression between the maximum total uptake of the relevant nutrient and the nutrient application rate. The slope of this regression line was considered the maximum recovery fraction (*MRF*), indicating the proportion of the fertiliser nutrient taken up by the crop. Since no plant chemical data were measured in Set 2 experiments, *SAN*, *SAP* and *SAK* values were estimated by the model from control plots (S10 and S15 in Table 2) at each site. *SAN*, *SAP* and *SAK* values obtained in Set 1 experiments were used as starting values. These starting values were subsequently adjusted until good agreements were found between simulated and observed yields on the control plots. After *SAN*, *SAP* and *SAK* values were obtained for Set 2 sites, the model's ability to estimate cassava yield in response to fertilizer applications was evaluated with treatments that did receive fertilizer in Set 2 experiments (S11-14 and S16-19, Table 2). This was first implemented with the average *MRF* values derived from Set 1 experiments (Table 5). In following runs, *MRF* values were adjusted per site to achieve good agreement between observed and QUEFTS calculated yields (Table 5). This adjustment of *MRF* values was implemented to check the need of site-specific *MRF* values and its influence on the model's performance.

2.3 Determination of balanced nutrition

The prerequisite for balanced nutrition assessment is the conversion of kg of N, P and K into crop nutrient equivalent (CNE), assuming that balanced nutrition is achieved when the supplies of these nutrients, expressed in CNE , become equal to each other. The conversion is based on the average or medium value of *PhE* denoted by *PhEmed*. *PhEmed* equals *(PhEmax +PhEmin)/2*. Since 1 kilo CNE (1 kCNE) of a nutrient is the quantity of that nutrient that has the same effect on yield as 1 kg of N under conditions of balanced nutrition, 1 kCNE equals 1 kg N. Conversion factors for P and K (*CFP* and *CFK*) were calculated using the ratio of *PhEmed* of N and *PhEmed* of P or K: *CFP* = *PhENmed/PhEPmed,* and *CFK* = *PhENmed/PhEKmed*. Hence, 1 kCNE of P (kCNEP) equals CFP kg P, and 1 kCNEK equals CFK kg K. In Set 1 experiment for instance, at *HI* = 0.50, 1kCNEP = 0.167 kg P, and 1kCNEK = 0.706 kg K (Table 4).

Total available N, P and K (*TAN*, *TAP* and *TAK*) were calculated by summing up available nutrients supplied by the soil and external fertiliser input ($TAN = SAN+MRFN \times I_N$; $TAP = SAP+MRFP \times I_P$; $TAK = SAK+MRFK \times I_K$, with *MRFN*, *MRFP* and *MRFK* standing for the maximum recovery fractions of N, P and K fertilisers applied and I_N, I_P and I_K for the respective amounts of fertilisers applied) and converted into CNE.

Cassava storage roots yields were calculated using the QUEFTS model for the following situations:

1. Without external nutrient applications. In this situation, *TAN, TAP* and *TAK* equals the soil supply of available N, P and K (*SAN, SAP* and *SAK*, Table 5). This is generally an unbalanced nutrient supply situation since nutrients are available in different proportions and quantities in the soil, resulting in unequal quantities of *TAN*, *TAP* and *TAK* as expressed in CNE.

2. Balanced nutrition situation at which *TAN* = *TAP* = *TAK* (as expressed in CNE): from the unbalanced nutrition situation, the balanced nutrition is reached by adding required quantities of fertiliser input (*I*) that raise the smallest amounts of available nutrients among *TAN*, *TAP* and *TAK* to the level of the largest amount in CNE. For instance, if *TAN*, *TAP* and *TAK* were 75, 25 and 40 kCNE, respectively, we need to increase TAP by 50 kCNE and *TAK* by 35 kCNE by adding P and K fertilisers to reach the level of *TAN*, hence attaining the balanced nutrition with *TAN* = *TAP* = *TAK* = 75 kCNE. The sum (*TAN*+*TAP*+*TAK*), denoted by ΣA, is then 225 kCNE.

3. From the situation of balanced nutrition (*TAN* = *TAP* = *TAK*), identical quantities of available nutrients from input fertilisers (*MRF* x *I*), expressed as CNE, are continuously and simultaneously added to *TAN*, *TAP* and *TAK* until the maximum yield (*YMAX*) is approached.

By plotting calculated yields (*Y*) against ΣA, a curve is obtained that is used for estimating optimal nutrient use efficiency at balanced nutrition. The slope of the linear part of this curve ($Y/\Sigma A$) is used as proxy of the optimal nutrient use efficiency of the three nutrients, which is expressed in storage roots DM per kCNE.

2.4 Assessing nutrient supply and fertiliser requirements for different target yields

At balanced nutrition, yield calculated by QUEFTS is α% of the product of *PhEmed* and ΣA expressed as CNE, where α is smaller than, but close to 100%. That α is smaller than 100% as the result of the procedure used for the calculation of *Y12* (see section 2.2). As a consequence, the maximum yield per kCNE of available N, P and K is α% of the product of *PhEmed* and ΣA.

For a certain target yield (*TgY*, Mg ha^{-1}), the required supply of available nutrient (*TgA*) can be calculated as follows:

$$TgA = (TgY/PhEmed)/\alpha \qquad \text{(Equation 3)}$$

TgA is expressed in kCNE and *PhEmed* in kg storage roots DM per kCNE of a given nutrient.

If *TgA* for N (*TgAN*) is more than the soil supply of available nitrogen (*SAN*), the target input of available nitrogen (*TgIAN*) is:

$$TgIAN = TgAN - SAN \qquad \text{(Equation 4)}$$

The target inputs of available P and K can be found as $TgIAP = TgAP - SAP$ and $TgIAK = TgAK - SAK$. Because *TgIAN*, *TgIAP* and *TgIAK* are expressed in kCNE, they must for practical agriculture be converted into kg; this is done by multiplying them by their respective conversion factors for a given *HI* (Table 4). *SAN*, *SAP* and *SAK* values used are presented in Table 5. At balanced nutrition, the values of both *TgAP* and *TgAK* expressed in CNE are equal to those of *TgAN*.

Only a fraction of the applied N, P and K, at most the maximum recovery fraction of N, P and K (*MRFN*, *MRFP*, *MRFK*), is available to the crop. Assuming the recovery fraction is optimal for the three nutrients at balanced nutrition, the total required inputs of N, P and K (*RIN*, *RIP* and *RIK*) expressed in kg are calculated as:

$$RIN = TgIAN/MRFN \qquad \text{(Equation 5)}$$

$$RIP = CFP \times TgIAP/MRFP \qquad \text{(Equation 6)}$$

$$RIK = CFK \times TgIAK/MRFK \qquad \text{(Equation 7)}$$

For *MRFN*, *MRFP* and *MRFK*, we used the average values of 0.50, 0.21 and 0.49, respectively obtained in Set 1 experiments to facilitate the comparison among sites.

2.5 Data analysis and economic assessment

The performance of the QUEFTS model used was first assessed by comparing simulated with observed yields using different indicators: the Normalised Root Mean Squared Error (*NRMSE)* (Loague and Green, 1991), the slope of the regression line between measured and simulated values, the Pearson coefficient of correlation (r) and the probability of the correlation (P value at 0.05). The calculated fertiliser rates at balanced nutrition were compared to existing national blanket fertiliser recommendations, referred to as blanket rates. This comparison was implemented based on the values of nutrient use efficiency ($Y/\Sigma A$), of the relative NPK availability over the sum of available nutrients (ΣA) and of the fertiliser nutrient requirements. Furthermore, a profitability analysis was conducted by calculating the gross revenues, costs and benefit:cost ratios (BCR) of the two types of fertiliser recommendations. Gross revenues were obtained as the product of the unit price of fresh storage roots at farm gate and fresh yields per site. Costs included fertiliser costs only and were calculated as fertiliser unit price multiplied by the quantity of fertiliser applied. No transportation nor application cost were considered. The BCR values were calculated by dividing the increase in gross revenue due to fertiliser application by the fertiliser costs. The increase in gross revenue due to fertiliser application is the difference between the gross revenue with fertiliser application and that of the control (no fertiliser application). National average values ± standard deviation of fertiliser prices were used: 1.72 ± 0.10 USD kg^{-1} N, 3.48 ± 0.37 USD kg^{-1} P and 1.82 ± 0.19 USD kg^{-1} K in Togo (average monthly fertiliser prices, October 2011 to January 2015, africafertilizer.org), and 1.05 ± 0.19 USD kg^{-1} N, 2.62 ± 0.64 USD kg^{-1} P and 1.37 ± 0.34 USD kg^{-1} K in Ghana (average of monthly fertiliser prices, June 2010 to October 2014, africafertilizer.org). Fresh storage roots prices at farm gates of

0.118 ± 0.040 USD kg^{-1} in Togo (annual average values, 2000 to 2014, CountrySTAT (2015)) and 0.051 ± 0.024 USD kg^{-1} in Ghana were considered (annual average values, 2005 to 2012, CountrySTAT (2015)). Three scenarios were compared for the economic evaluation of the recommended and the balanced fertiliser rates: i) Scenario 0: average fertiliser price and average fresh storage roots price; ii) Scenario 1: maximum fertiliser prices and minimum storage roots price; iii) Scenario 2: the same fertiliser prices as Scenario 1 but with maximum storage roots price. The minimum and maximum prices refer to the average price minus and plus the standard deviation, respectively.

3. Results

3.1 QUEFTS model performance

Simulated storage roots yields were in good agreement with the measured yields on fertilised plots in Set 2 sites for a common average *MRF* for NPK of 0.50 – 0.21 – 0.49 (Fig. 1a). The slope of the regression line between simulated and observed yields was 0.84, with a strong positive correlation ($r = 0.80$; $P < 0.001$), and an acceptable *NRMSE* of 0.21, indicating that root mean squared errors represented 21% of the average observed yield. Model performance was further improved by using site-specific *MRF* values (Fig. 1b) resulting in a smaller NRMSE (0.10), a regression line slope (0.96) closer to 1 and a stronger positive correlation ($r = 0.93$; $P < 0.001$) between simulated and observed yields.

3.2 Relations between yield and nutrient supply at balanced nutrition

The relation between yield and nutrient supply from soil and inputs is depicted in the curves of yield (*Y*) versus the sum of available nutrients (ΣA) for the varieties Gbazekoute and Afisiafi (Fig. 2). The slopes of the linear part of the two curves are different because the two cultivars have different harvest indices (*HI*) and hence different values for *PhEmax* and *PhEmin* (Table 4).

In the two Y versus ΣA curves (Fig. 2), four sections can be distinguished for the common situation that soil available N, P and K (*SAN*, *SAP* and *SAK*) are not balanced. Since the values of the soil available nutrient do not affect nutrient use efficiency determined at balanced nutrition, *SAN*, *SAP* and *SAK* were arbitrarily set at 150, 84 and 28 kCNE ha^{-1}, giving a sum of 262 kCNE ha^{-1}. This represents an unbalanced situation, where K is the most limiting nutrient, followed by P. A balanced nutrition was reached by supplying first K, then P to achieve the same quantity as the supply of available N expressed in CNE. In Section 1i of Fig. 2 (with Section 1i-a for Gbazekoute and Section 1i-b for Afisiafi), only the most limiting nutrient K was applied, increasing *TAK* (supply of K from soil and input) from 29 to 84 kCNE ha^{-1}, which equals the value of *SAP*. In Section 1ii (Fig. 2), the most limiting two nutrients (K and P) are added in balanced proportions. At the border between Section 1ii and Section 2, both *TAK* and *TAP* have increased to the level of *SAN*, which is 150 kCNE ha^{-1}. Hence, here ΣA is three times 150 equalling 450 kCNE ha^{-1}. The second section of Fig. 2 is a straight line representing balanced nutrition, with equal input of available nutrients expressed as CNE. The third section of the graph is curvilinear. At the border between Section 2 and Section 3, the estimated storage-roots yield (*YE*) is 22.4 Mg dry matter (DM) ha^{-1} for cultivar Gbazekoute, and 20.7 Mg DM ha^{-1} for Afisiasi, which is 93 and 86% of *YMAX*, respectively. The fourth section of the graph is a plateau where Y equals *YMAX* (set at 24 Mg storage roots DM ha^{-1}). Further inputs of nutrients do not increase yield, but only the nutrient mass fractions of the crop components.

The regression lines for Section 2 (Fig. 2) have the same slopes ($Y/\Sigma A$) as the lines for balanced nutrition, drawn between the origin and the border of Sections 1ii and 2. These lines differ between the two varieties: 20.5 and 31.7 kg DM yield / kCNE for Gbazekoute and Afisiasi respectively. Further simulations showed that changing the starting value of *SAN*, *SAP* and *SAK* did not change these balanced nutrition slopes (not shown). Simulations also showed that the linear part of the graph (Section 2, Fig. 2) ends at 77-93% of *YMAX* with various values of *YMAX* (16 to 24 Mg DM ha^{-1} for *SAN*, *SAP* and *SAK* values of 150, 84 and 28 kCNE ha^{-1}) (not shown). Above this target yield threshold of 77-93% *YMAX*, the slope rapidly decreases (Section 3, Fig. 2).

The slope of the regression lines for Section 2 was used as a proxy to estimate nutrient use efficiency. The values of 20.5 and 31.7 kg storage roots DM per kCNE correspond to the supply (from soil and input) of 16.2 kg N, 2.7 kg P and 11.5 kg K to produce 1000 kg storage roots DM of Gbazekoute and 10.5 kg N, 1.9 kg P and 8.4 kg K for Afisiafi. The resulting optimal NPK supply ratios are 6.1 – 1.0 – 4.2 and 5.3 – 1.0 – 4.2 for Gbazekoute and Afisiafi, respectively.

3.3 Fertiliser requirements for different target yields at the experimental sites

At balanced nutrition, yield calculated by QUEFTS was 90-91% (α) of the product of *PhEmed* and ΣA. For Gbazekoute, *PhEmed* of N equals 68.5 kg DM per kCNE of N, or 22.8 kg DM per kCNE of ΣA. The maximum value of $Y/\Sigma A$ (Fig. 2) is 20.5, which is 90% of 22.8. For Afisiasi, *PhEmed* of N equalled 104.5 per kCNE of N, or 34.8 kg per kCNE of ΣA. The maximum value of $Y/\Sigma A$ (Fig. 2) is 31.7, which is 91% of 34.8.

Table 6 presents additional plant needs of N, P and K for different target yields at balanced nutrition, as calculated with Equations 3 to 7, with α set at 90% for a range of sites in Togo and Ghana. Nutrient requirements varied between target yields and sites. K was the nutrient most in demand at all sites in Togo at target yields of 8 and 12 Mg ha^{-1}. N and P were required to supplement indigenous soil nutrient supplies at larger target yields: 12 Mg ha^{-1} at Davié, Sevekpota White Soil and Sevekpota Red Soil, and 16 Mg ha^{-1} at Gbave and Sevekpota Black Soil. At the sites in Ghana, no nutrient input was needed to achieve 8 Mg ha^{-1} since simulated yields without fertiliser application were larger than or equal to 8 Mg ha^{-1} (8.0 Mg ha^{-1} at

Gbanlahi, 9.0 Mg ha^{-1} at Kumasi, 9.4 Mg ha^{-1} at Nyankpala and 12.4 Mg ha^{-1} at Savelugu). N was most needed at larger target yields at Nyankpala, Gbanlahi and Savelugu. At Kumasi, both N and K were limiting with target yields from 12 Mg ha^{-1}.

3.4 Performance of recommended blanket fertiliser rates

The recommended blanket fertiliser rates (blanket rates) for cassava in Togo and Ghana did not provide balanced proportions of N, P and K at most sites (Table 7). $Y/\Sigma A$ ratios achieved with these blanket rates were in general smaller than those of the site-specific balanced nutrition (referred to as balanced rates). This result implies that fertiliser application based on balanced nutrition leads to larger yield increases per unit of fertiliser applied than the blanket rates. Blanket rates in Southern Togo supplied too much N and too little K as revealed by the proportion of these nutrients over ΣA (Table 7). In Ghana, blanket rates supplied too much K and too little P, except in Kumasi. Fertiliser requirements calculated at balanced nutrition were different to the blanket rates to attain the same yields as simulated for the blanket rates (Table 7). One exception, however, was Kumasi where the blanket rate provided the $Y/\Sigma A$ ratio required at balanced nutrition. The variation in fertiliser requirements from site to site indicates large differences in soil fertility, which is confirmed by the variation in yields obtained without fertiliser at these sites (Table 7).

The economic analysis of the recommended and balanced fertiliser rates (Table 8) revealed a larger benefit of the balanced rates over recommended rates in terms of costs of fertilisers and benefit:cost ratio (BCR) ($P < 0.001$). BCR of the balanced fertiliser rates were 1.1 to 2.0 times greater than those of the blanket rates, except in Kumasi where similar BCR values were obtained. Average BCR values of 2.4±0.9 and 3.8±1.1 were obtained for the blanket rates and the balanced rates, respectively, when average unit prices of fertiliser and of fresh storage roots (Scenario 0) were considered. BCR values were sensitive to fluctuations in fertiliser and fresh storage roots prices. The worst case scenario was the drop in BCR values caused by an increase in fertiliser prices on the market and a reduction in farm-gate prices of storage roots (Scenario 1). The best scenario for farmers consisted of a reduction in fertiliser prices and an increase in storage roots farm-gate prices (Scenario 2).

4. Discussion

We obtained optimum nutrient use efficiencies of 20.4 and 31.4 kg storage roots dry matter per kCNE supplied for Gbazekoute and Afisiafi cultivars, respectively (Fig. 2). This implies that supplies of 48.9 and 31.8 kCNE are required to produce 1000 kg of cassava storage roots DM. These values are equivalent to 16.3 kg N, 2.7 kg P and 11.3 kg K and 10.6 kg N, 2.0 kg P and 8.3 kg K for the production of 1000 kg storage roots DM of Gbazekoute and Afisiafi, respectively. The cultivar Afisiafi had a relatively high nutrient use efficiency, but it is difficult to attribute this to the cultivar itself or to site effects, since cultivar and location of the trials were confounded. It follows from Equations 1 and 2 that nutrient use efficiencies increase with *HI*. Afisiafi had higher average *HI* (0.65) than Gbazekoute (0.50). N supply was especially high at Davié where Gbazekoute was grown, and large N uptakes may have resulted in a relatively small *HI* through large top biomass production at the expense of storage roots (Howeler, 2002). Therefore, differences in nutrient use efficiencies obtained may be attributed more to differences in *HI* rather than cultivar differences.

The optimal NPK supply ratios simulated at balanced nutrition are 6.1 – 1.0 – 4.2 at *HI* 0.50 (Gbazekoute) and 5.4 – 1.0 – 4.2 at *HI* 0.65 (Afisiafi). Expressed in N-P_2O_5-K_2O, these are 2.7 – 1.0 – 1.8 and 2.4 – 1.0 – 1.8 at *HI* 0.50 and 0.65, respectively. These ratios are quite similar to the ratios of 2 – 1 – 2 or 2 – 1 – 3 reported by Fermont (2009) for inorganic fertiliser recommendations in East Africa. However, the supply in these latter ratios refers to fertiliser only, whereas in our study it refers to fertiliser as well as the soil supplies of nutrients.

The calculated optimal fertiliser nutrient requirements increased with target yields and varied between sites (Table 6). At all sites in Togo, K was the most limiting nutrient for cassava production, especially at a target yield of 8 Mg ha^{-1} storage roots DM. This indicates that K deficiencies are important and probably widespread in Southern Togo, especially on the Ferralsols (Davié, Davié Tekpo and Gbave). Carsky and Toukourou (2005) also reported K deficiencies in cassava production systems on Ferralsols in Southern Benin. However, K deficiency is not limited to Ferralsols only. This issue can arise in the long term in any other soil where cassava production is practised frequently with insufficient supply of external K fertiliser because cassava extracts more K than any other nutrient from the soil (Hillocks et al., 2002). Therefore, K management should be optimised to ensure good yields. K deficiency was less obvious on the Ghana sites, especially at Nyankpala, Gbanlahi and Savelugu indicating a good supply of this nutrient from the soil. N was the most needed nutrient at these sites. The small soil organic carbon (SOC) content (4.3 g kg^{-1}) and the high exchangeable K content (3.1 mmol kg^{-1}) of the Nyankpala soil support this conclusion. Unfortunately, no soil chemical analysis data are available for Gbanlahi and Savelugu sites.

We observed that blanket fertiliser rates were in general unbalanced (Table 7). The rates of 76 kg N, 13 kg P and 25 kg K ha^{-1} in Southern Togo and of 68 kg N, 20 kg P and 57 kg K ha^{-1} in Ghana were rather different from the site-specific optimal needs of input that we calculated for the same target yields. The blanket rate of Ghana was quite balanced and suitable for use in Kumasi only. A key reason for this difference between the performance of the blanket rates and the calculated optimal nutrient needs is the difference in soil fertility among these sites, as reflected by the difference in measured yields without fertiliser application (Table 7) and in indigenous soil supplies (Table 5). The application of blanket rates irrespective of indigenous soil nutrient supplies not only leads to less yield, but is also likely to generate nutrient losses where the applied nutrient is not needed. Nutrient losses will be prominent for instance for N in southern Togo, and K in Northern Ghana where those nutrients were not limiting yet, if blanket rates of fertiliser were used. The application of blanket rates irrespective of plant needs also leads to lower returns to investments in fertiliser. An average BCR value of 2.4±0.9 obtained at blanket fertiliser rates will be less attractive to farmers than a BCR of 3.8±1.1 achieved at balanced fertiliser rates. The sub-optimal economic performance at blanket rates can discourage farmers to invest in fertiliser use for cassava production.

External P fertiliser supply requirements were fairly small at a target yield of 8 Mg ha^{-1} across all sites, even at Davié, Kumasi and Nyankpala, which have soils with small concentrations of available P (3-5 mg kg^{-1}). Cassava is efficient at capturing soil P at small concentrations through vesicular mycorrhizal symbiosis (Kang and Okeke, 1984; Sieverding and Leihner, 1984)

In summary, with the exception of K in southern Togo sites, no external fertiliser is required to produce 8 Mg storage roots DM ha^{-1}, which is twice the current average yield in West Africa. The simulation results are supported with the assumption of improved crop management practices including planting healthy cuttings, planting on time, maintaining well the plot with weeding, and a good control of pest and diseases. Yields measured under improved management conditions on our fields experiments without fertiliser applications (5.6 – 12.2 Mg ha^{-1}; Table 7) were by far superior to the national average yields in farmers' fields of 2.2 and 4.9 Mg ha^{-1} storage roots DM in Togo and Ghana (FAOSTAT, 2014), assuming a DM content of 36% in the fresh roots. This suggests that substantial increase of cassava storage roots yields could be achieved in the region by promoting good crop management practices. However, the positive effect of good management practices can be undermined by drought. This was the key reason for the relatively poor yield in Nyankpala compared with the other sites in Ghana. External P as well as external N fertiliser requirements arose at or beyond target yields of 12 Mg ha^{-1}.

These findings apply to sole cassava which generally provides larger yields compared with intercropped cassava. Apart from yields, nutrients requirements of cassava may be different in the intercropping system due to competition for nutrients, water and light with the intercrop. N deficiency can be exacerbated in Northern Ghana when cassava is intercropped with cereals without applying external N fertilisers (Carsky et al., 2001). Legume integration (intercrop or rotation crop) in such systems can reduce the need for external N fertilisers through atmospheric nitrogen fixation, although legumes need sufficient P for adequate growth and symbiotic N_2-fixation (Giller and Cadisch, 1995). Since intercropping cassava with cereals and or legumes is common in West Africa, further research is needed to determine the balanced nutrition needs of intercropping systems.

The formulation of site-specific fertiliser recommendations based on optimal NPK supply ratios requires a good assessment of (indigenous) soil nutrient supplies and of fertiliser recovery fractions. Nutrient omission trials are the best way to quantify indigenous soil nutrient supplies (Dobermann et al., 2002). Nevertheless, in the absence of data on indigenous soil nutrient supplies, yields from farmers' plots without fertiliser application can be used to estimate them, preferably when good management of these plots was carried out (planting of healthy cuttings at the right time, at the recommended planting density, providing good weed and pest control, etc.) and rainfall amount and distribution was reasonable. In general, soil nutrient supply determined from farmers' plots yields without fertiliser application are smaller than the potential soil nutrient supply values expected from nutrient omission trials. In Set 1, the measured soil supply of nutrients was on average 1.3, 1.6 and 1.2 times as large, for N, P and K, respectively in the nutrient omission plots (treatments S1, S3 and S5 for zero N, zero P and zero K in Table 2) compared with the control plots (S0) (not shown). These multiplication factors are indicative of the relevance to correct for the estimates of soil supply of nutrients derived from farmers' plots yields without fertiliser applications. When yields on plots without fertiliser application and the harvest index are known, the estimate of actual soil nutrient supply can be performed using the reciprocal nutrient supply efficiency, which is the nutrient supply requirement to produce 1 Mg ha^{-1} of storage roots DM. In this study, this reciprocal nutrient supply efficiency was (16.3 kg N, 2.7 kg P and 11.3 kg K for HI = 0.50 and 10.6 kg N, 2.0 kg P and 8.3 kg K for HI=0.65). For other values of HI, the reciprocal nutrient supply efficiency (1000/$PhEm$) can be derived from Equations 1 and 2. Fertiliser recovery fractions (*MRF*) are sometimes assessed in any fertiliser trial comprising a treatment without fertiliser. But this leads to an overestimation of *MRF*. *MRF* are ideally estimated in nutrient omission trials. On the sites of our own trials (Set 1), *MRF* values varied between 33 – 69% for N, 3 – 44% for P and 10 – 100% for K with average values of 50% for N, 21% for P and 49% for K (Table 5). In the same trials, the indigenous soil supplies ranged between 74 – 250 kg N, 15 – 34 kg P and 48 – 136 kg K ha^{-1} (Table 5). These wide ranges of *MRF* and indigenous soil supplies emphasise the need of site-specific fertiliser recommendations for cassava production. However, it will be unrealistic to provide unique fertiliser recommendations to individual farmers or fields, especially to smallholder farmers who generally do not have financial capacity to pay for plant and soil chemical analyses. Another key challenge is that single fertilisers, which allow a farmer to apply exactly the estimated required amount of nutrients, are generally more expensive compared with standard blended fertilisers (NPK: 15-15-15 for instance), except for urea that costs often as much as (subsidised) blended fertiliser in West Africa. Fertiliser recommendations on the basis of major soil types and agro-ecological zones can be more practical than recommendations for individual farms. This could also increase the demand of specific fertiliser nutrients on the input market and result in more affordable fertiliser prices for farmers. The assessment of nutrient supplies per major soil type in main cassava production agro-ecological zones and the balanced nutrition approach used in this study will be useful for formulating soil type and agro-ecologically specific fertiliser recommendations for enhanced cassava production in West Africa.

5. Conclusions

The QUEFTS model proved useful to assess balanced nutrition, to derive optimum fertiliser requirements for target yields and to explore diversity among sites in West Africa. We showed how the use of balanced fertiliser rates following NPK supply ratios of 6.1 – 1.0 – 4.2 at *HI* of 0.50 and 5.4 – 1.0 – 4.2 at *HI* of 0.65 enhanced nutrient use efficiency of NPK and increased value to cost ratios compared with recommended blanket rates. We found that K is the most needed nutrient to achieve a target yield of 8 Mg ha^{-1} of storage roots DM, especially on the Togo sites. The need for N and P fertiliser inputs became necessary at larger target yields on most sites. These results suggest that good management practices are key to substantial improvement of cassava production below a target yield of 8 Mg ha^{-1}, and that external nutrients are needed to produce beyond a target yield of 12 Mg ha^{-1} depending on the indigenous soil fertility status of the soil. The variation in indigenous soil fertility status and in nutrient input needs highlighted a key disadvantage of recommended blanket rates. Shifting from these blanket rates to soil or agroecologically specific recommendations will be a great accomplishment towards enhancing nutrient use efficiency and yields in cassava production systems in West Africa, in addition to promoting good management practices.

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Table 1. Characteristics of the sites in the Set 1 experiments

Site	Davié	Kumasi	Nyankpala
Country, district	Togo, Maritime Region	Ghana, Ashanti Region	Ghana, Northern Region
Geographic coordinates	6.385° N, 1.205°E	6.686° N, 1.622° W	9.396°N, 0.989°W
Altitude (m above sea level)	89	267	170
Soil type	Rhodic ferralsol	Ferric acrisol	Gleyi-ferric lixisol
Agro-ecological zone	Coastal Savannah	Humid Forest	Southern Guinea Savannah
Rainfall distribution	Bi-modal	Bi-modal	Mono-modal
Season* 1	May 10-March 17, 2007-2008	June 28–March 22, 2008-2009	June 29 - Feb. 25, 2007-2008
Season 2	April 26– Feb. 23, 2008-2009	June 15–March 15, 2009-2010	May 23 - Dec. 03, 2008
Rainfall (mm, seasons 1 and 2)	731, 813	986, 938	731, 1017
Cultivar	Gbazekoute**	Afisiafi**	Afisiafi
Planting density (per stem cutting)***	0.8 x 0.8 m	1 x 1 m	1 x 1 m

* Season refers to the period from planting to harvest of the crop

** Gbazekoute is TMe-419; Afisiafi is TMe-771.

*** Planting schemes follow the recommended densities for cassava in the study sites. These correspond to 15625 and 10000 plants ha^{-1}, respectively for 0.8 x 0.8m and 1 x 1m.

Table 2. Fertiliser rates applied in Set 1 and 2 experiments.

Experiment	Location	Treatment number	N	P	K
			(kg ha^{-1})		
Set 1	Davié, Kumasi & Nyankpala	S0	0	0	0
		S1	0	40	130
		S2	40	40	130
		S3	80	0	130
		S4	80	20	130
		S5	80	40	0
		S6	80	40	65
		S7	80	40	130
		S8	40	20	65
		S9	100	50	170
Set 2	Gbave, Davié-Tekpo and Sevekpota	S10	0	0	0
		S11	20	10	80
		S12	40	20	65
		S13	60	25	120
		S14	100	40	150
	Savelugu and Gbanli	S15	0	0	0
		S16	48	0	95
		S17	68	28	155
		S18	82	28	155
		S19	98	55	183

Table 3. Characteristics of the sites in the Set 2 experiments.

Site	Gbave	Davié Tekpo	Sevekpota	Gbanlahi	Savelugu
Country, district	Togo, Maritime Region	Togo, Maritime Region	Togo, Maritime Region	Ghana, Northern Region	Ghana, Northern Region
Geographic coordinates	6.459° N, 1.586°E	6.385° N, 1.205°E	6.437° N, 0.959°E	9.436°N, 0.755°W	9.641°N, 0.840°W
Altitude (m above sea level)	80	89	121	159	156
Soil type	Rhodic ferralsol	Rhodic ferralsol	Alfisol	Gleyi-ferric lixisol	Gleyi-ferric lixisol
Agro-ecological zone	Coastal Savannah	Coastal Savannah	Coastal Savannah	Southern Guinea Savannah	Southern Guinea Savannah
Rainfall distribution	Bi-modal	Bi-modal	Bi-modal	Mono-modal	Mono-modal
Season (Planting to harvest)	April 26, 2010 to March 22, 2011	April 26, 2010 to March 22, 2011	April 26, 2010 to March 22, 2011	June 21, 2011 to Dec 18, 2012	June 22, 2011 to Dec 12, 2012
Rainfall during the season (mm)	1017	1039	845	1920	1920
Cultivar	Gbazekoute	Gbazekoute	Gbazekoute	Afisiafi	Afisiafi
Planting density (per stem cutting)	0.8 x 0.8 m	0.8 x 0.8 m	0.8 x 0.8 m	1 x 1 m	1 x 1 m

Table 4. Harvest index (*HI*), physiological nutrient use efficiency for maximum accumulation (*PhEmin)* and maximum dilution (*PhEmax)*, and the conversion factors for P (CFP) and K (CFK) used in model calculations for two cultivars (Gbazekoute and Afisiafi) in Set 1 and Set 2 experiments.

Cultivar	*HI*	*PhEmin*			*PhEmax*			*PhEmed*			CFP	CFK
		N	P	K	N	P	K	N	P	K		
Gbazekoute-Set 1	0.50	41	232	34	96	589	160	69	411	97	0.167	0.706
Gbazekoute-Set 2	0.55	47	262	38	112	653	178	80	458	108	0.174	0.736
Afisiafi-Set 1	0.65	61	329	47	148	782	214	105	556	131	0.188	0.801
Afisiafi-Set 2	0.70	70	365	53	170	848	233	120	607	143	0.198	0.839

Table 5. Soil supply of available N, P and K (*SAN*, *SAP* and *SAK* in kg ha^{-1}) and maximum recovery fractions (*MRFN*, *MRFP* and *MRFK*).

Dataset	Sites	*SAN*	*SAP*	*SAK*	*MRFN*	*MRFP*	*MRFK*
Set 1	Davié	177	24	70	0.69	0.44	1.05
	Kumasi	94	21	65	0.33	0.15	0.10
	Nyankpala	86	18	104	0.49	0.03	0.33
	Average				***0.50***	***0.21***	***0.49***
Set 2	Gbave	170	23	67	0.95	0.60	0.95
	Davié Tekpo	250	34	99	0.95	0.60	0.95
	Sevekpota Black Soil	186	25	74	0.69	0.44	0.80
	Sevekpota White Soil	122	17	48	0.81	0.51	0.80
	Sevekpota Red Soil	147	20	58	0.69	0.44	0.80
	Gbanlahi	74	15	89	0.69	0.21	0.46
	Savelegu	113	24	136	0.64	0.20	0.43

Table 6. Additional plant nutrient requirements to achieve balanced nutrition for different target yields for variety Gbazekoute (Togo sites) and Afisiafi (Ghana sites).

Site	Target yield (Mg storage roots DM ha $^{-1}$)	Additional nutrients required (kg ha^{-1})		
		N	P	K
Davié	8	0	0	22
	12	18	8	67
	16	83	19	113
Gbave	8	0	0	15
	12	0	6	56
	16	54	16	98
Davié Tekpo	8	0	0	0
	12	0	0	24
	16	0	5	66
Sevekpota Black Soil	8	0	0	8
	12	0	4	49
	16	38	14	91
Sevekpota White Soil	8	0	2	34
	12	46	12	75
	16	102	22	117
Sevekpota Red Soil	8	0	0	24
	12	21	9	65
	16	77	19	107
Kumasi	8	0	0	3
	12	34	3	37
	16	76	11	71
Nyankpala	8	0	0	0
	12	42	6	0
	16	84	14	32
Gbanlahi	8	0	0	0
	12	37	7	4
	16	74	14	35
Savelegu	8	0	0	0
	12	0	0	0
	16	35	5	0

Table 7. Blanket rates, observed dry storage-yields without fertiliser, simulated yields, relative NPK availability over ΣA at recommended blanket fertiliser rates, $Y/\Sigma A$ and balanced nutrient requirements to reach the same yields as for the recommended rates at the study sites. Indigenous soil supply values in Table 5 were used with the average *MRF* for NPK of 0.50 – 0.21 – 0.49. ΣA is the sum of available N, P and K expressed in crop nutrient equivalent. A relative NPK availability proportion of about 33% for each of the nutrients N, P and K is expected at balanced nutrition. **$Y/\Sigma A$** is a proxy for overall nutrient use efficiency.

Site	Blanket rates, kg ha^{-1}			Observed yield without fertiliser, Mg DM ha^{-1}	Simulated Yield for blanket rates, Mg DM ha^{-1}	Relative NPK availability over ΣA when blanket rates are used, %	$Y/\Sigma A$		Balanced rates, kg ha^{-1}		
	N	P	K				Blanket rate recommendation	Balanced nutrition	N	P	K
Davié	76	13	25	8.8	9.8	44-33-24	20.0	20.5	0	13	87
Gbave	76	13	25	7.7	9.5	45-32-23	20.5	23.9	0	0	63
Davié Tekpo	76	13	25	11.8	13.3	44-32-23	20.5	23.9	0	0	78
Sevekpota Black Soil	76	13	25	8.7	10.3	45-32-23	20.5	23.9	0	0	65
Sevekpota White Soil	76	13	25	5.8	7.3	45-32-23	20.4	23.9	0	3	55
Sevekpota Red Soil	76	13	25	6.9	8.4	45-32-23	20.5	23.9	0	2	58
Kumasi	68	20	57	8.6	12.0	34-35-31	31.7	31.7	67	14	75
Nyankpala	68	20	57	5.6	12.2	30-29-41	30.3	31.7	88	31	0
Gbanlahi	68	20	57	8.0	10.8	31-28-40	31.3	36.5	52	23	0
Savelegu	68	20	57	12.2	15.2	30-29-40	31.4	36.5	56	19	0
P* (0.05)							***<0.001***				

***** *P* is the probability of differences between paired samples t-test with 95% confidence interval across all locations

Table 8. Partial budget analysis for the application of blanket and balanced fertiliser rates for cassava production at the study sites following different scenarios of input and product prices. This budget was based on yields (converted in fresh storage roots) and fertiliser rates provided in Table 7.

Site	Scenario 0						Scenario 1		Scenario 2	
	Gross revenue without fertiliser	Gross revenue with fertiliser (blanket and balanced rates)	Cost for blanket rates	Cost for balanced rates	BCR for blanket rates	BCR for balanced rates	BCR for blanket rates	BCR for balanced rates	BCR for blanket rates	BCR for balanced rates
	USD ha^{-1}									
Davié	2730	3058	221	203	1.5	1.6	0.9	1.0	1.8	2.0
Gbave	2385	2949	221	115	2.5	4.9	1.6	2.9	3.2	5.9
Davié Tekpo	3665	4145	221	142	2.2	3.4	1.3	2.0	2.7	4.1
Sevekpota Black Soil	2710	3189	221	118	2.2	4.1	1.3	2.4	2.7	4.9
Sevekpota White Soil	1786	2256	221	110	2.1	4.3	1.3	2.6	2.6	5.2
Sevekpota Red Soil	2151	2614	221	114	2.1	4.1	1.3	2.4	2.6	4.9
Kumasi	1211	1696	202	210	2.4	2.3	1.0	1.0	2.9	2.8
Nyankpala	788	1730	202	172	4.7	5.5	2.0	2.4	5.6	6.6
Gbanlahi	1127	1527	202	113	2.0	3.5	0.9	1.5	2.4	4.3
Savelegu	1727	2157	202	107	2.1	4.0	0.9	1.8	2.6	4.9
Average ± STDEV**	2028±878	2532±821	214±10	140±40	2.4±0.9	3.8±1.1	1.3±0.4	2.0±0.7	2.9±1.0	4.6±1.4
P	***< 0.001***		***< 0.001***		***< 0.001***		***< 0.001***		***< 0.001***	

***** *P* is the probability value of differences between paired samples t-test with 95% confidence interval across all locations;

** STDEV is standard deviation.

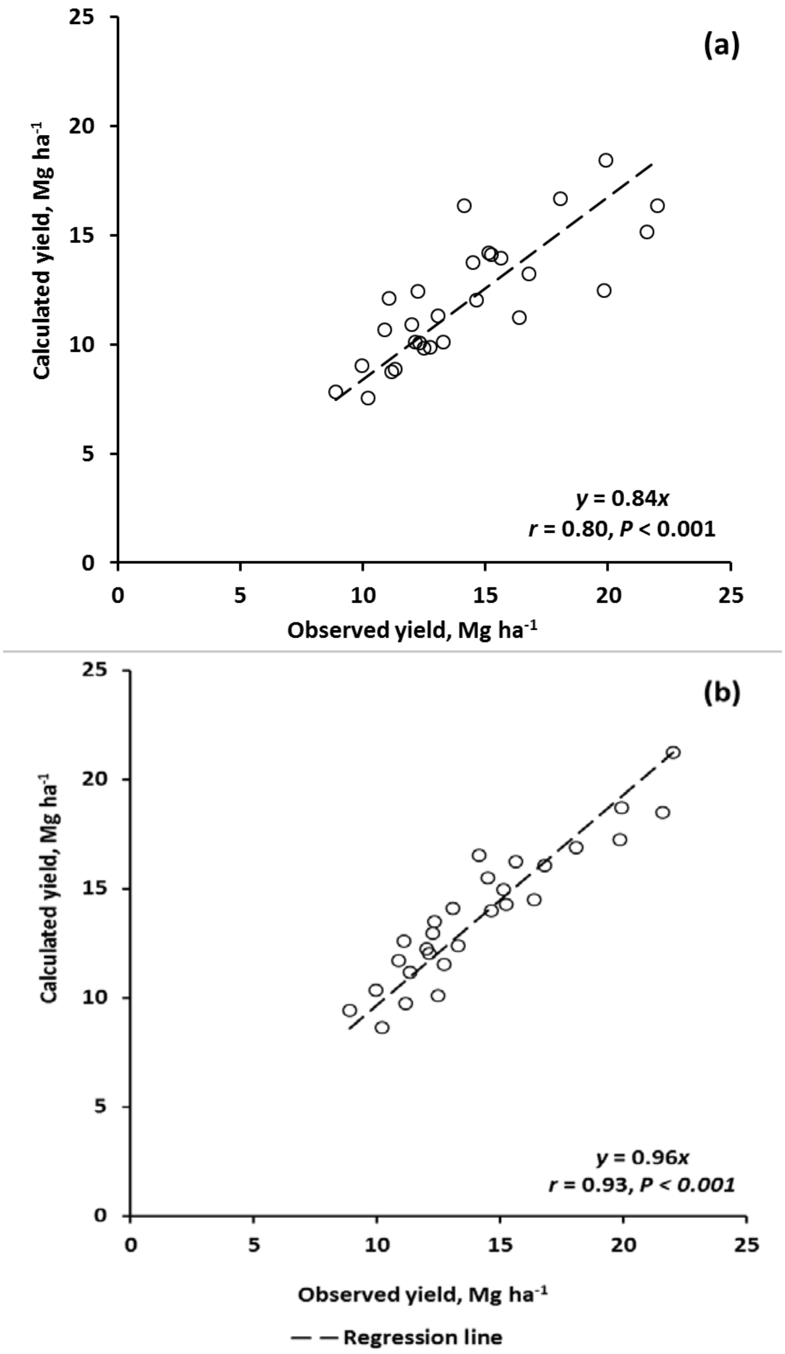

Fig. 1. Observed vs calculated storage roots DM yields of cassava on Set 2 sites with average (a) and site-specific *MRF* values (b). The average *MRF* NPK values used were 0.50 – 0.21 – 0.49. The specific *MRF* values are presented in Table 5.

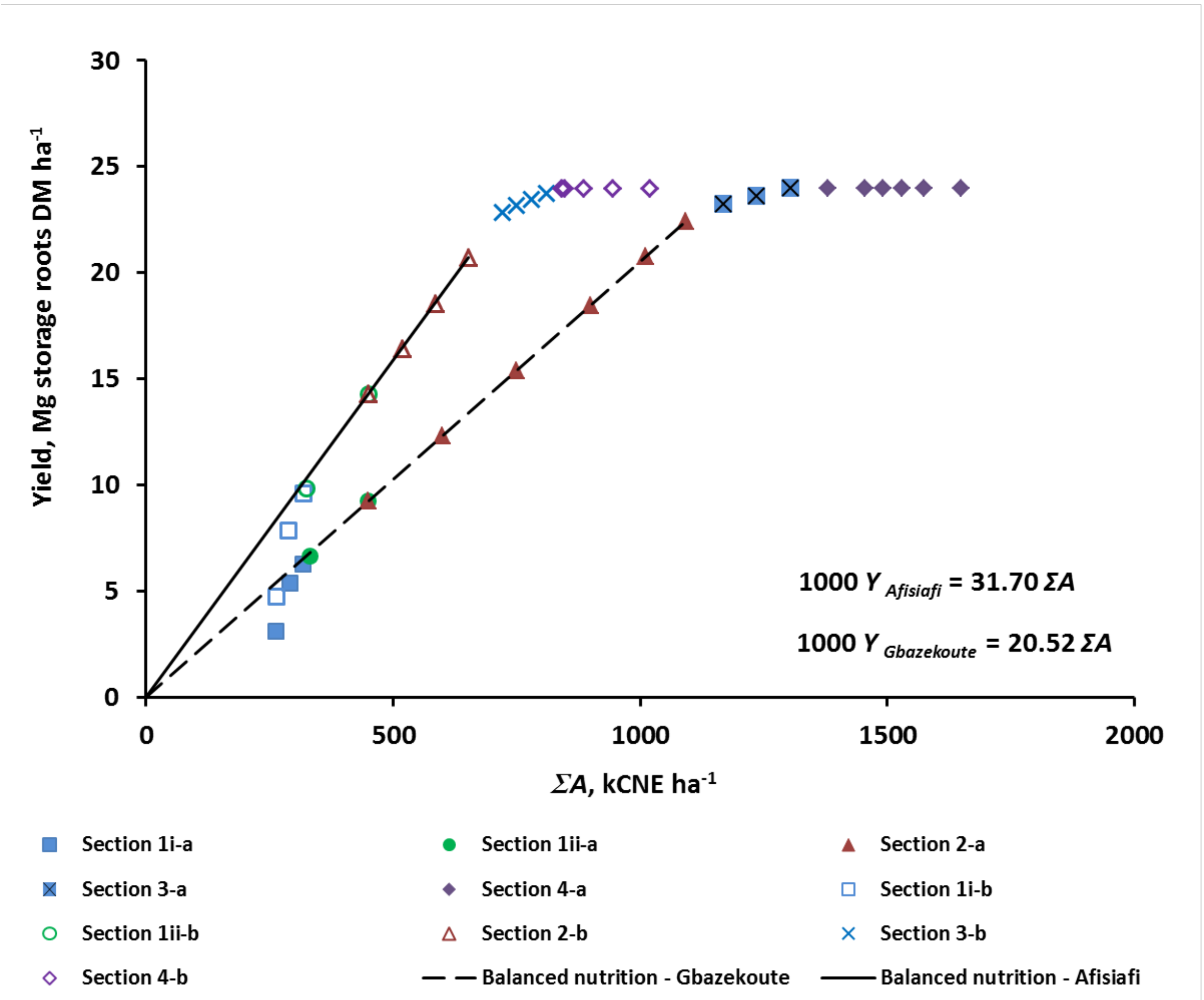

Fig. 2. Simulated relations of cassava storage roots yield to the sum of available N, P and K expressed in CNE (ΣA) for cultivars Gbazekoute and Afisiafi. 1000 Y expresses the linear relationship between the yield (Y) and ΣA at balanced nutrition for each cultivar. The slope of this linear regression ($1000Y/\Sigma A$) is considered as the nutrient use efficiency of the cultivar for a specific harvest index (0.50 for Gbazekoute and 0.65 for Afisiafi in this graph) and is expressed in kg storage roots DM per kCNE. Sections 1i-a, 1ii-a, 2-a, 3-a and 4-a refer to Gbazekoute and Sections 1i-b, 1ii-b, 2-b, 3-b and 4-b refer to Afisiafi.