

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

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15 **Abstracts**

16 Insufficient and unbalanced fertiliser use widens cassava yield gaps. We assessed the spatial
17 variability of optimal fertiliser requirements of cassava for enhanced nutrient use efficiency
18 and increased yield using the balanced nutrition approach of the QUEFTS model. Two
19 datasets comprised of five fertiliser experiments conducted at eight locations across Southern
20 Togo, Southern Ghana and Northern Ghana from 2007 to 2012 were used. The ratio of
21 storage roots dry matter yield over the sum of available N, P and K expressed in crop nutrient
22 equivalent from the soil and nutrient inputs was used as a proxy to estimate nutrient use

23 efficiency. Nutrient use efficiencies of 20.5 and 31.7 kg storage roots dry matter per kilo crop
24 nutrient equivalent were achieved at balanced nutrition at harvest index (*HI*) values of 0.50
25 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,
26 1.9 and 8.4 kg at an *HI* of 0.65 were required to produce 1000 kg of storage roots dry matter.
27 The corresponding optimal NPK supply ratios are 6.0 – 1.0 – 4.2 and 5.3 – 1.0 – 4.2. Nutrient
28 use efficiencies decreased above yields of 77-93% of the maximum. Evaluation of the
29 performance of blanket fertiliser rates recommended by national research services for cassava
30 production resulted in average benefit:cost ratios of 2.4 ± 0.9 , which will be unattractive to
31 many farmers compared to 3.8 ± 1.1 for the balanced fertiliser rates. The indigenous soil supply
32 of nutrients revealed that, at balanced nutrition, K was the most limiting nutrient to achieve
33 storage roots yields up to 8 Mg dry matter ha⁻¹ at most sites, whereas N and P were needed at
34 greater yields. Dry weight of storage roots measured on the control plots in our researcher
35 managed experiment ranged from 5.6 to 12.2 Mg ha⁻¹, and were larger than the average
36 weight in farmers' fields in West Africa of 4 Mg ha⁻¹. Substantial yield increase could be
37 attained in the region with improved crop management and fertiliser requirements formulation
38 on the basis of balanced nutrition.

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

41 **1. Introduction**

42 Cassava (*Manihot esculenta* Crantz) has long been considered a subsistence crop, but is
43 becoming increasingly commercialised. The world production of fresh cassava storage roots
44 increased tremendously from 176 to 277 million Mg between 2000 and 2013 (FAOSTAT,
45 2014). West Africa produces 28% of the world's cassava and the rest of Africa a further 26%
46 (FAOSTAT, 2014). The increase in production was achieved through both expansion of the

47 cultivated area and enhanced yields of cassava. Although average yields in West Africa
48 increased between 2000 and 2013 from 9.7 to 13 Mg ha⁻¹ of fresh storage roots (FAOSTAT,
49 2014), a large yield gap remains, given that yields close to 60 Mg ha⁻¹ have been attained in
50 researcher-managed fields in the region (Odedina et al., 2009).

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

67 Balanced nutrition of a given nutrient refers to supplying that nutrient to the plant in
68 accordance with the plant's need while maximizing the use efficiency of this nutrient. When
69 more than one nutrient is considered, e.g. N, P and K together, balanced nutrition refers to the
70 optimization of the use efficiency of these nutrients together giving the strongest response to
71 their supply in congruence with plant needs. The term optimising is used given the difficulty

72 of maximising the use efficiency of several nutrients simultaneously. The method developed
73 by Janssen (Janssen, 1998; Janssen, 2011) can handle several nutrients simultaneously by
74 assuming that balanced nutrition is achieved when the supplies of all nutrients expressed in
75 crop nutrient equivalent (CNE) units are equal. As a unit, 1 kilo CNE (kCNE) or 1000 CNE of
76 a nutrient is defined as the quantity of that nutrient that has the same effect on yield as 1 kg of
77 N under conditions of balanced nutrition. The concept of CNE allows summing up the total
78 supply of N, P and K and quantitatively describing balanced nutrition as the situation where
79 the supplies of each of the three nutrients are equal. Both CNE and balanced nutrition
80 concepts were also applied by Maro et al. (2014) for coffee production in Tanzania using
81 QUEFTS model.

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

94 **2. Materials and methods**

95 **2.1 Field experiments**

96 Two datasets, referred to as Set 1 and Set 2, were used in this study. Set 1 was collected in
97 three field experiments at three locations in southern Togo (Davié), southern Ghana (Kumasi)
98 and northern Ghana (Nyankpala, Table 1). The trials were laid out in a randomised complete
99 block design (RCBD) with four blocks at each site containing 10 NPK fertiliser combinations
100 (Table 2). N, P and K rates were defined in Set 1 to assess the indigenous supply of nutrients
101 by the soil (S1, S3 and S5 in Table 2), as well as the response of the crop to different rates of
102 fertilisers (other treatments). N was applied as urea (46%N, Davié and Kumasi) or sulphate of
103 ammonia (21%N, Nyankpala), P as triple super phosphate (TSP: 20%P) and K as muriate of
104 potash (MOP: 50%K). All TSP and one third of the urea and MOP were applied 4 weeks after
105 planting, the remaining urea and MOP at 10 weeks after planting. Set 2 was collected in two
106 other field experiments at five locations across southern Togo (Gbave, Davié Tekpo and
107 Sevekpota) and northern Ghana (Gbanlahi and Savelugu) (Table 3) in agro-ecological zones
108 that are similar to those in Set 1. Set 2 experiments comprised five NPK fertiliser
109 combinations (Table 2). These fertiliser combinations were used to evaluate performance of
110 the QUEFTS model in simulating yields in response to fertiliser applications. At each site, Set
111 2 experiments were laid out following a RCBD with four blocks in a single field, except for
112 Sevekpota where seven farmers each harboured a single block (replication) of the full set of
113 treatments. Fertilizer was applied in a similar way in both Set 1 and Set 2.

114 **2.2 Description, parameterisation and verification of QUEFTS**

115 The original QUEFTS model simulates crop yields in response to nutrient supplies following
116 four steps (Janssen et al., 1990, Janssen and Guiking, 1990). In Step 1, QUEFTS estimates
117 nutrient supplies from soil and inputs of organic materials or fertilizer. In Step 2, the actual
118 uptake of a nutrient is calculated as a function of the total supply of that nutrient, and of the
119 interaction with the two other macronutrients. In Step 3, two yields are calculated by the
120 model for each nutrient uptake, one corresponding to a situation where the nutrient is

121 maximally diluted in the crop, and another one corresponding to a situation of maximum
122 accumulation of that nutrient. The relation between yield and nutrient uptake is indicated by
123 the physiological nutrient use efficiency (PhE), which varies between $PhEmin$ and $PhEmax$.
124 $PhEmax$ represents the situation where the nutrient is maximally diluted in the crop; $PhEmin$
125 the situation of maximum nutrient accumulation. In Step 4, the yield is calculated for pairs of
126 nutrients ($Y12$, yield in response to nutrient 1 with $PhEmin$ and $PhEmax$ of nutrient 2 as
127 boundary conditions) denoted by YNP , YNK , YPN , YPK , YKN and YKP using the yield ranges
128 defined in Step 3; the average yield of all pairs of nutrients is retained as the final yield
129 estimate of the crop.

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

140 Data from Set 1 were used to derive $PhEmax$ and $PhEmin$ values for each nutrient (Table 4).
141 $PhEmin$ and $PhEmax$ depend on harvest index (HI) (Sattari et al., 2014), which is the ratio of
142 the weight of the economic plant component (grain for cereals, and storage roots in the case of
143 cassava in this study) over the weight of the whole plant (total biomass including stems,
144 leaves and storage roots). $PhEmax$ and $PhEmin$ were obtained using the following equations:

145 $PhEmax = 1000 \times HI / (HI \times C_{min,roots} + (1 - HI) \times C_{min,tops})$ (Equation 1)

146 $PhEmin = 1000 \times HI / (HI \times C_{max,roots} + (1 - HI) \times C_{max,tops})$ (Equation 2)

147 C_{min} and C_{max} are the minimum and maximum values of mass fractions (g kg^{-1}) in the roots
148 ($C_{min,roots}$ and $C_{max,roots}$) and in the top biomass including stems and leaves ($C_{max,tops}$ and
149 $C_{min,tops}$). 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}
150 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
151 the tops obtained from Set 1 were used.

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

170 2.3 Determination of balanced nutrition

171 The prerequisite for balanced nutrition assessment is the conversion of kg of N, P and K into
172 crop nutrient equivalent (CNE), assuming that balanced nutrition is achieved when the
173 supplies of these nutrients, expressed in CNE, become equal to each other. The conversion is
174 based on the average or medium value of PhE denoted by PhE_{med} . PhE_{med} equals $(PhE_{max}$
175 $+PhE_{min})/2$. Since 1 kilo CNE (1 kCNE) of a nutrient is the quantity of that nutrient that has
176 the same effect on yield as 1 kg of N under conditions of balanced nutrition, 1 kCNE equals 1
177 kg N. Conversion factors for P and K (CFP and CFK) were calculated using the ratio of
178 PhE_{med} of N and PhE_{med} of P or K: $CFP = PhEN_{med}/PhEP_{med}$, and $CFK =$
179 $PhEN_{med}/PhEK_{med}$. Hence, 1 kCNE of P (kCNEP) equals CFP kg P, and 1 kCNEK equals
180 CFK kg K. In Set 1 experiment for instance, at $HI = 0.50$, $1kCNEP = 0.167$ kg P, and
181 $1kCNEK = 0.706$ kg K (Table 4).

182 Total available N, P and K (TAN , TAP and TAK) were calculated by summing up available
183 nutrients supplied by the soil and external fertiliser input ($TAN = SAN + MRFN \times I_N$; $TAP =$
184 $SAP + MRFP \times I_P$; $TAK = SAK + MRFK \times I_K$, with $MRFN$, $MRFP$ and $MRFK$ standing for the
185 maximum recovery fractions of N, P and K fertilisers applied and I_N , I_P and I_K for the
186 respective amounts of fertilisers applied) and converted into CNE.

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

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

194 2. Balanced nutrition situation at which $TAN = TAP = TAK$ (as expressed in CNE): from the
195 unbalanced nutrition situation, the balanced nutrition is reached by adding required
196 quantities of fertiliser input (I) that raise the smallest amounts of available nutrients
197 among TAN , TAP and TAK to the level of the largest amount in CNE. For instance, if
198 TAN , TAP and TAK were 75, 25 and 40 kCNE, respectively, we need to increase TAP by
199 50 kCNE and TAK by 35 kCNE by adding P and K fertilisers to reach the level of TAN ,
200 hence attaining the balanced nutrition with $TAN = TAP = TAK = 75$ kCNE. The sum
201 ($TAN+TAP+TAK$), denoted by ΣA , is then 225 kCNE.

202 3. From the situation of balanced nutrition ($TAN = TAP = TAK$), identical quantities of
203 available nutrients from input fertilisers ($MRF \times I$), expressed as CNE, are continuously
204 and simultaneously added to TAN , TAP and TAK until the maximum yield (Y_{MAX}) is
205 approached.

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

210 **2.4 Assessing nutrient supply and fertiliser requirements for different target yields**

211 At balanced nutrition, yield calculated by QUEFTS is $\alpha\%$ of the product of $PhEmed$ and ΣA
212 expressed as CNE, where α is smaller than, but close to 100%. That α is smaller than 100% as
213 the result of the procedure used for the calculation of $YI2$ (see section 2.2). As a consequence,
214 the maximum yield per kCNE of available N, P and K is $\alpha\%$ of the product of $PhEmed$ and
215 ΣA .

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

$$218\ TgA = (TgY/PhEmed)/\alpha \quad \text{(Equation 3)}$$

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

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

$$222\ TgIAN = TgAN - SAN \quad \text{(Equation 4)}$$

223 The target inputs of available P and K can be found as $TgIAP = TgAP - SAP$ and $TgIAK =$
224 $TgAK - SAK$. Because $TgIAN$, $TgIAP$ and $TgIAK$ are expressed in kCNE, they must for
225 practical agriculture be converted into kg; this is done by multiplying them by their respective
226 conversion factors for a given HI (Table 4). SAN , SAP and SAK values used are presented in
227 Table 5. At balanced nutrition, the values of both $TgAP$ and $TgAK$ expressed in CNE are equal
228 to those of $TgAN$.

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

$$233\ RIN = TgIAN/MRFN \quad \text{(Equation 5)}$$

$$234\ RIP = CFP \times TgIAP/MRFP \quad \text{(Equation 6)}$$

$$235\ RIK = CFK \times TgIAK/MRFK \quad \text{(Equation 7)}$$

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

238 **2.5 Data analysis and economic assessment**

239 The performance of the QUEFTS model used was first assessed by comparing simulated with
240 observed yields using different indicators: the Normalised Root Mean Squared Error
241 (*NRMSE*) (Loague and Green, 1991), the slope of the regression line between measured and
242 simulated values, the Pearson coefficient of correlation (*r*) and the probability of the
243 correlation (*P* value at 0.05). The calculated fertiliser rates at balanced nutrition were
244 compared to existing national blanket fertiliser recommendations, referred to as blanket rates.
245 This comparison was implemented based on the values of nutrient use efficiency ($Y/\Sigma A$), of
246 the relative NPK availability over the sum of available nutrients (ΣA) and of the fertiliser
247 nutrient requirements. Furthermore, a profitability analysis was conducted by calculating the
248 gross revenues, costs and benefit:cost ratios (BCR) of the two types of fertiliser
249 recommendations. Gross revenues were obtained as the product of the unit price of fresh
250 storage roots at farm gate and fresh yields per site. Costs included fertiliser costs only and
251 were calculated as fertiliser unit price multiplied by the quantity of fertiliser applied. No
252 transportation nor application cost were considered. The BCR values were calculated by
253 dividing the increase in gross revenue due to fertiliser application by the fertiliser costs. The
254 increase in gross revenue due to fertiliser application is the difference between the gross
255 revenue with fertiliser application and that of the control (no fertiliser application). National
256 average values \pm standard deviation of fertiliser prices were used: 1.72 ± 0.10 USD kg⁻¹ N,
257 3.48 ± 0.37 USD kg⁻¹ P and 1.82 ± 0.19 USD kg⁻¹ K in Togo (average monthly fertiliser
258 prices, October 2011 to January 2015, africafertilizer.org), and 1.05 ± 0.19 USD kg⁻¹ N, 2.62
259 ± 0.64 USD kg⁻¹ P and 1.37 ± 0.34 USD kg⁻¹ K in Ghana (average of monthly fertiliser prices,
260 June 2010 to October 2014, africafertilizer.org). Fresh storage roots prices at farm gates of

261 0.118 ± 0.040 USD kg⁻¹ in Togo (annual average values, 2000 to 2014, CountrySTAT (2015))
262 and 0.051 ± 0.024 USD kg⁻¹ in Ghana were considered (annual average values, 2005 to 2012,
263 CountrySTAT (2015)). Three scenarios were compared for the economic evaluation of the
264 recommended and the balanced fertiliser rates: i) Scenario 0: average fertiliser price and
265 average fresh storage roots price; ii) Scenario 1: maximum fertiliser prices and minimum
266 storage roots price; iii) Scenario 2: the same fertiliser prices as Scenario 1 but with maximum
267 storage roots price. The minimum and maximum prices refer to the average price minus and
268 plus the standard deviation, respectively.

269 **3. Results**

270 **3.1 QUEFTS model performance**

271 Simulated storage roots yields were in good agreement with the measured yields on fertilised
272 plots in Set 2 sites for a common average *MRF* for NPK of 0.50 – 0.21 – 0.49 (Fig. 1a). The
273 slope of the regression line between simulated and observed yields was 0.84, with a strong
274 positive correlation ($r = 0.80$; $P < 0.001$), and an acceptable *NRMSE* of 0.21, indicating that
275 root mean squared errors represented 21% of the average observed yield. Model performance
276 was further improved by using site-specific *MRF* values (Fig. 1b) resulting in a smaller
277 *NRMSE* (0.10), a regression line slope (0.96) closer to 1 and a stronger positive correlation (r
278 = 0.93; $P < 0.001$) between simulated and observed yields.

279 **3.2 Relations between yield and nutrient supply at balanced nutrition**

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

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

305 The regression lines for Section 2 (Fig. 2) have the same slopes ($Y/\Sigma A$) as the lines for
306 balanced nutrition, drawn between the origin and the border of Sections 1ii and 2. These lines
307 differ between the two varieties: 20.5 and 31.7 kg DM yield / kCNE for Gbazekoute and
308 Afisiyasi respectively. Further simulations showed that changing the starting value of SAN ,
309 SAP and SAK did not change these balanced nutrition slopes (not shown). Simulations also

310 showed that the linear part of the graph (Section 2, Fig. 2) ends at 77-93% of Y_{MAX} with
311 various values of Y_{MAX} (16 to 24 Mg DM ha⁻¹ for *SAN*, *SAP* and *SAK* values of 150, 84 and
312 28 kCNE ha⁻¹) (not shown). Above this target yield threshold of 77-93% Y_{MAX} , the slope
313 rapidly decreases (Section 3, Fig. 2).

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

320 **3.3 Fertiliser requirements for different target yields at the experimental sites**

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

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

334 Gbanlahi, 9.0 Mg ha⁻¹ at Kumasi, 9.4 Mg ha⁻¹ at Nyankpala and 12.4 Mg ha⁻¹ at Savelugu). N
335 was most needed at larger target yields at Nyankpala, Gbanlahi and Savelugu. At Kumasi,
336 both N and K were limiting with target yields from 12 Mg ha⁻¹.

337 **3.4 Performance of recommended blanket fertiliser rates**

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

351 The economic analysis of the recommended and balanced fertiliser rates (Table 8) revealed a
352 larger benefit of the balanced rates over recommended rates in terms of costs of fertilisers and
353 benefit:cost ratio (BCR) ($P < 0.001$). BCR of the balanced fertiliser rates were 1.1 to 2.0 times
354 greater than those of the blanket rates, except in Kumasi where similar BCR values were
355 obtained. Average BCR values of 2.4 ± 0.9 and 3.8 ± 1.1 were obtained for the blanket rates and
356 the balanced rates, respectively, when average unit prices of fertiliser and of fresh storage
357 roots (Scenario 0) were considered. BCR values were sensitive to fluctuations in fertiliser and

358 fresh storage roots prices. The worst case scenario was the drop in BCR values caused by an
359 increase in fertiliser prices on the market and a reduction in farm-gate prices of storage roots
360 (Scenario 1). The best scenario for farmers consisted of a reduction in fertiliser prices and an
361 increase in storage roots farm-gate prices (Scenario 2).

362 **4. Discussion**

363 We obtained optimum nutrient use efficiencies of 20.4 and 31.4 kg storage roots dry matter
364 per kCNE supplied for Gbazekoute and Afisiafi cultivars, respectively (Fig. 2). This implies
365 that supplies of 48.9 and 31.8 kCNE are required to produce 1000 kg of cassava storage roots
366 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
367 P and 8.3 kg K for the production of 1000 kg storage roots DM of Gbazekoute and Afisiafi,
368 respectively. The cultivar Afisiafi had a relatively high nutrient use efficiency, but it is
369 difficult to attribute this to the cultivar itself or to site effects, since cultivar and location of the
370 trials were confounded. It follows from Equations 1 and 2 that nutrient use efficiencies
371 increase with *HI*. Afisiafi had higher average *HI* (0.65) than Gbazekoute (0.50). N supply was
372 especially high at Davié where Gbazekoute was grown, and large N uptakes may have
373 resulted in a relatively small *HI* through large top biomass production at the expense of
374 storage roots (Howeler, 2002). Therefore, differences in nutrient use efficiencies obtained
375 may be attributed more to differences in *HI* rather than cultivar differences.

376 The optimal NPK supply ratios simulated at balanced nutrition are 6.1 – 1.0 – 4.2 at *HI* 0.50
377 (Gbazekoute) and 5.4 – 1.0 – 4.2 at *HI* 0.65 (Afisiafi). Expressed in N-P₂O₅-K₂O, these are
378 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
379 similar to the ratios of 2 – 1 – 2 or 2 – 1 – 3 reported by Fermont (2009) for inorganic
380 fertiliser recommendations in East Africa. However, the supply in these latter ratios refers to

381 fertiliser only, whereas in our study it refers to fertiliser as well as the soil supplies of
382 nutrients.

383 The calculated optimal fertiliser nutrient requirements increased with target yields and varied
384 between sites (Table 6). At all sites in Togo, K was the most limiting nutrient for cassava
385 production, especially at a target yield of 8 Mg ha⁻¹ storage roots DM. This indicates that K
386 deficiencies are important and probably widespread in Southern Togo, especially on the
387 Ferralsols (Davié, Davié Tekpo and Gbave). Carsky and Toukourou (2005) also reported K
388 deficiencies in cassava production systems on Ferralsols in Southern Benin. However, K
389 deficiency is not limited to Ferralsols only. This issue can arise in the long term in any other
390 soil where cassava production is practised frequently with insufficient supply of external K
391 fertiliser because cassava extracts more K than any other nutrient from the soil (Hillocks et al.,
392 2002). Therefore, K management should be optimised to ensure good yields. K deficiency
393 was less obvious on the Ghana sites, especially at Nyankpala, Gbanlahi and Savelugu
394 indicating a good supply of this nutrient from the soil. N was the most needed nutrient at these
395 sites. The small soil organic carbon (SOC) content (4.3 g kg⁻¹) and the high exchangeable K
396 content (3.1 mmol kg⁻¹) of the Nyankpala soil support this conclusion. Unfortunately, no soil
397 chemical analysis data are available for Gbanlahi and Savelugu sites.

398 We observed that blanket fertiliser rates were in general unbalanced (Table 7). The rates of 76
399 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
400 Ghana were rather different from the site-specific optimal needs of input that we calculated
401 for the same target yields. The blanket rate of Ghana was quite balanced and suitable for use
402 in Kumasi only. A key reason for this difference between the performance of the blanket rates
403 and the calculated optimal nutrient needs is the difference in soil fertility among these sites, as
404 reflected by the difference in measured yields without fertiliser application (Table 7) and in
405 indigenous soil supplies (Table 5). The application of blanket rates irrespective of indigenous

406 soil nutrient supplies not only leads to less yield, but is also likely to generate nutrient losses
407 where the applied nutrient is not needed. Nutrient losses will be prominent for instance for N
408 in southern Togo, and K in Northern Ghana where those nutrients were not limiting yet, if
409 blanket rates of fertiliser were used. The application of blanket rates irrespective of plant
410 needs also leads to lower returns to investments in fertiliser. An average BCR value of
411 2.4 ± 0.9 obtained at blanket fertiliser rates will be less attractive to farmers than a BCR of
412 3.8 ± 1.1 achieved at balanced fertiliser rates. The sub-optimal economic performance at
413 blanket rates can discourage farmers to invest in fertiliser use for cassava production.

414 External P fertiliser supply requirements were fairly small at a target yield of 8 Mg ha^{-1} across
415 all sites, even at Davié, Kumasi and Nyankpala, which have soils with small concentrations of
416 available P ($3\text{-}5 \text{ mg kg}^{-1}$). Cassava is efficient at capturing soil P at small concentrations
417 through vesicular mycorrhizal symbiosis (Kang and Okeke, 1984; Sieverding and Leihner,
418 1984)

419 In summary, with the exception of K in southern Togo sites, no external fertiliser is required
420 to produce $8 \text{ Mg storage roots DM ha}^{-1}$, which is twice the current average yield in West
421 Africa. The simulation results are supported with the assumption of improved crop
422 management practices including planting healthy cuttings, planting on time, maintaining well
423 the plot with weeding, and a good control of pest and diseases. Yields measured under
424 improved management conditions on our fields experiments without fertiliser applications
425 ($5.6 - 12.2 \text{ Mg ha}^{-1}$; Table 7) were by far superior to the national average yields in farmers'
426 fields of 2.2 and 4.9 Mg ha^{-1} storage roots DM in Togo and Ghana (FAOSTAT, 2014),
427 assuming a DM content of 36% in the fresh roots. This suggests that substantial increase of
428 cassava storage roots yields could be achieved in the region by promoting good crop
429 management practices. However, the positive effect of good management practices can be
430 undermined by drought. This was the key reason for the relatively poor yield in Nyankpala

431 compared with the other sites in Ghana. External P as well as external N fertiliser
432 requirements arose at or beyond target yields of 12 Mg ha⁻¹.

433 These findings apply to sole cassava which generally provides larger yields compared with
434 intercropped cassava. Apart from yields, nutrients requirements of cassava may be different in
435 the intercropping system due to competition for nutrients, water and light with the intercrop.
436 N deficiency can be exacerbated in Northern Ghana when cassava is intercropped with cereals
437 without applying external N fertilisers (Carsky et al., 2001). Legume integration (intercrop or
438 rotation crop) in such systems can reduce the need for external N fertilisers through
439 atmospheric nitrogen fixation, although legumes need sufficient P for adequate growth and
440 symbiotic N₂-fixation (Giller and Cadisch, 1995). Since intercropping cassava with cereals
441 and or legumes is common in West Africa, further research is needed to determine the
442 balanced nutrition needs of intercropping systems.

443 The formulation of site-specific fertiliser recommendations based on optimal NPK supply
444 ratios requires a good assessment of (indigenous) soil nutrient supplies and of fertiliser
445 recovery fractions. Nutrient omission trials are the best way to quantify indigenous soil
446 nutrient supplies (Dobermann et al., 2002). Nevertheless, in the absence of data on indigenous
447 soil nutrient supplies, yields from farmers' plots without fertiliser application can be used to
448 estimate them, preferably when good management of these plots was carried out (planting of
449 healthy cuttings at the right time, at the recommended planting density, providing good weed
450 and pest control, etc.) and rainfall amount and distribution was reasonable. In general, soil
451 nutrient supply determined from farmers' plots yields without fertiliser application are smaller
452 than the potential soil nutrient supply values expected from nutrient omission trials. In Set 1,
453 the measured soil supply of nutrients was on average 1.3, 1.6 and 1.2 times as large, for N, P
454 and K, respectively in the nutrient omission plots (treatments S1, S3 and S5 for zero N, zero P
455 and zero K in Table 2) compared with the control plots (S0) (not shown). These multiplication

456 factors are indicative of the relevance to correct for the estimates of soil supply of nutrients
457 derived from farmers' plots yields without fertiliser applications. When yields on plots
458 without fertiliser application and the harvest index are known, the estimate of actual soil
459 nutrient supply can be performed using the reciprocal nutrient supply efficiency, which is the
460 nutrient supply requirement to produce 1 Mg ha⁻¹ of storage roots DM. In this study, this
461 reciprocal nutrient supply efficiency was (16.3 kg N, 2.7 kg P and 11.3 kg K for *HI* = 0.50 and
462 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
463 supply efficiency ($1000/PhEm$) can be derived from Equations 1 and 2. Fertiliser recovery
464 fractions (*MRF*) are sometimes assessed in any fertiliser trial comprising a treatment without
465 fertiliser. But this leads to an overestimation of *MRF*. *MRF* are ideally estimated in nutrient
466 omission trials. On the sites of our own trials (Set 1), *MRF* values varied between 33 – 69%
467 for N, 3 – 44% for P and 10 – 100% for K with average values of 50% for N, 21% for P and
468 49% for K (Table 5). In the same trials, the indigenous soil supplies ranged between 74 – 250
469 kg N, 15 – 34 kg P and 48 – 136 kg K ha⁻¹ (Table 5). These wide ranges of *MRF* and
470 indigenous soil supplies emphasise the need of site-specific fertiliser recommendations for
471 cassava production. However, it will be unrealistic to provide unique fertiliser
472 recommendations to individual farmers or fields, especially to smallholder farmers who
473 generally do not have financial capacity to pay for plant and soil chemical analyses. Another
474 key challenge is that single fertilisers, which allow a farmer to apply exactly the estimated
475 required amount of nutrients, are generally more expensive compared with standard blended
476 fertilisers (NPK: 15-15-15 for instance), except for urea that costs often as much as
477 (subsidised) blended fertiliser in West Africa. Fertiliser recommendations on the basis of
478 major soil types and agro-ecological zones can be more practical than recommendations for
479 individual farms. This could also increase the demand of specific fertiliser nutrients on the
480 input market and result in more affordable fertiliser prices for farmers. The assessment of

481 nutrient supplies per major soil type in main cassava production agro-ecological zones and the
482 balanced nutrition approach used in this study will be useful for formulating soil type and
483 agro-ecologically specific fertiliser recommendations for enhanced cassava production in
484 West Africa.

485 **5. Conclusions**

486 The QUEFTS model proved useful to assess balanced nutrition, to derive optimum fertiliser
487 requirements for target yields and to explore diversity among sites in West Africa. We showed
488 how the use of balanced fertiliser rates following NPK supply ratios of 6.1 – 1.0 – 4.2 at *HI* of
489 0.50 and 5.4 – 1.0 – 4.2 at *HI* of 0.65 enhanced nutrient use efficiency of NPK and increased
490 value to cost ratios compared with recommended blanket rates. We found that K is the most
491 needed nutrient to achieve a target yield of 8 Mg ha⁻¹ of storage roots DM, especially on the
492 Togo sites. The need for N and P fertiliser inputs became necessary at larger target yields on
493 most sites. These results suggest that good management practices are key to substantial
494 improvement of cassava production below a target yield of 8 Mg ha⁻¹, and that external
495 nutrients are needed to produce beyond a target yield of 12 Mg ha⁻¹ depending on the
496 indigenous soil fertility status of the soil. The variation in indigenous soil fertility status and in
497 nutrient input needs highlighted a key disadvantage of recommended blanket rates. Shifting
498 from these blanket rates to soil or agroecologically specific recommendations will be a great
499 accomplishment towards enhancing nutrient use efficiency and yields in cassava production
500 systems in West Africa, in addition to promoting good management practices.

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590

591 **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 |

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

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

594 *** Planting schemes follow the recommended densities for cassava in the study sites. These correspond to
595 15625 and 10000 plants ha⁻¹, respectively for 0.8 x 0.8m and 1 x 1m.

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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 | | |

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601

602 **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 |

603

604

605 **Table 4.** Harvest index (*HI*), physiological nutrient use efficiency for maximum accumulation
606 (*PhEmin*) and maximum dilution (*PhEmax*), and the conversion factors for P (CFP) and K
607 (CFK) used in model calculations for two cultivars (Gbazekoute and Afisiafi) in Set 1 and Set
608 2 experiments.

| Cultivar | <i>HI</i> | <i>PhEmin</i> | | | <i>PhEmax</i> | | | <i>PhEmed</i> | | | 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 |

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

| Dataset | Sites | <i>SAN</i> | <i>SAP</i> | <i>SAK</i> | <i>MRFN</i> | <i>MRFP</i> | <i>MRFK</i> |
|---------|----------------------|------------|------------|------------|-------------|-------------|-------------|
| 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 |
| | <i>Average</i> | | | | 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 |

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618 **Table 6.** Additional plant nutrient requirements to achieve balanced nutrition for different
619 target yields for variety Gbazeokoute (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 |

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622 **Table 7.** Blanket rates, observed dry storage-yields without fertiliser, simulated yields, relative NPK availability over ΣA at recommended
623 blanket fertiliser rates, $Y/\Sigma A$ and balanced nutrient requirements to reach the same yields as for the recommended rates at the study sites.
624 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
625 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
626 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 |
| <i>P*</i> (0.05) | | | | | | | <0.001 | | | | |

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

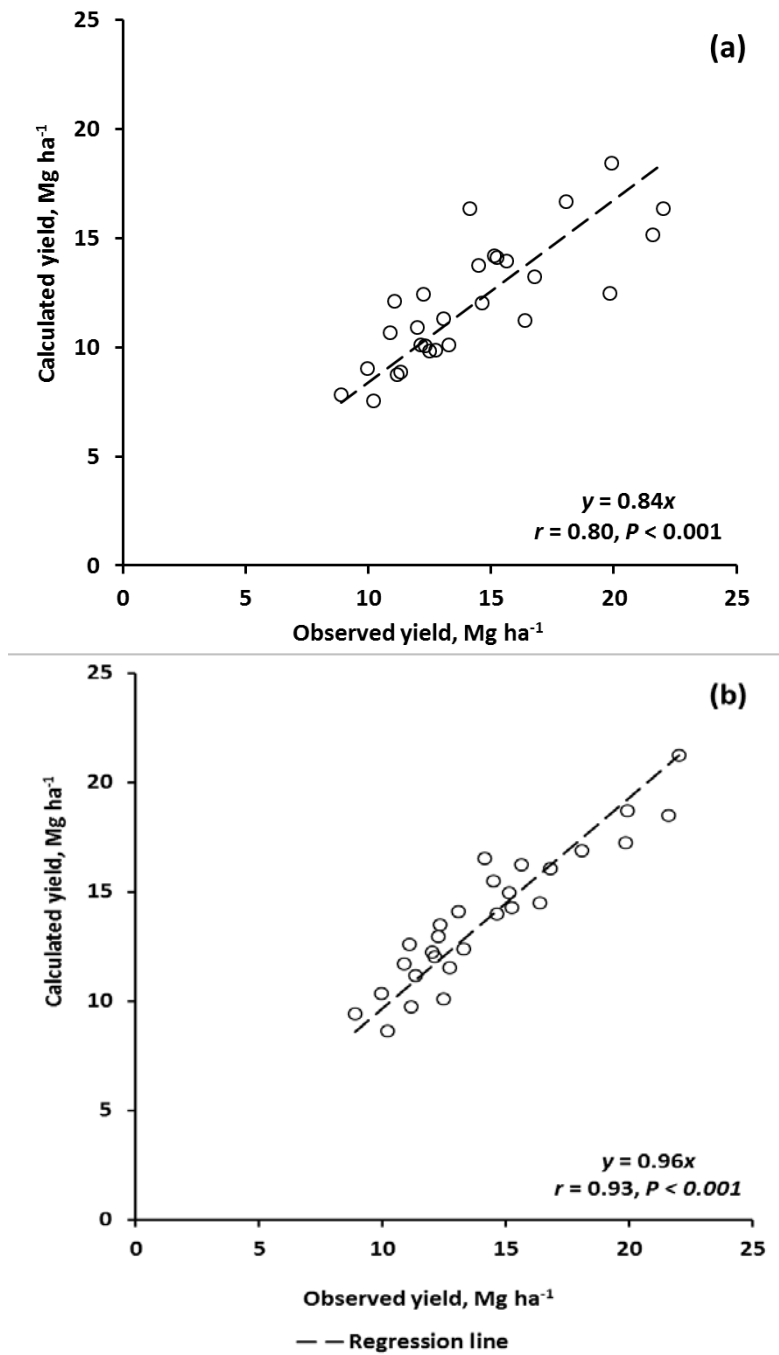
628

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

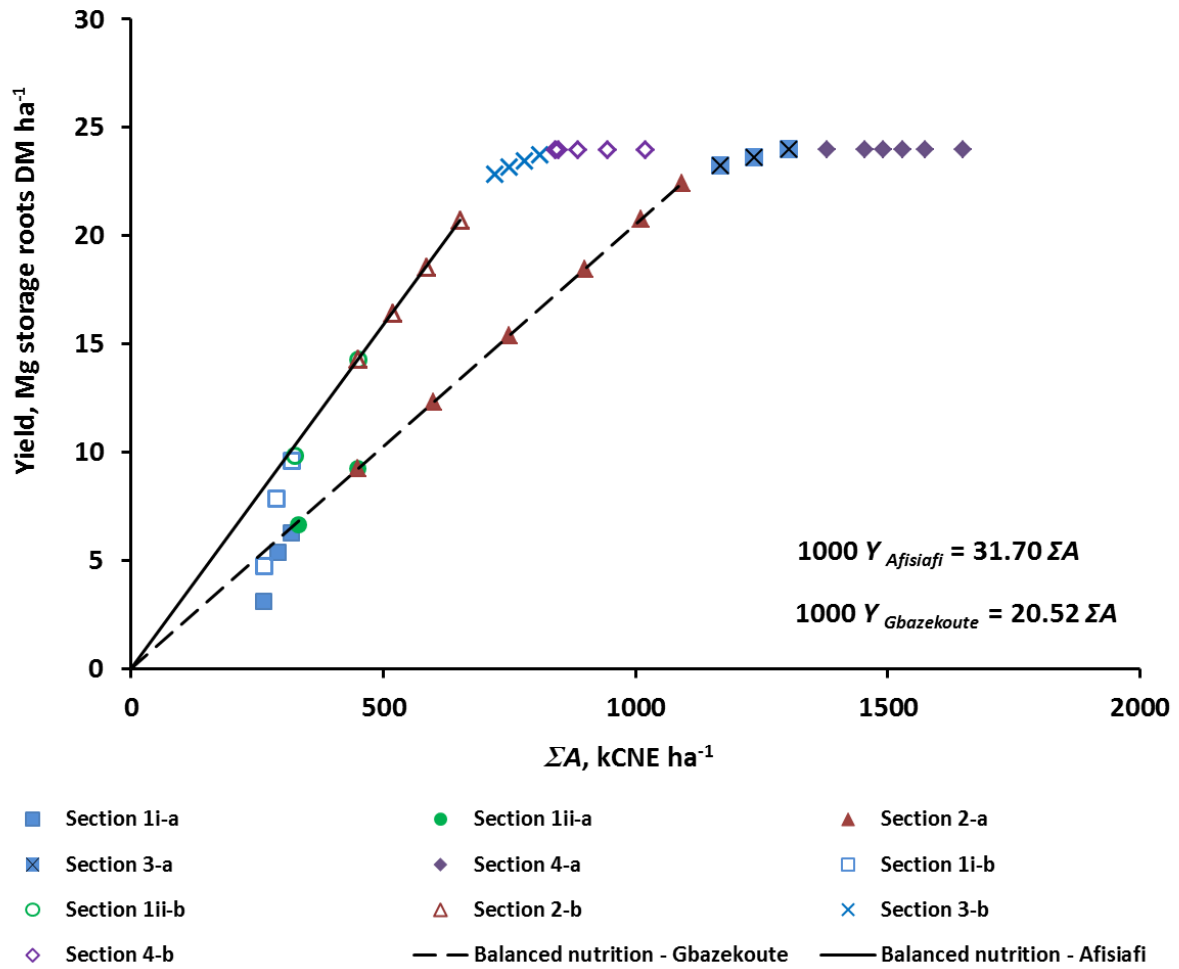
| Site | Scenario 0 | | | | Scenario 1 | | Scenario 2 | | | |
|----------------------|----------------------------------|--|------------------------|-------------------------|-----------------------|------------------------|-----------------------|------------------------|-------------------|---------|
| | 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 | | |
| 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 | |

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

633 ** STDEV is standard deviation.



634 **Fig. 1.** Observed vs calculated storage roots DM yields of cassava on Set 2 sites with average
 635 (a) and site-specific *MRF* values (b). The average *MRF* NPK values used were 0.50 – 0.21 –
 636 0.49. The specific *MRF* values are presented in Table 5.



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

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