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ABSTRACT

Heterogeneity in soil fertility conditions impacts fertiliser use efficiency in smallholder cropping systems in sub-Saharan Africa. A study was performed to generate insights in nutrient limitations for cassava (*Manihot esculenta* Crantz.). We conducted 627 nutrient omission trials over three years in South East (SEN) and South West Nigeria (SWN), and in the Southern (TSZ) and Lake Zone of Tanzania (TLZ) to quantify variation in root yield responses to N, P and K, and relate these to digital soil maps and weather information. Mean fresh root yields were 30, 21, 13 and 15 Mg ha^{-1} with an application of 150–40-180 kg N-P-K ha^{-1} and 20, 16, 11 and 14 Mg ha^{-1} without nutrient addition in the four study areas, respectively. Root yield response to nutrients was largest in SEN, with mean root yield reductions of 5.7, 3.3 and 2.7 Mg ha^{-1} due to omission of N, P and K, respectively. Differences in yield and yield response to fertiliser between study areas were governed by rainfall conditions, which were most favourable in SEN, and least favourable in the TLZ. Within study areas, large spatial variation was observed, while temporal variation was limited. Spatial variation in yield response was largest in SEN with standard deviations (sd) of 4.2 Mg ha^{-1} for K, 3.2 Mg ha^{-1} for P and 3.0 Mg ha^{-1} for N, opposite to the order of the mean yield responses. More than 75% of the variation in root yield response was observed at $<$ 10 km scale, and close to 50% at $<$ 1 km scale. Large variation (sd $=$ 1.8 – 2.5 Mg ha^{-1}) in response to N was also observed in all other study areas, and to K in SWN (sd $=$ 2.4 Mg ha^{-1}) and in the TSZ (sd $=$ 2.1 Mg ha^{-1}). Responses to N and P were weakly but significantly correlated to organic C, total N and clay contents, while response to K was correlated to extractable cations and clay content. Random forest models explained 16 – 59% of the variation in nutrient responses within study areas using digital soil maps and weather information. Our results confirm that responses to fertiliser nutrients vary in smallholder systems at a very local scale, and patterns vary between study areas and between individual nutrients. Digital soil maps and weather information can explain some of this variation and could support the development of site-specific recommendations at an appropriate scale. However, digital soil map data are unlikely sufficient to provide reliable advice at farm or plot level. Further research is needed to evaluate the capability of other factors, particularly local indicators of soil fertility, crop productivity and crop management intensity to complement digital soil maps in the development of field-specific fertiliser advice.

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1. Introduction

Agricultural productivity in smallholder systems in sub-Saharan Africa (SSA) is generally low (van Ittersum et al., 2016). This applies in particular to cassava production systems across the humid forest and derived savannah agroecological zones, with average yields of 10 – 15 Mg ha^{-1}, while potential yields range between 60 and 100 Mg ha^{-1} (Adiele et al., 2020b; Odedina et al., 2009). Production constraints in cassava systems are predominantly related to poor soil fertility (Kintché et al., 2017), often as a result of soil depletion due to inadequate or lack of use of nutrient inputs (Smaling et al., 1997), as well as water stress and poor weed control (Fermont et al., 2009). Sustainable intensification requires mineral fertiliser use to boost production (Vanlauwe and Dobermann, 2020). Many studies have shown that cassava responds to fertiliser (Howeler, 2002; Carsky and Toukourou, 2005; Fermont et al., 2010; Senkoro et al., 2018; Onasanya et al., 2021), and there is growing recognition of the importance of fertiliser use in smallholder systems, importantly driven by the increased need for root produce by the starch industry (Cock and Connor, 2021).

Balanced mineral nutrition is required to realise cassava's high yield potential (Howeler, 1981), and the specific nutrient requirements of cassava vary between geographical areas. Ezui et al. (2016), for example, showed that a balanced nutrient management treatment outperformed national blanket recommendations in a study in Togo and Ghana, and that potassium was the most needed external nutrient to increase yields. Adiele et al. (2020a) observed high recovery and yield response to all three nutrients in Nigeria, while Fermont et al. (2010) observed larger responses to N and P application than to K application in nutrient omission trials in Uganda and Kenya. Senkoro et al. (2018) showed that cassava was highly responsive to N in all trial locations in Ghana, Kenya and Tanzania, while a response to P was observed in Ghana and an N × P interaction in Tanzania, and a response to K was only observed in Ghana. Several studies have shown that responses to fertiliser N, P and K depend on the soil's nutrient availability (Carsky and Toukourou, 2005; Fermont et al., 2009; Tetteh et al., 2018), and that data collected from nutrient omission trials, alongside with soil information are critical to develop balanced fertiliser recommendations.

Heterogeneity in smallholder farming systems results in inconsistent returns on investment in fertiliser (Njoroge et al., 2017; Palmas and Chamberlin, 2020), an important reason for low fertiliser use by smallholders. Large variation exists in land management practices, crop husbandry and soil fertility, with their interactive effects resulting in large differences in crop yield and fertiliser use efficiency, often aggravated by the effects of unpredictable weather and climate change (Traore et al., 2015). Typically, only blanket recommendations for fertiliser use are available, but these cannot address the heterogeneity in the biophysical conditions, and frequently fail to result in lucrative crop yield increases (Kihara et al., 2016). The necessity to consider variability within and between farms has been demonstrated by several studies (Vanlauwe et al., 2006; Tittonell et al., 2008a) including studies on cassava (Fermont et al., 2010; Ezui et al., 2017). Variation in soil fertility, both indigenous and management-induced, is considered as one of the most important underlying causes of variation in fertiliser use efficiency (Chivenge et al., 2022). In cassava, as also observed in other crops, response to added N is commonly correlated with parameters such as soil organic C or total N contents, while response to P can often be related to measures of soil P availability, and response to K is most often related to exchangeable cations and texture (Howeler, 2002; Fermont et al., 2010). These relationships are however not always pronounced; some studies did not find soil properties to be defining factor to explain variation in fertiliser response (Kihara et al., 2016; Maman et al., 2018). Crop yield and nutrient response in smallholder farms are also importantly governed by other factors, for example factors related to rainfall and weed management (Fermont et al., 2010).

Recent advances in the development of high-resolution digital soil maps (Hengl et al., 2017; Shepherd and Walsh, 2007) offer an appealing, new, and freely available tool to support agronomic advisory applications, including site-specific fertiliser recommendation systems (Hengl et al., 2021; Ichami et al., 2020). Meaningful use of digital soil maps for that purpose requires investments in on-farm field experimentation to gain insights in variation in crop response in target intervention areas. Ample data on crop yield response collected using rigorous sampling frames to represent the heterogeneity in the on-farm context are needed to permit the calibration, evaluation and validation of site-specific nutrient management interventions based on such digital soil maps (Chivenge et al., 2022). Such georeferenced crop yield data are often lacking, dispersed or not available in a standardised, open and easily usable format, while such data resources offer opportunities to unravel critical limitations to fertiliser use efficiency (e.g., Bonilla-Cedrez et al., 2021; Abera et al., 2022).

High resolution digital soil maps present a valuable tool to refine fertiliser advice in heterogeneous smallholder production systems. On-farm nutrient omission trials were conducted to quantity variation in storage root yield response to fertiliser N, P and K in four cassava-growing areas in Nigeria and Tanzania, and to relate this variation to soil properties from digital soil maps and weather information. We hypothesize that nutrient responses vary strongly within and between study areas and that an important portion of this variation can be explained using soil properties and from digital soil maps and satellite-based rainfall information. Insights gained aim to contribute to the development of site-specific fertiliser advisory tools for smallholder production systems in SSA.

2. Materials and methods

This study was conducted in major cassava-growing areas of Nigeria and Tanzania (Phillips et al., 2004; Government of the United Republic of Tanzania, 2006) (Fig. 1). Trials were conducted in SE Nigeria (SEN) in Anambra, Benue, Cross River, Delta, Ebonyi, Edo, Enugu states, and in SW Nigeria (SWN) in Ogun, Osun and Oyo states. Locations in SWN, as well as Benue and the northern parts of Edo and Cross River were in the derived savanna agroecology with unimodal rainfall of 1500 – 2000 mm peaking between August and September. The locations in the other states were in the rainforest belt with a bimodal rainfall pattern of 2000 – 3000 mm, with peaks in June to July and in September, followed by a dry season from late November to early March. Mean temperatures were 25 – 27 °C in the rainforest zone, and 26 – 28 °C in the derived savanna, and altitudes were below 300 m. Soils were predominantly Nitisols and Ferralsols in the rainforest zone in SEN, while in the derived savanna, main soils were Acrisols and Nitisols in SEN and Luvisols and Nitisols in SWN. In Tanzania, trials were conducted in the Mtwara and Lindi regions in the Southern Zone (TSZ), and in the Geita, Kagera, Mara and Mwanza regions in the Lake Zone (TLZ). Locations in TSZ were in the southern savanna, with unimodal rainfall of 800 – 1300 mm between November and March, mean temperatures of 24 – 26 °C, altitudes below 500 m and predominantly Arenosols and Acrisols. Locations in TLZ were in the derived savanna, with bimodal rainfall of 800 – 1200 mm peaking in November – December and March – April, annual temperature of 26 °C, altitudes of 1000 –1600 m and predominantly Acrisols, Luvisols, Vertisols and Cambisols.

Field trial locations were selected following a stratified random sampling frame to ensure they provide a representative sample of typical smallholder cassava farms within the study areas (Fig. 1). First, each study area was separately characterised based on weather, soil and vegetation properties obtained from open-source geospatial information layers. These include soil organic C, total N, pH, exchangeable K, sum of exchangeable bases and sand content from the SoilGrids Africa database at 250 m resolution (soilgrids.org; Hengl et al., 2017), annual mean temperature and precipitation, seasonality and mean precipitation in the driest and wettest quarter (worldclim.org) and average NDVI and net primary production (africasoils.net). Only areas relevant for cassava cropping were included by applying a cassava crop mask (IFPRI, 2020).

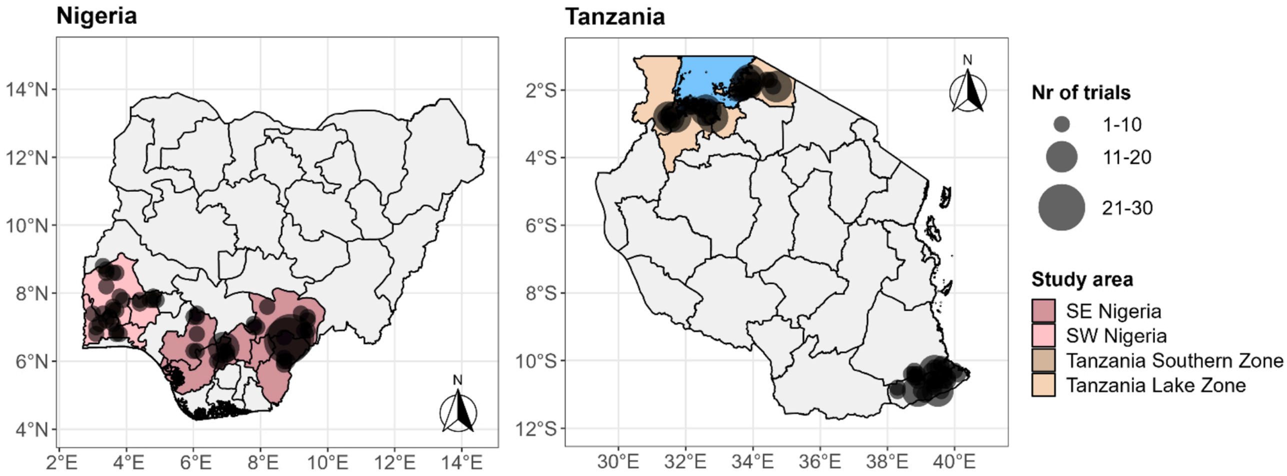

Fig. 1. Trial locations in the study areas in Nigeria and Tanzania. Locations are shown in groups of trials located within 10 km distance.

A principal component analysis was conducted on scaled measurements for all geospatial variables to reduce dimensionality and weight of correlated variables; the number of axes retained was determined using visual inspection of the scree plot. Next, each study area was categorised in five to ten distinct environmental classes using k-means clustering on the principal component scores. The number of classes was determined by evaluating within and between cluster variation in selected soil and weather variables, ensuring that environmental clusters adequately capture the large differences in conditions across the study area (ACAI, 2017). These maps were then overlayed with the locations of extension workers of NGO or private sector partners of the African Cassava Agronomy Initiative (ACAI) who assisted with the identification of volunteer smallholder farmers. In each environmental class, we randomly selected one to five extension workers, proportional to the total area of each cluster. Each extension worker was tasked to list the villages within a 5 km radius from their base location, and randomly select two or three villages. In each village, the extension worker then randomly selected two to five farming households who commonly grow cassava and identified one field per household. Selected fields must have been uniformly managed and cultivated with at least one cassava crop during the past two years, and not be degraded or located on steep slopes. Each extension worker maximally selected 10 fields. In three out of 10 fields, two replicate trials were established, while in the other fields, a single replicate trial was installed. A total of 937 trials were established, of which 627 trials (193 in SEN, 82 in SWN, 166 in the TSZ and 186 in TLZ) provided valid yield data. Main reasons for loss of trials included damage due to floods, livestock grazing or bushfire, theft or disengagement by the farmer or extension worker. Trials were

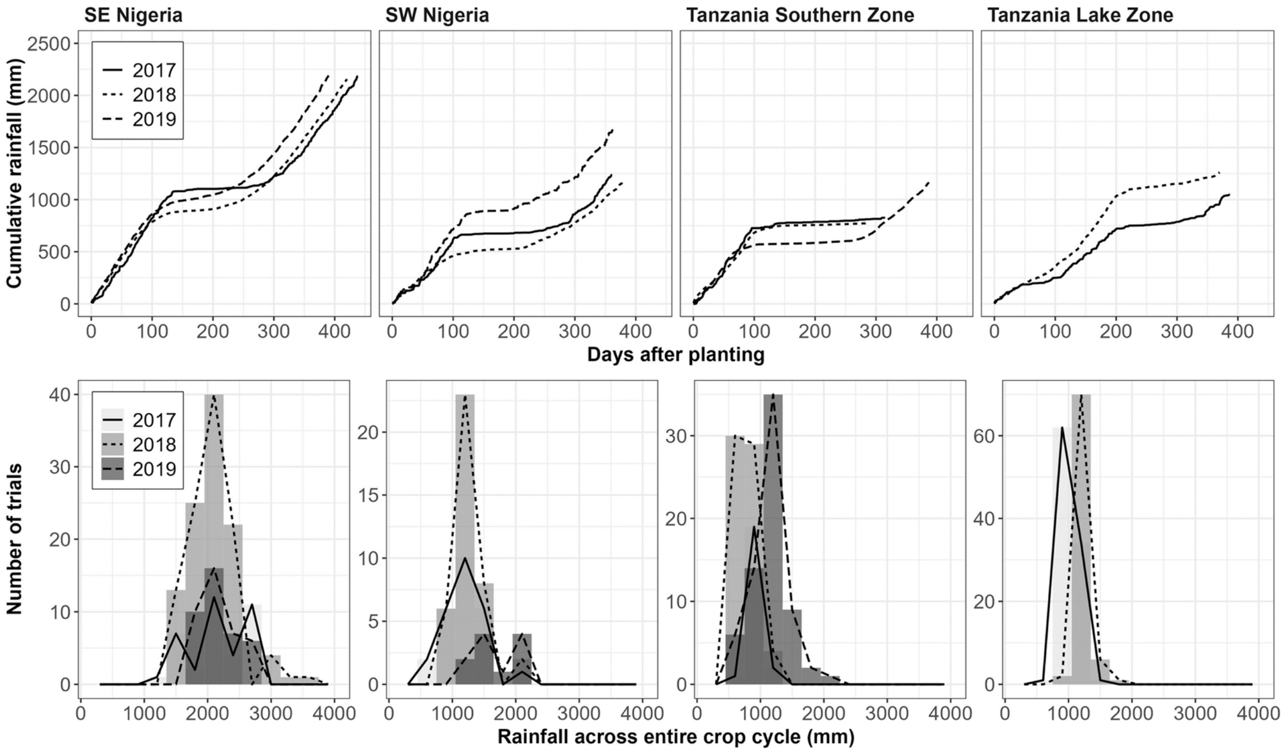

Fig. 2. Mean cumulative rainfall distribution across trial locations in the 4 study areas for the median crop duration (top) and distributions in total rainfall between planting and harvest (bottom). Trials were repeated in different locations in three different years in Nigeria and TSZ, and in two years in TLZ. Daily rainfall data was obtained from the CHIRPs rainfall layer using the geographic coordinates of the trial locations.

established in three consecutive years (184 harvested in 2017, 314 harvested in 2018, and 129 harvested in 2019), but not repeated in the same fields; in each year, new farmers and new fields were identified. In the TLZ, trials were only conducted during two years, harvested in 2017 and 2018. In Nigeria, the cassava crop was planted during April – July and harvested in April – August the following year, after 12 – 13 months. In the TLZ, trials were planted in October – November and harvested in November – December after about 12 – 13 months. In the Coastal Zone, trials were planted in December – January and harvested after 10 months in October – December in the first two years, and planted in February and harvested in April after 13 months in the last year. While farmers in the study areas do extend planting windows beyond these periods and may delay harvest up to 14 or 15 months after planting, we targeted the most common planting and harvest schedules, so that the crop received sufficient rainfall during the first four months after planting. Based on CHIRPS rainfall data (Funk et al., 2015), rainfall in the initial four months after planting was 500 – 1500 mm in SEN, 400 – 900 in SWN, 400 – 800 mm in TSZ and 300 – 500 mm in TLZ (Fig. 2). Rainfall in the entire cropping period was 1500 – 2800 mm in SEN, 1500 – 2000 mm in SWN, 500 – 1500 mm in TSZ and 700 – 1500 mm in TLZ. Rainfall amounts varied more between locations within each of the three years than between years.

Each trial was established following a nutrient omission experimental setup with eight plots. Treatments included a control (CON) without fertiliser addition, two replicate reference plots with N, P and K applied at rates expected to eliminate nutrient deficiencies (NPK), plots with omission of N (PK), P (NK) and K (NP), and the other two nutrients supplied at the same rate as the refence plot, a treatment with N, P and K supplied and additional Ca, Mg, S, Zn and B (NPK+), and a treatment with N, P and K supplied at half the rates in the reference plot (½NPK). In the reference treatment, N, P and K were supplied at 150 kg N ha^{-1}, 40 kg P ha^{-1} and 180 kg K ha^{-1}. In the NPK+ treatment, additional nutrients were applied at 17 kg S ha^{-1}, 10 kg Ca ha^{-1}, 10 kg Mg ha^{-1}, 5 kg Zn and 1 kg B ha^{-1}. Nutrients were supplied using urea, triple super phosphate (TSP), muriate of potash (MOP), $CaCO_3$, $MgSO_4$, $ZnSO_4$ and H_3BO_3. Fertiliser application regimes differed between study areas and according to the rainfall regime, with P applied at planting, N in two or three splits within 1 – 3 months after planting (MAP), K in 2 or 3 splits within 1 – 4 months after planting, and secondary nutrients in a single application between 2 and 3 months after planting. Fertiliser was applied in full-circle furrows (20 cm radius) around each plant and covered with soil.

Fields were cleared, ploughed, and ridged manually by hand hoe following farmer's common practice. During land preparation, one composite soil sample per trial was collected from the 0 – 20 cm soil layer following a 'W' pattern across the entire trial area. Plots were then laid out and treatments assigned randomly. Plot sizes were 7 m by 8 m planted at 1 m between and 1 m within rows in Tanzania, and 7 m by 6.4 m planted at 1 m between and 0.8 m within rows in Nigeria. Net plots contained 30 plants (5 m by 6 m in Tanzania, and 5 m by 4.8 m in Nigeria). Trials were planted with disease-free cuttings of an improved variety commonly available in each study area (TME419 in Nigeria, Mkombozi in TLZ, and Kiroba in TSZ). Varieties used in Tanzania are tolerant to cassava mosaic and brown streak disease and are early-branching, while TME419 is a late-branching variety. Cuttings of 25 to 30 cm with at least five nodes were planted in slanted orientation; after 4 weeks, missing stands were replaced by transplanting spare cuttings to ensure a good plant stand. Trials were regularly monitored to ensure timely weeding, and any issues related to crop management, pests and diseases, drought, floods or lodging were recorded. At harvest, plant stand was recorded, and the plants in the net plot were uprooted, storage roots were separated and cleaned, and total fresh root mass measured.

Soil samples were air-dried, ground and sieved to pass 2 mm. A random subset of 15 samples per study area (60 samples in total) was sent to the IITA laboratories in Ibadan, Nigeria and Dar es Salaam, Tanzania for standard wet chemistry analysis to enable comparison with digital soil map properties. Soil properties were determined using: the Bouyoucos hydrometer method for texture (Gee and Bauder, 1986); Mehlich-III extraction (Mehlich, 1984) for extractable P, K, Mg and Ca; Walkley and Black wet digestion for organic C (Nelson and Sommers, 1996); an elemental analyser for total N; and pH in 1:2.5 soil:water suspension (Thomas, 1996). The latitude and longitude of each trial were used to extract the soil property predictions for the 0 – 30 cm depth from the ISRIC SoilGrids Africa database at 250 m resolution (soilgrids.org; Hengl et al., 2017), and 0 – 20 cm depth from the iSDA soil maps at 30 m resolution (iSDA-africa.com/iSDAsoil/; Hengl et al., 2021).

Data were analysed using the R statistical software version 4.1.1 (R core team, 2021). Three different random effects models were applied to test specific hypotheses using the *lmer* function of the *lme4* package. First, a simple model was fitted to evaluate overall yield responses in the different study areas. Treatment, study area and their interaction were included as fixed effects, as well as a fixed intercept for year within study area, while trial location was included as a random intercept. A square root transformation was used to obtain a homoscedastic distribution of residuals. The *emmeans* package was used to extract least square mean estimates, and to perform post-hoc comparisons to evaluate pairwise differences between the reference treatment and all other treatments in each study area using the *contrast* function with *sidak* adjustment. Marginal and conditional R^2 values of the model were obtained using the *r.squaredGLMM* function of the *MuMIn* package, to estimate the variance explained by the fixed effects, and the entire model (both fixed and random effects), respectively. A second model was fitted that additionally included a fixed treatment × year within study area interaction term to test the hypothesis that yield responses differ between years in each study area. Finally, a more complex model was fitted to quantify the structural variation in yield response to N, P and K between locations within study area. This model considered year, treatment and their interaction as fixed effects and included uncorrelated random slopes for treatment within trial location. This model was fitted separately for each study area as variation in nutrient response differed strongly between areas, and the yield data from the ½NPK and NPK+ treatments was excluded. Fitting this model was possible because the design included replication of the NPK reference treatment in each location, as well as full replication of all treatments in a portion of the locations. To evaluate the relationship between yield responses and soil and weather parameters, it is beneficial to only carry forward the structural variation in nutrient response and eliminate the random noise. Our approach permits doing so without necessitating costly fully replicated designs in each field. Best linear unbiased predictors (BLUPs) were extracted to reflect the structural variation in yield response between trial locations, eliminating only the plot-level random error. To evaluate variability in yield response at different spatial scales, these BLUPs were grouped based on distance between trial locations (calculated using the *sp* package) using hierarchical clustering at different cut-off distances. At each cut-off distance, yield responses were averaged within group, and variance in yield response between groups was calculated and plotted against the cut-off distance used. BLUPs were also used to evaluate relationships between nutrient responses and soil properties or weather parameters. First, simple Pearson correlation coefficients were calculated with individual soil parameters obtained from iSDA or ISRIC, as well as weather parameters calculated from the CHIRPs daily rainfall, including the total rainfall amount between planting and harvest, rainfall in the first three months (as this is important for uptake of fertiliser nutrients), and rainfall in the three months prior to harvest (as this is important for root bulking). Next, random forest regression models (*randomForest* package) were fitted using all soil and weather parameters as predictors. Model fits were evaluated by calculating R^2 values, and variable importance was evaluated using the mean decrease in accuracy obtained with the *importance* function.

3. Results

Cassava root yields varied substantially between trial locations within each study area (Fig. 3). In Nigeria, average fresh root yields were 28 and 20 Mg ha^{-1} in SEN and SWN, respectively, with approximately normal distributions and large standard deviations of 11 and 10 Mg ha^{-1}, respectively. In Tanzania, fresh root yields were lower (on average 13 and 17 in TSZ and TLZ, respectively), and followed right-skewed distributions, with many locations showing rather low yields. First quartiles were 5 and 9 Mg ha^{-1}, respectively, which are very low yields for cassava. Nutrient treatments affected yield means and distributions, especially in Nigeria. In SEN, the mean yield of the control was 21 Mg ha^{-1} with a standard deviation of 9 Mg ha^{-1}. In the NPK+ treatment (with addition of N, P and K and secondary and micronutrients), the highest mean yield (32 Mg ha^{-1}) and largest spread in the yield data (standard deviation of 13 Mg ha^{-1}) was observed. N omission resulted in the largest decrease in mean yield (– 6 Mg ha^{-1}) relative to the NPK reference treatment and yield in the PK treatment showed a standard deviation comparable to the control (9 Mg ha^{-1}). Mean root yield decreases due to P and K omission were smaller (– 3 Mg ha^{-1}), and the spread in the yield data remained large, comparable to the NPK reference treatment. In SWN, the same patterns were observed but less pronounced, and no decrease in mean yield due to P or K omission was observed. In Tanzania, this pattern was much less evident. In TSZ, the mean control root yield (12 Mg ha^{-1}) was lower than the yield in the NPK reference treatment (14 Mg ha^{-1}) and also showed a lower spread, but the effects of N, P and K omission were not apparent. Also in TLZ, differences between treatments were minimal.

An ANOVA confirmed differences in mean yields between treatments, within each study area across years (Table 1). A highly significant ($P < 0.001$) interaction between treatment and study area was observed. Fresh root yields were highest in the NPK reference treatment in all four study areas (30, 21, 13 and 15 Mg ha^{-1} in SEN, SWN, TSZ and TLZ, respectively), and addition of secondary and micronutrients (Ca, Mg, S, Zn and B) did not result in a further increase in yield (Fig. 4). Fresh root yields were lowest in the control (20, 16, 11 and 14 Mg ha$^{-1,}$ respectively), indicating that NPK fertilisers can increase yields by 10 – 45%. Responses to fertiliser nutrients differed between study areas. Omission of N (NPK – PK) reduced yield by 5.7 Mg ha^{-1} in SEN and 2.8 Mg ha^{-1} in SWN. P omission (NPK – NK) and K omission (NPK – NP) only reduced yields in SEN by 3.3 and + 2.7 Mg ha^{-1}, respectively. The ½NPK treatment increased yields by 3.0 Mg ha^{-1} in SEN and 2.4 Mg ha^{-1} in SWN relative to the control, attaining 68% and 55% of the yield response in the NPK treatment, respectively. The omission treatments and ½NPK treatment did not significantly affect yields in the study areas in Tanzania.

Table 1
Analysis of variance results of the three models used for the analysis of the root yield data. The simple model considers fixed effects for treatment, study area and year within study area, and an interaction between treatment and study area, and a random intercept for trial location. A second model (year interaction model) considers in addition an interaction between year (within study area) and treatment. Site-specific models are fitted separately for each study area and excluded the ½NPK and NPK+ treatments; this model considers fixed effects for year, treatment and their interaction and uncorrelated random slopes for treatment within trial location. Significance levels are indicated at P < 0.001, 0.01, 0.05, 0.1 and P > 0.1 as ***, **, *, . and ns, respectively. Marginal and conditional R^2 values refer to the variance explained by the fixed effects, and the entire model (both fixed and random effects), respectively.

	Simple model	Year int. model	Site-specific effects model			
			SEN	SWN	TSZ	TLZ
Treatment (T)	***	***	***	***	**	ns
Study area (S)	***	***	n/a	n/a	n/a	n/a
T x S	***	***	n/a	n/a	n/a	n/a
S/year (Y)	***	***	ns	ns	***	ns
T x S/Y	n/a	**	ns	ns	.	*
R^2 marginal	0.326	0.330	0.101	0.088	0.217	0.006
R^2 conditional	0.768	0.770	0.715	0.739	0.840	0.666

n/a = not applicable

Yields differed between years within study areas (Table 1), but between-year variation was smaller than variation within and between study areas. In SEN, mean yield was highest for trials harvested in 2017 (29.7 Mg ha^{-1}) and lowest in 2019 (25.4 Mg ha^{-1}), while in SWN, mean yield was highest in 2019 (23.6 Mg ha^{-1}) and lowest in 2018 (17.3 Mg

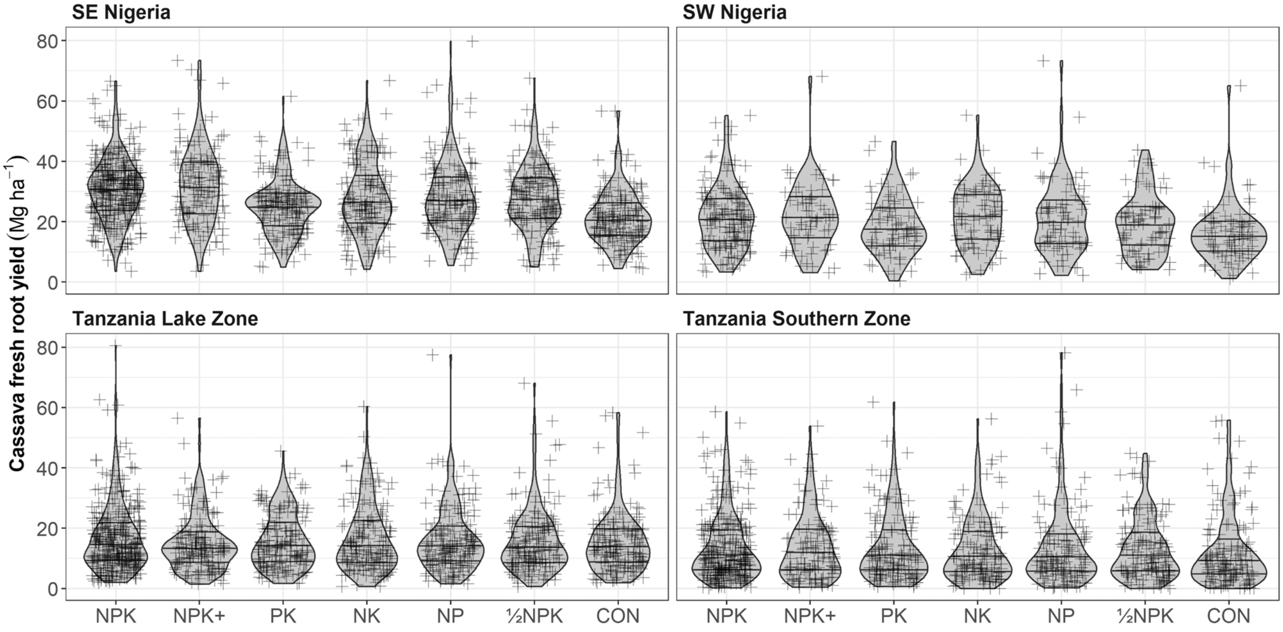

Fig. 3. Violin plots showing observed root yield distributions in the study areas during 3 years as affected by nutrient treatments (NPK: addition of N, P and K; NPK+: addition of N, P, K, Ca, Mg, S, Zn and B; PK: addition of P and K; NK: addition of N and K; NP: addition of N and P; ½NPK: addition of N, P and K at half rate of NPK treatment; CON: control without nutrient addition).

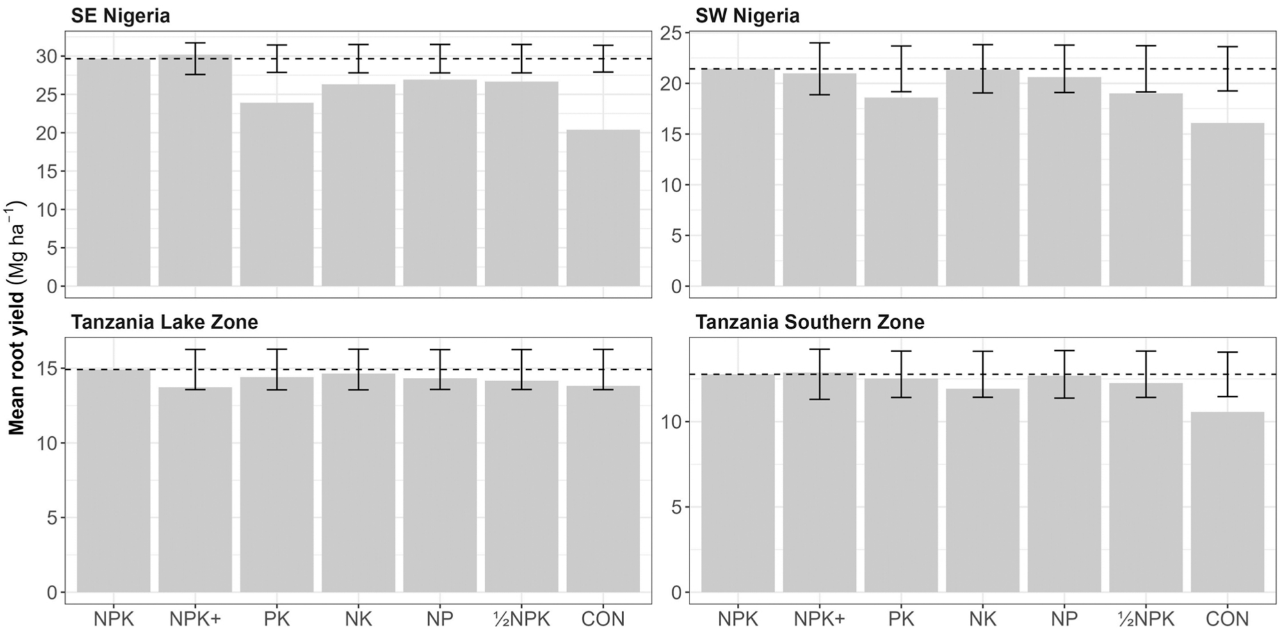

Fig. 4. Mean fresh root yield in the different study areas as affected by nutrient treatments (NPK: addition of N, P and K; NPK+: addition of N, P, K, Ca, Mg, S, Zn and B; PK: addition of P and K; NK: addition of N and K; NP: addition of N and P; ½NPK: addition of N, P and K at half rate of NPK treatment; CON: control without nutrient addition). Error bars represent the 95% confidence interval on the yield difference relative to the NPK reference treatment.

ha^{-1}). In Tanzania, mean yields varied little between years in TLZ (15.5 – 16.1 Mg ha^{-1}) but substantially in TSZ (8.8 – 21.8 Mg ha^{-1}). A more complex model including treatment interactions with year within study area in the fixed model terms showed a slightly better fit (Table 1). Similarly as the simpler model without interactions with year, it showed highly significant ($P < 0.001$) effects of treatment, study area and treatment × study area effects, but in addition, a significant ($P < 0.01$) interaction between treatment and year within study area. In the two study areas in Nigeria, no interaction between treatment and year within site was observed. In the study areas in Tanzania, in contrast, significant treatment effects were only observed in 2018. In TLZ, significant ($P < 0.05$) yield reductions were observed in the PK (–2.0 Mg ha^{-1}) and CON treatment (–2.3 Mg ha^{-1}), while in TSZ, yield reductions were observed in the NK (–2.1 Mg ha^{-1}) and CON treatment (–3.9 Mg ha^{-1}), relative to the NPK reference treatment. No significant effects were observed between other treatments or in other years. Comparing the marginal R^2 value of the simple model and the model including the treatment × year interaction showed that the variance explained by the fixed effects hardly improved. The mean yield differences between the NPK reference treatment and the nutrient omission treatments for each study area and year were plotted against the cumulative rainfall received by the crop during the entire cropping cycle, as well as during

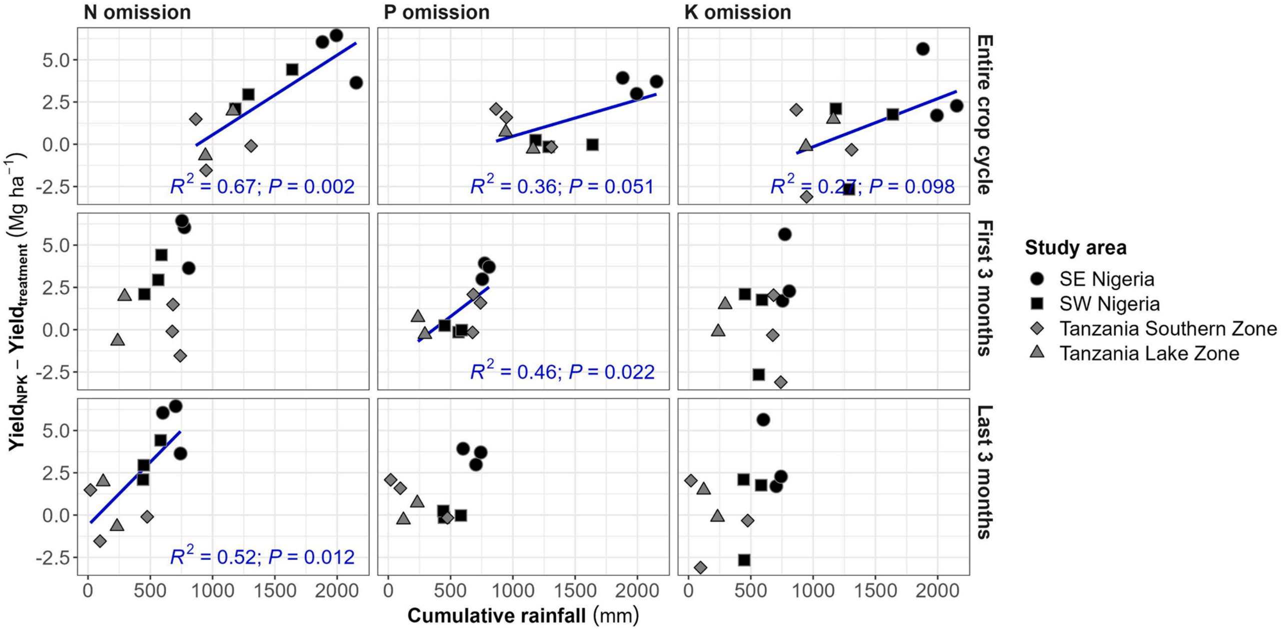

Fig. 5. Mean yield differences (Yield$_{NPK}$ – Yield$_{treatment}$) observed for the N, P and K omission treatments (PK, NK and NP, respectively) in the four study areas for three consecutive years, as related to the cumulative rainfall received during the entire cropping cycle, during the first three months after planting, or during the last three months prior to harvest.

the first three months after planting and the last three months prior to harvest (Fig. 5). Average responses in the different years within study areas were correlated with rainfall received, but differences in relationships were observed depending on the rainfall parameter and nutrient considered. The strongest correlation ($R^2 = 0.70$; $P < 0.001$) was observed between the yield response to N addition with the cumulative rainfall received during the entire cropping period, with largest responses in SEN (+6.0, +6.4 and +3.6 Mg ha^{-1} in 2017, 2018 and 2019, respectively), followed by SWN (+2.9, +2.1 and +4.4 Mg ha^{-1}) and the two study areas in Tanzania (<2.0 Mg ha^{-1}). Cumulative rainfall received during the entire cropping cycle was largest in SEN (2100 – 2200 mm), followed by SWN (1200 – 1650 mm) and the two study areas in Tanzania (850 – 1350 mm). Yield response to N addition was also significantly correlated ($R^2 = 0.56$, $P < 0.01$) with cumulative rainfall received during the last 3 months prior to harvest, but not with rainfall received during the first three months after planting. Response to P addition, contrarily, was best correlated with ainfalll received during the first three months ($R^2 = 0.46$, $P < 0.05$) and rainfall received during the entire cropping cycle ($R^2 = 0.42$, $P < 0.05$), but not with rainfall received during the last three months prior to harvest. Response to K addition was only marginally correlated with rainfall received during the entire cropping cycle ($R^2 = 0.34$, $P = 0.06$).

Variation in fresh root yield responses to N, P and K between trial locations within study area was substantial, especially in SEN (Fig. 6). By fitting a linear mixed effects model and extracting BLUPs for nutrient responses, random plot-level error (or within-field variation) was separated from the structural, location-related variation. Only a minor portion of this structural variation, quantified using the conditional R^2, was captured by the fixed effects (marginal R^2) (Table 1). This again illustrates how variation between locations was much larger than variation across years. The BLUPs showed sensible patterns revealing reductions in yields due to N, P or K omission relative to the NPK reference treatment. The raw observations contrarily showed much more scatter and more frequently seemingly positive yield effects of nutrient omission. The patterns observed in the BLUPs were biologically meaningful; therefore, the mixed effects model approach applied to the dataset with minimal replication (only the NPK treatment was repeated within each trial location, and only 25% of trials were replicated twice within field) was assumed to effectively distinguish the structural variation in yield response to N, P and K. This structural variation was largest in SEN for all three nutrients. In SWN and TSZ, important variation was observed to N and K, while in TLZ, meaningful variation was only observed to N addition. The extent of the variation also varied depending on the yield in the NPK reference treatment. For trial locations with low yields below 10 Mg ha^{-1} in the NPK reference treatment, response to N, P and K was absent or minimal. Variation in response to N, P and K increased with increasing yields in the NPK reference treatment and was largest when yields were in the range of 25 – 40 Mg ha^{-1}. Few locations were available with yields exceeding 40 Mg ha^{-1} to evaluate if the extent and variation in yield response persisted at higher yield levels.

BLUP nutrient responses were clustered based on distance between trial locations, and the variance in yield response calculated after averaging BLUPs within each cluster to evaluate variation in nutrient response at different spatial scales (Fig. 7). A good portion of fields were located within 300 m distance from each other (31%, 24%, 19% and 20% of fields in SEN, SWN, TSZ and TLZ, respectively). When responses in nutrient response were clustered for trials within 300 m distance, variation in fertiliser response declined by 12 – 29%, 17 – 21% and 11 – 19% for N, P and K, respectively, across study areas with meaningful variation in nutrient response. A much larger decrease in variation was observed after clustering at 3 km: the structural variation decreased by 39 – 60%, 46 – 68% and 37 – 55% of the variation in response to N, P and K, respectively, relative to the variation observed at field level (30 m). When clustering at 10 km and 30 km, variation captured was only 20 – 30% and 10 – 20% of the total structural variation observed, demonstrating that variation in nutrient response occurred at a very local scale. Variation in nutrient response differed between study areas, and

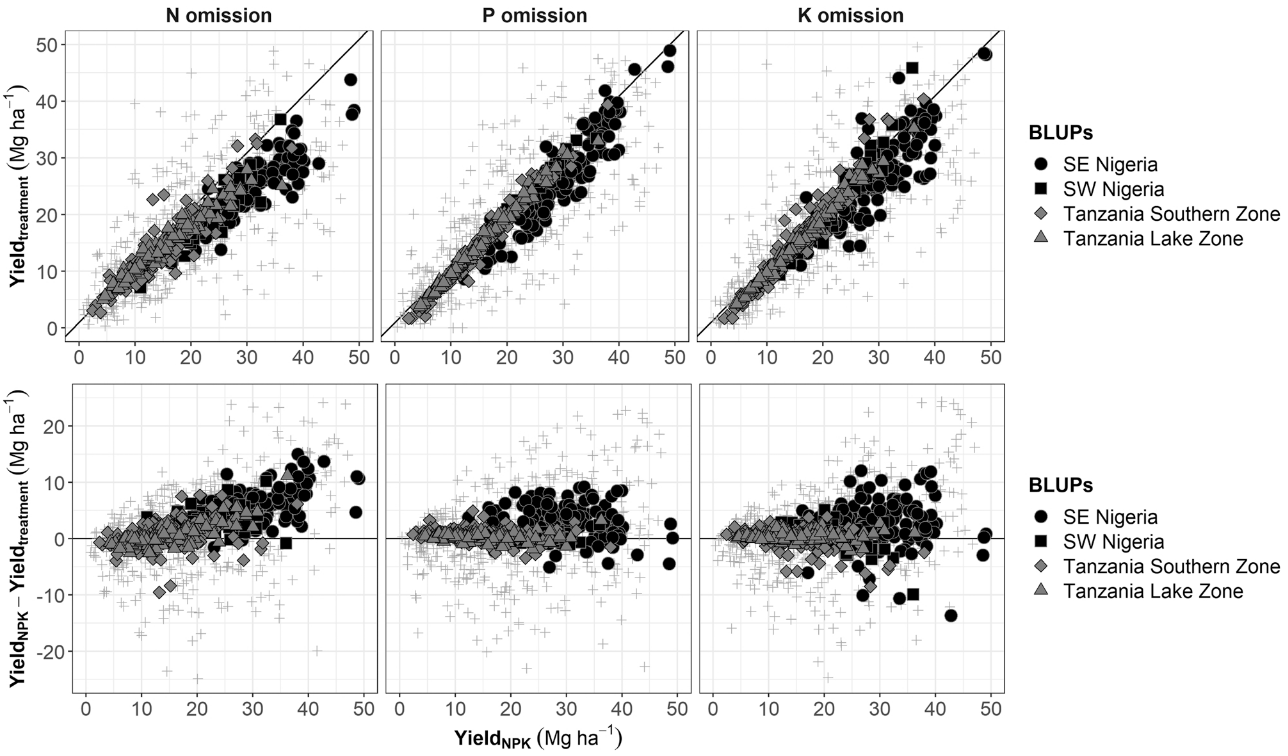

Fig. 6. Best linear unbiased predictors (BLUPs) of yield in omission treatments (top) and yield response to N, P or K (bottom) versus yield in the NPK reference treatment for the 4 study areas (during 3 years). N, P and K omission refer to the PK, NK and NP treatments, respectively. Grey (+) symbols mark the raw observed data.

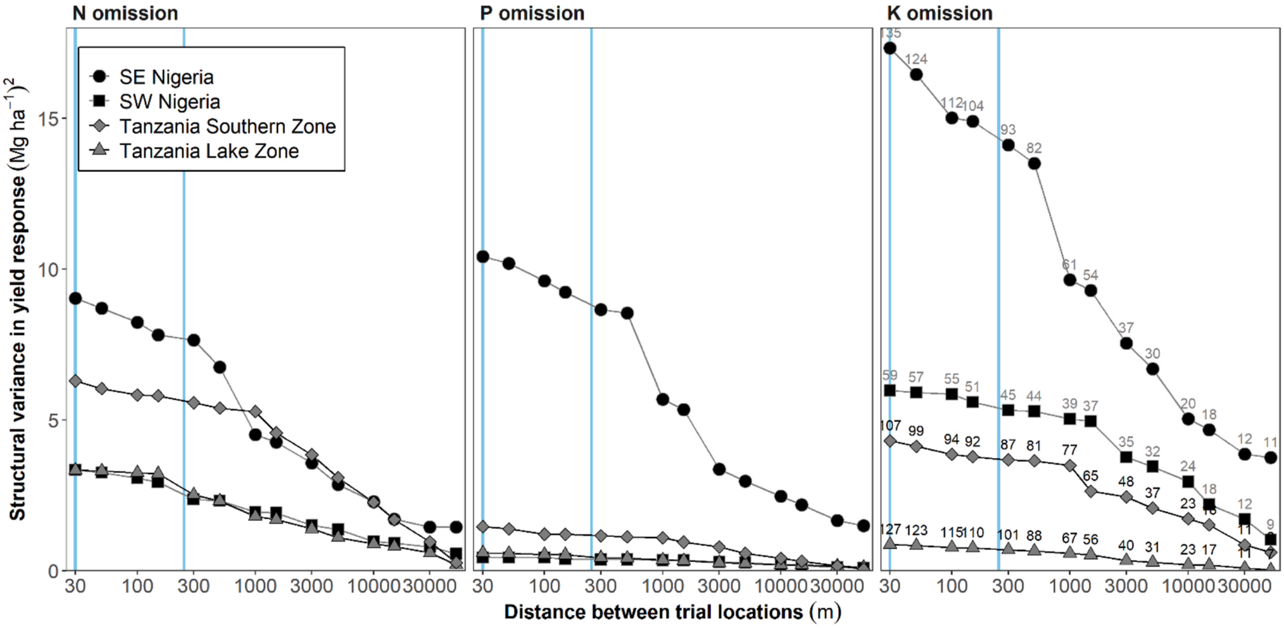

Fig. 7. Structural variance in yield response to N, P and K ($Yield_{NPK} - Yield_{treatment}$) within the four study areas at varying spatial scales. BLUP responses to N, P and K are clustered according to the distance between trial locations and variance in cluster means are calculated. The number of trial clusters at different cut-off distances between trial locations are marked in the K omission facet. Vertical lines mark the spatial resolution of the iSDA (30 m) and ISRIC (250 m) digital soil maps.

between the three nutrients. In SEN, where the largest mean responses to N, P and K were observed, also the largest variation in response was found. However, while the mean reduction in yield was largest for N omission, the variation in response was much larger for K. In SWN, where only a mean reduction in yield was observed for N omission, also more structural variation in response to K was observed than to N. In TSZ, where no mean reductions in yield due to nutrient omission were observed, still significant amounts of variation in N and K response were observed, indicating that a proportion of the trial locations responded positively to N and K application. Only P omission did not result in yield reductions and did not show structural variation in yield response in SWN and in both study areas in Tanzania.

Soils in the study areas were generally poor as shown by soil measurements on the subset of samples analysed in the lab, as well as values extracted from the iSDA and ISRIC digital soil maps (Table 2). Generally, mean values and ranges were comparable for all 3 sources of soil information. Relatively large variation in soil properties was observed, as shown by ranges in values, and variation between study areas was generally much smaller than variation within the areas. Soils were neutral to moderately acidic with pH values varying between 5.0 and 7.1. Lowest mean pH values were observed in SEN (pH 5.7) while highest mean pH values were observed in the TLZ (pH 6.2). Organic C contents were generally low in all study areas, but lowest in the TSZ (on average 7 g kg^{-1}) compared to the other areas (8 – 9 g kg^{-1}). Similarly, total N values were overall low (about 0.9 g kg^{-1}), with lower values in TSZ (on average (0.7 g kg^{-1}) than in the other areas (0.8 – 1.0 g kg^{-1}). Extractable P values were also low in all areas, with mean values of about 8 mg P kg^{-1} in the study areas in Nigeria, versus 9 and 13 mg P kg^{-1} in Tanzania according to the ISRIC and iSDA soil maps, respectively. Extractable cation levels were highest in the TLZ (150, 1050 and 250 mg kg^{-1} of K, Ca and Mg, respectively) in comparison with the other areas (90, 600 and 140 mg kg^{-1} of K, Ca and Mg, respectively). Extractable cation levels implied overall low effective cation exchange capacity (ECEC) in all areas, with mean values of 7.6 cmol$_c$ kg^{-1} in the TLZ and 4.3 cmol$_c$ kg^{-1} in the other areas. Mean clay content was 21% with the lowest mean value in SWN (18%) and the highest mean value in the TLZ (23%). Mean sand content was lowest in SEN (59%) and highest in the TSZ (72%).

Soil parameters from digital soil maps were significantly and positively correlated with lab measurements, with the exception of sand

Table 2
Overview of soil properties (mean and ranges) across the different study areas obtained using wet chemistry lab measurements on topsoil (0–20 cm) collected from a set of 60 randomly selected trial locations, or extracted from iSDA's digital soil map (0–20 cm) and ISRIC's soilGRIDS map (0–30 cm) using the geographic coordinates of all trial locations. Properties include pH H_2O 1:2.5 (pH), organic C content (orgC), total N content (totalN), Mehlich-III extractable P (extrP), extractable K (extrK), extractable Ca (extr Ca), extractable Mg (extrMg), clay content (clay), and sand content (sand). Pearson correlation coefficients for relationships between lab measurements and digital soil map values are indicated, along with significance levels at $P < 0.001$, 0.01, 0.05, 0.1 and $P > 0.1$ as ***, **, *, . and ns, respectively.

		Lab measurements		iSDA soil map			ISRIC soilGrids		
		Mean	(range)	Mean	(range)	Pearson r	Mean	(range)	Pearson r
pH		6.20	(5.80–6.80)	5.88	(5.00–7.10)	0.404 *	5.75	(4.97–6.97)	0.683 * **
orgC	(g kg^{-1})	6.03	(2.70–15.8)	8.00	(4.50–13.9)	0.657 * **	9.52	(5.00–15.8)	0.456 *
totalN	(g kg^{-1})	0.52	(0.22–1.31)	0.90	(0.40–1.70)	0.594 * *	0.88	(0.47–1.59)	0.385.
extrP	(mg kg^{-1})	7.55	(0.60–47.4)	8.73	(5.70–21.2)	ns	11.1	(4.46–25.7)	ns
extrK	(mg kg^{-1})	126	(27.4–368)	91.5	(32.1–329)	0.679 * **	120	(52.0–446)	0.701 * **
extrCa	(mg kg^{-1})	n/a		559	(163–3293)	n/a	883	(191–4183)	n/a
extrMg	(mg kg^{-1})	n/a		138	(48.4–734)	n/a	202	(20.0–856)	n/a
clay	(g kg^{-1})	138	(60–380)	204	(90–340)	0.412 *	214	(120–368)	0.553 * *
sand	(g kg^{-1})	771	(410–870)	623	(450–770)	0.394 *	656	(447–810)	ns

n/a = not available

content for SoilGrids, and extractable P for both soil maps (Table 1). Highest Pearson r values of 0.6 – 0.7 were observed for organic C and pH for the iSDA soil map, and for pH and extractable K for ISRIC's SoilGrids. Correlations were rather weak ($r < 0.5$) for pH and sand and clay content for the iSDA soil map, and for organic C and total N content for SoilGrids.

These soil map-derived properties were frequently significantly correlated with the BLUP nutrient responses within each study area where meaningful structural variance was observed, but relationships were rather weak. The highest absolute Pearson correlation coefficients found was 0.42 for the relationship between pH and response to K in SWN (Table 3). Responses to N were consistently negatively correlated with clay content ($r = -0.27 - -0.15$) and total N content ($r = -0.29 - -0.15$) in SEN, SWN and the TSZ, indicating that larger N responses occurred in soils with lower clay and lower N content. Responses to N were also negatively correlated with organic C and total N content for both digital soil maps. Responses to P in SEN, the only study area where structural variation in P response was observed, were also negatively correlated with organic C content obtained from both soil maps, and with clay content from the iSDA soil map. Responses to P were negatively correlated with extractable P obtained from the ISRIC soil layer. Responses to K were mostly negatively correlated with extractable Ca, K or Mg in all relevant study areas, and sometimes negatively with clay content, and/or positively with sand content, indicating that larger K responses tend to occur in more sandy soils with lower extractable cations. Significant relationships with pH were observed, but the direction differed depending on the nutrient and study area considered. Effects of nutrient omission were also correlated with rainfall parameters, particularly for K omission with total rainfall (TRF) and rainfall during the last 3 months prior to harvest (RH3) in SWN, and for N omission with TRF and rainfall in the first 3 months after planting (RP3) in TLZ.

Performance of random forest models predicting nutrient response using soil and weather parameters was generally not affected by the digital soil map resource used, but differed substantially between study areas and nutrient omission treatments (Table 3). Response to P in SEN were generally best predicted with R^2 values of almost 0.6. Predictions were poorest for N omission effects in SWN and the TSZ, with R^2 values of 0.16 – 0.22. For other treatment and study area combinations, R^2 values were 0.4 – 0.5, except for K omission effects in SWN using ISRIC soil data ($R^2 = 0.58$). Average importance of all variables was about 10%, but varied depending on the treatment and study area (Fig. 8). No predictor variable stood out as substantially more important than others. Rainfall parameters generally ranked highest, particularly for N and P omission in SEN, for K omission in the TSZ, and for N omission in TLZ. Amongst the soil parameters, importance tended to be higher for sand content, pH, extractable Mg and K, and total N. The relative importance of variables differed between study areas and omission treatments but was rather consistent and correlated ($R^2 = 0.42 – 0.52$, $P < 0.001$) between the two digital soil maps.

4. Discussion

Cassava fresh root yields in the control treatment were low (on average 18 Mg ha^{-1} in Nigeria and 12 Mg ha^{-1} in Tanzania) but well above national average values of 9 and 6 Mg ha^{-1} (FAOSTAT, 2022), likely due to the use of improved varieties and good agronomic practices applied in the on-farm trials, particularly for land preparation and weed control. While good agronomic practices can raise fresh root yields to 10 – 25 Mg ha^{-1} under smallholder conditions in SSA, higher yields require investment in NPK fertilisers. NPK application increased mean root yield to 28 Mg ha^{-1} in Nigeria and 15 Mg ha^{-1} in Tanzania, with maximal values of 49 and 38 Mg ha^{-1}, respectively. Similar yield increases due to application of NPK fertilisers have also been demonstrated by Adiele et al. (2020a); b) in Nigeria, Ezui et al. (2017) in Togo and Ghana, and Fermont et al. (2010) in Uganda and Kenya. In our study, largest responses were to N, while mean responses to P and K were only observed in SEN, demonstrating that nutrient deficiencies differ between regions,

Table 3

Pearson correlation coefficients for relationships between BLUP yield responses to N, P and K ($\text{Yield}_{NPK} - \text{Yield}_{PK}$, $\text{Yield}_{NPK} - \text{Yield}_{NK}$, $\text{Yield}_{NPK} - \text{Yield}_{NP}$, referred to as N, P and K omission, respectively) in the four study areas and soil parameters (see Table 2 for parameter descriptions) obtained from ISRIC's SoilGrids (0–30 cm) or iSDA's iSDAsoil (0–20 cm) digital soil maps or rainfall parameters obtained from CHIRPs (TRF = total rainfall amount between planting and harvest, RP3 = rainfall in the first 3 months after planting and RH3 = rainfall in the last 3 months prior to harvest), and R^2 values for a random forest regression model using the soil and weather data as predictors. Only study areas with meaningful structural variation in nutrient response are included in the analysis. Significance levels of correlation tests are indicated at $P<0.001$, 0.01, 0.05, 0.1 and $P > 0.1$ as ***, **,*, . and ns, respectively.

	Source	SE Nigeria			SW Nigeria		Tanzania Southern Zone		Tanzania Lake Zone
		N omission	P omission	K omission	N omission	K omission	N omission	K omission	N omission
Pearson correlation coefficients									
pH	iSDA	0.182 *	0.138.	0.186 *	ns	-0.260 *	ns	-0.216 **	-0.131.
	ISRIC	0.261 ***	0.192 **	ns	0.240 *	-0.421 ***	ns	-0.217 **	-0.134.
orgC	iSDA	-0.258 ***	-0.249 ***	ns	-0.254 *	0.248 *	-0.166 *	ns	ns
	ISRIC	-0.232 **	-0.137.	ns	-0.195.	ns	ns	ns	ns
totalN	iSDA	-0.194 **	-0.290 ***	-0.156 *	ns	ns	-0.286 ***	-0.318 ***	ns
	ISRIC	-0.146 *	-0.177 *	-0.172 *	-0.203.	0.248 *	ns	ns	0.190 *
extrP	iSDA	ns	ns	ns	0.202.	ns	0.227 **	ns	ns
	ISRIC	ns	-0.133.	ns	ns	ns	ns	ns	ns
extrK	iSDA	ns	ns	ns	ns	ns	-0.137.	-0.369 ***	ns
	ISRIC	-0.203 **	ns	0.185 *	ns	-0.229 *	ns	ns	ns
extrCa	iSDA	0.133.	ns	-0.158 *	ns	-0.252 *	-0.150.	-0.155.	ns
	ISRIC	ns	ns	ns	ns	ns	ns	-0.218 **	-0.135.
extrMg	iSDA	0.176 *	ns	-0.168 *	0.198.	-0.219.	-0.138.	-0.142.	-0.189 *
	ISRIC	ns	ns	0.185 *	ns	-0.248 *	ns	-0.187 *	-0.148 *
clay	iSDA	ns	-0.247 ***	-0.354 ***	-0.211.	ns	-0.168 *	-0.162 *	ns
	ISRIC	-0.196 **	ns	ns	-0.267 *	ns	-0.154.	ns	ns
sand	iSDA	ns	0.237 **	0.368 ***	ns	ns	0.139.	0.271 ***	ns
	ISRIC	ns	ns	0.156 *	0.280 *	ns	0.197 *	0.185 *	ns
TRF	CHIRPs	ns	ns	ns	0.336.	0.516 **	ns	ns	0.37 ***
RP3	CHIRPs	-0.139.	ns	ns	ns	ns	ns	ns	0.342 ***
RH3	CHIRPs	ns	ns	0.186 *	ns	0.599 ***	ns	ns	ns
Random forest model R^2									
iSDA+CHIRPs		0.39	0.58	0.48	0.22	0.46	0.18	0.42	0.40
ISRIC+CHIRPs		0.40	0.59	0.46	0.16	0.58	0.21	0.43	0.39

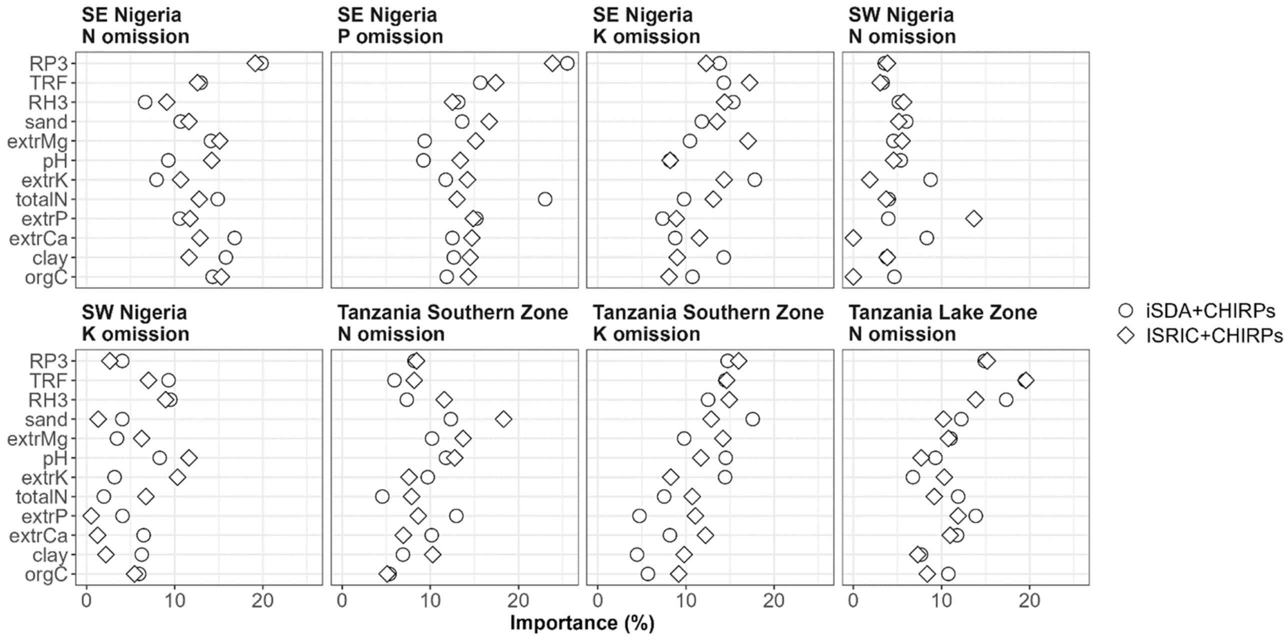

Fig. 8. Relative importance of soil and weather parameters in the random forest models predicting cassava root yield response to N, P or K in the different study areas, ordered based on overall mean importance. Only study areas with meaningful structural variation in nutrient response are included. Soil parameters (see Table 2 for parameter descriptions) are sourced either from ISRIC's SoilGrids (0–30 cm) or iSDA's iSDAsoil (0–20 cm) digital soil maps, and weather parameters (TRF, RP3 and RH3) are obtained from CHIRPs.

as was also found in other studies (Ezui et al., 2016; Fermont et al., 2010; Senkoro et al., 2018). We did not find mean responses to additional secondary or micronutrients in any of the study areas, nor did we observe meaningful variation in BLUP responses to addition of Ca, Mg, S, Zn and B (not shown), similar to Senkoro et al. (2018) and Adiele et al. (2020b). Yield responses to these nutrients are rare in field-grown cassava and only occur in very acid, alkaline or sandy soils (Howeler, 1981; Goldberg, 1997). Such soils did not occur in our study areas. Raising productivity in cassava systems in the four study areas can therefore focus on supply of N, P and K.

Major differences in yield responses between study areas were likely governed by differences in agro-ecology, particularly total rainfall and rainfall distribution. Rainfall was most favourable in SEN (1500 – 3000 mm, of which half fell in the first four months after planting) and least favourable in TLZ (about 1000 mm of which only 250 mm in the first 3 months). Fermont et al. (2010) observed that cassava yield response to fertiliser was reduced in on-farm trials if total rainfall was less than 1500 mm, or if rainfall during the first three months did not exceed 400 mm. While cassava is able to withstand long periods of drought (El-Sharkawy, 2006) and produce acceptable yields with less than 1000 mm of rainfall, optimal yields are obtained with at least 1500 mm of rainfall (Keating et al., 1982). As such, rainfall was sufficient to ensure yield responses to fertiliser in SEN and SWN, while in the study areas in Tanzania, crop growth was likely much more limited by water supply. Mean yield responses were correlated with total rainfall between planting and harvest (Fig. 5). In addition, BLUP responses to N increased with increasing rainfall quantities during the first three months in both study areas in Tanzania (not shown), confirming the observations by Fermont et al. (2010). During these first months, more than 50% of the total uptake of N, P and K occurs (Adiele et al., 2021), and cassava initiates the formation of storage roots. Drought stress during this process reduces the crop's sink capacity and nutrient uptake, substantially affecting crop yield and response to fertiliser (Duque and Setter, 2019; El-Sharkawy and Cadavid, 2002). Total rainfall amount and distribution were rather similar in the three years, which may explain the relative consistency of responses to nutrients across the different years, especially in Nigeria. Fermont et al. (2010) also observed consistent cassava yield responses to fertiliser across seasons in Uganda, but not in Kenya, which could be explained by large differences in rainfall. Seasonal rainfall importantly affects fertiliser response in cassava, although perhaps less so than in other crops such as maize (e.g., Njoroge et al., 2017) or soybean (Ronner et al., 2016). Still, fertiliser advice in cassava should consider the planting time and expected rainfall during crop growth.

While important differences were observed in mean responses between the four study areas, considerable variation in response was observed within each of the study areas. Fertiliser response is known to vary under smallholder conditions in SSA in cassava (Fermont et al., 2010), as in other crops such as maize (Sileshi et al., 2010; Kihara et al., 2016; Njoroge et al., 2017), grain legumes (Ronner et al., 2016; Roobroeck et al., 2021). This variability can be observed within farms or communities and is related to soil fertility gradients, which are typically caused by differential crop management and past use of organic and inorganic inputs (Tittonell et al., 2008a). In our study, the extent of this variation differed between the study areas and between the three nutrients N, P and K (Fig. 7). This variation was largest in SEN, where 50%, 45% and 44% of the variation in response to N, P and K, respectively, occurred at a scale < 1 km, and was largest for K, followed by P and lastly N, opposite to the order of the mean effect sizes. In the other regions, more than 40% of the variation in N response occurred at short-range distances (< 1 km). This confirms that variation in nutrient response occurs at a very 'local' scale. Understanding this variation is critical to tailor fertiliser advice to local soil conditions and increase productivity in an effective and sustainable manner (Giller et al., 2011; Vanlauwe et al., 2014).

Responses to K occurred more often in trials with yields > 25 Mg ha^{-1} in the NPK treatment and were almost absent below this value (Fig. 6), implying that K demand only becomes important in more productive fields. Deficiency in K frequently occurs in highly weathered soils with low activity clays and low K reserves such as Ferralsols, Nitisols and Acrisols, which are common in SEN, and becomes more apparent with increased cultivation intensity (Howeler, 2011). K is a critical nutrient for carbohydrate synthesis and translocation; cassava roots contain high concentrations of K (Fernandes et al., 2017), resulting in substantial K exports and depletion of soil K reserves in continuous production systems (Howeler, 2002; Chua et al., 2020). Several long-term studies have illustrated that K deficiency and response to applied K increases over time when cassava is grown year after year (Howeler, 2017), a practice which is common in SEN. Variation in response to K (sd = 4.2 Mg ha^{-1}) is very large relative to the mean response (2.7 Mg ha^{-1}). Also in SWN and TSZ, yield decreases due to K omission occurred most often in more productive fields, but these only constituted a minority of the trial locations (28% and 15% in the two study areas, respectively). The soils in these areas likewise have low activity clays or are sandy with low K reserves. In smallholder systems, K application should therefore be recommended to fields with high production potential that have been cultivated with cassava during several years to maximise cost effectiveness of fertiliser investments.

Our results suggest that P was a critical limitation only in SEN, as only in SEN we observed an overall response to P (+3.3 Mg ha^{-1}) and variation in response to P between field locations (sd = 3.2 Mg ha^{-1}). Possibly, P only became limiting under the overall more favourable conditions for cassava production in SEN. However, unlike K, no relationship with yield in the NPK reference treatment was observed (Fig. 6), suggesting that P deficiency not only occurs in highly productive fields. Response to P depends on the soil P supply but can also be influenced by varietal traits (Pellet and El-Sharkawy, 1993). However, in our study, the same variety TME419 was used in both SEN and SWN, and available P levels were comparably low in both study areas (median Mehlich-III extractable levels of 6 mg P kg^{-1}). Still, even in the most productive fields in SWN, no substantial yield losses were recorded due to P omission. Cassava is known to be extremely tolerant to low levels of available P, as it is able to acquire P through effective association with vesicular arbuscular mycorrhizae and produce high yields in low-P soils (Howeler et al., 1982). Differences in response to P may be attributed to the efficiency of the mycorrhizal populations (Howeler and Sieverding, 1983) or other physical and biological processes that control P availability. Management practices and fallowing can indirectly influence the abundance and effectiveness of native mycorrhiza (Thanni et al., 2022). This may provide an explanation for the differential responses between the two study areas, and the variation in P response observed in SEN, as production systems are very different. Fallow periods in SEN are commonly short; land clearing by slash and burn is a common practice, as well as use of moderate amounts of fertiliser (mostly urea). In SWN, fallow periods of two years are common; land preparation is done more frequently by tractor, and fertiliser is rarely used in cassava systems. Further investigation would be required to unravel the underlying processes that lead to the differential responses to P between the two study areas in Nigeria. Our results imply that only in SEN, P must be included in balanced fertiliser recommendations, and similarly as for K, P application should be targeted to responsive fields, given the large variation in response between locations within the study area. In the other study areas, P can be omitted from fertiliser recommendations for short term profit optimisation but moderate maintenance applications should be considered to sustain long term productivity.

Variation in N response was observed in all four study areas, and was again largest in SEN (sd = 3.0 Mg ha^{-1}) and smallest in TLZ (sd = 1.8 Mg ha^{-1}). While mean responses were only observed in the two study areas in Nigeria, N deficiency occurs in an important portion of the locations in all study areas. In all areas, response to N increased with increasing yield levels in the NPK reference treatment, and largest responses to N were observed in trial locations where the fresh root yield in the NPK reference treatment exceeded 20 Mg ha^{-1}. These can be presumed to represent conditions in which rainfall (or other factors not related to nutrient deficiency) are less limiting for crop growth. Several studies have shown that N is commonly the most limiting nutrient for cassava growth (Fermont et al., 2010; Oliveira et al., 2017; Senkoro et al., 2018), and variation in responses occur depending on the N supply capacity of the soil, which is influenced by the soil organic matter content, texture and pH (Howeler, 2002; 2017). Our results confirm that N application is essential for cassava cultivation, and relevant in all study areas. In SEN, the mean response to N was largest while variation in N response was lower than that in P or K response, but still substantial to justify adjusting N application rates to local soil conditions. In the other study areas as well, our results suggest that N fertiliser use is required to optimise cassava production, and blanket recommendations would not be suitable given the high variability in N response.

By relating variation in nutrient response to soil properties, fertiliser use can be targeted to responsive fields and effective fertiliser recommendations can be formulated (Tittonell et al., 2008b; Abera et al., 2022). Howeler (2002) demonstrated relationships between relative cassava yields and soil organic matter content, available P concentrations and exchangeable K levels, and Fermont et al. (2010) found that relative cassava root yield responses to NPK fertiliser were negatively associated with soil organic C and total N, albeit weakly. Soil tests are an established approach to tailor fertiliser advice, but smallholder farmers are unlikely to be able to access or afford soil analytical services. The ISRIC and iSDA digital soil maps offer a resource of sufficient resolution to explain the short-range variation in BLUP yield responses. As measured soil properties on a subset of soil samples were correlated with the predictions of these soil maps (Table 2), these digital soil maps are potentially informative to explain crop response. We found that response to K was correlated to extractable cations and clay content, while responses to N and P were significantly correlated to organic C, total N and clay contents. These soil parameters are evidently related to the soil organic matter content, which affects nutrient supply and retention, soil structure, water infiltration and storage (Allison, 1973). Other studies have shown that soil organic matter has an important influence on responsiveness to mineral fertiliser, but that relationships with individual soil parameters are generally weak (Kihara et al., 2016; Njoroge et al., 2017; Vanlauwe et al., 2006).

By using all soil parameters alongside with rainfall data as predictors in random forest models, roughly 40% of variation in response to fertiliser nutrients could be explained (Table 3); omitting the rainfall parameters only marginally decreased the variation explained (not shown). All soil variables contributed meaningfully, but their relative importance varied depending on the omission treatment and study area. Ichami et al. (2020) similarly found that soil properties from a digital soil map accounted for 31% of the farm-level variation in maize yield. Digital soil maps combined with machine learning therefore show promise to develop site-specific fertiliser recommendations. Blanket recommendations, or recommendations disaggregated by agroecological zone or administrative units would fail to adequately capture the short-range variation in fertiliser response. On-farm experimentation is critical to gain insights in the spatial variability in response to fertiliser nutrients, and results in one study area cannot simply be extrapolated to other areas. A substantial portion of the variation however remains unexplained. Under farmer management, variable crop performance (including response to fertiliser) within and across farms cannot be ascribed solely to soil nutrient availability (Tittonell et al., 2008b). Other aspects including cropping history, land management, weed types and population, and crop husbandry determine crop performance and fertiliser use efficiency. Fertiliser advisory tools may benefit by considering farm-specific information, in addition to soil information (Chivenge et al., 2022).

5. Conclusions

Our results demonstrate that fertiliser response in smallholder cassava production systems is highly variable, and that variation occurs at a very ‘local’ scale. Blanket recommendations would not be suitable to cost-effectively address nutrient constraints. Large differences in mean responses and spatial variation were observed between the three nutrients and between study areas. Results from one area cannot simply be extrapolated to another area, emphasising the need for on-farm experimentation to develop fertiliser recommendations at an appropriate scale. Nutrient responses were weakly but significantly associated with individual soil parameters such as soil organic C, total N, texture, and extractable cations, in agreement with expected relationships observed in the literature. Random forest models could explain approximately 40% of the variation in nutrient response using soil parameters obtained from digital soil maps. Digital soil maps have clear value to develop fertiliser recommendations for cassava smallholder systems but are unlikely sufficient to provide accurate advice at field level. Further research should evaluate whether complementing digital soil maps with information on cropping history, past input use and/or local indicators of soil fertility and crop productivity can improve the overall prediction of crop response to fertiliser nutrients.

CRediT authorship contribution statement

Masunga Habai Rafael: Data curation, Formal analysis, Writing – original draft. **Chernet Meklit**: Data curation, Formal analysis, Writing – original draft. **Ezui Kodjovi Senam**: Conceptualization, Writing – review & editing. **Mlay Peter Deusdedit**: Investigation, Resources, Writing – review & editing. **Olojede Adeyemi**: Investigation, Resources, Writing – review & editing. **Florence Olowokere**: Investigation, Resources, Writing – review & editing. **Mutiu Busari**: Investigation, Resources, Writing – review & editing. **Hauser Stefan**: Methodology, Investigation, Writing – review & editing. **Kreye Christine**: Methodology, Investigation, Writing – review & editing. **Baijukya Frederick**: Methodology, Investigation, Writing – review & editing. **Merckx Roel**: Supervision, Writing – review & editing. **Pypers Pieter**: Project administration, Funding acquisition, Conceptualization, Formal analysis, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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