Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms

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Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms

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Abstract

Large variability in crop responses to macronutrient application at various spatial scales present challenges for developing effective fertilizer recommendations for crop production in smallholder farming systems of sub-Saharan Africa. We assessed maize yield responses to nitrogen (N), phosphorus (P) and potassium (K) application and evaluated relationships between crop responses to N, P and K application and soil analysis data. Nutrient omission trials were conducted on 23 farms located in Sidindi, Western Kenya, selected to be representative of the main soil and management factors in maize based systems in Siaya County. Treatments included a control and PK, NK, NP and NPK applications. The trials ran for six consecutive cropping seasons, without changing treatments or plot location, covering the period 2013–2015. Strong spatial-temporal patterns in maize yield responses to N, P and K applications were observed. Average maize yields in the control, PK, NK, NP and NPK treatments were 2.8, 3.2, 5.1, 5.1 and 5.5 t ha^{-1} at 88% dry matter respectively in the first cropping season, and 1.1, 1.4, 2.9, 3.6 and 5.3 t ha^{-1} at 88% dry matter respectively in the sixth cropping season. In all seasons, variability in maize yield between fields was greatest in the control treatment followed by the NK treatment and least in the NPK treatment. Mean relative yield was 0.6, 0.92 and 0.93 for N, P and K respectively, in the first cropping season, and 0.25, 0.52 and 0.68, respectively, in the sixth cropping season. Six main maize yield response categories were identified that differed in the maize grain yield responses to recursive N, P and K applications. Maize yield responses to N, P and K were not fully accounted for by soil organic matter, soil available P and exchangeable K respectively. Our results indicate that current methods for soil analysis do not adequately predict the response to application of N, P and K fertilizer under the highly variable soil fertility conditions encountered in smallholder farming systems. The strong spatial-temporal patterns observed present major challenges for the development of effective site-specific fertilizer recommendations. Potential avenues for future research and options for more effective intensification strategies are discussed.

1. Introduction

Crop production in smallholder systems in sub-Saharan Africa (SSA) is strongly limited by poor soil fertility that results from continuous cropping with little or no nutrient replenishment (Kihara *et al.*, 2015; Sanchez, 2002), with an average fertilizer application rate of 13 kg ha^{-1} (Minot and Benson, 2009). Soil deficiencies of macronutrients are widespread in the region, with negative nutrient balances reported for nitrogen (N), phosphorus (P) and potassium (K) in most parts of SSA (Xu *et al.*, 2014). As a result, the yields obtained by farmers using local practices of important food crops in the majority of smallholder farming systems in SSA are far below the attainable yield (Van Ittersum *et al.*, 2016) resulting in yield gaps, defined as difference between actual and potential yields under rainfed conditions without nutrient deficiency, pest or diseases (Van Ittersum and Rabbinge, 1997). In the last decade for SSA, actual rainfed maize yields ranged from 1.2 to 2.2 t ha^{-1}, representing only 15-27% of the potential yield under rainfed conditions (Van Ittersum *et al.*, 2016). Consequently, SSA has been identified as one of the regions in the world with the lowest cereal sufficiency ratio defined as the ratio between domestic production and total consumption (Van Ittersum *et al.*, 2016).

Given that up to 75% of the population in SSA depend directly or indirectly on agriculture as a livelihood source (Nziguheba *et al.*, 2010; Sanchez *et al.*, 2007), the sector's large contribution to the overall economy (Diao *et al.*, 2010), and the projected decrease in cereal self sufficiency over time (Van Ittersum *et al.*, 2016), agricultural intensification is urgently needed (Tittonell and Giller, 2013). Considerable ‘low hanging’ opportunities exist for intensification of production of major cereals in SSA (Mueller *et al.*, 2012) when N, P and K deficiencies are addressed (Adediran and Banjoko, 1995). Since the launch of the Alliance for Green Revolution in African (AGRA) in 2006 (AGRA, 2016), and the recommendations of the Africa fertilizer summit of 2006 (Summit, 2006), a number of research programmes have focused on intensification of crop productivity in smallholder farming systems in SSA (Chikowo *et al.*, 2014). Although fertilizer use has increased in a number of countries in SSA, its use efficiency remains low due to poor crop management practices (Byerlee *et al.*, 2007; Sheahan and Barrett, 2014), the predominance of inherently low fertility sandy soils (Bationo *et al.*, 2012), and unbalanced blanket fertilizer recommendations that do not address the complexity of smallholder farming systems (Chikowo *et al.*, 2014; Giller *et al.*, 2011). Further, the occurrence of “non-responsive soils” where application of available fertilizers does not result in increased crop productivity (Vanlauwe *et al.*, 2010) has an additional adverse effect on fertilizer use efficiency. Such non-responsiveness may be due to a range of factors including macro- and micronutrient depletion, poor germination due to slaking or top-soil erosion, aluminium toxicity in relation to soil acidification and increased sensitivity to drought conditions (Tittonell and Giller, 2013; Vanlauwe *et al.*, 2015). As a result, crop productivity intensification programmes in SSA have faced large variations in yield responses to applied nutrients at farm and field scales (Tittonell *et al.*, 2008b; Vanlauwe *et al.*, 2006). This raises the need for fertilizer recommendations that are tailored for specific farm and field conditions (Smaling *et al.*, 1992; Tittonell *et al.*, 2008a). Although, inherent soil fertility is related to soil forming factors including geomorphology, local climate and vegetation (Deckers, 2002; Smaling *et al.*, 1993), cropping intensity and past soil management have been identified as major drivers of variability (Tittonell *et al.*, 2005). The centripetal net transport of nutrients by animals also results in strong gradients at landscape level (van Keulen and Breman, 1990). The strong effects of management often result in patterns of decreasing soil fertility with increasing distance from homesteads within farms (Tittonell *et al.*, 2005; Zingore *et al.*, 2007a) and decreasing soil fertility with decreasing resource availability and use among farms (Giller *et al.*, 2006; Tittonell *et al.*, 2005).

Consequently, regions and or farms with similar inherent soil fertility may over time develop strong heterogeneity in soil fertility and associated responses to macronutrients (N, P and K) applications. There is a paucity of information on both spatial and temporal patterns of such responses. Spatio-temporal patterns refer to differences in the dynamics of crop yield responses to macronutrients applications in an area with similar climatic conditions. This is because most nutrient management technologies were developed at research stations without sufficiently acknowledging the complexity of farming systems (Chikowo *et al.*, 2014). Such information would help to target the right fertilizer and application rates to specific crops and locations and improve the efficiency of fertilizer use (Kihara *et al.*, 2016). Further, understanding the relationships between spatial-temporal responses to macronutrients application and soil analysis results would help in quantifying the value of soil analysis, which is considered an important component of restoring and managing soil fertility in smallholder farming systems (Sanginga and Woomer, 2009). Controlled experiments in a series of heterogeneous farmers' fields therefore offer the most conceptually straight forward way to study spatial temporal variations in responses to macronutrients (Lobell *et al.*, 2009; Vanlauwe *et al.*, 2006). Further insight on the magnitude, and consistency of observed spatial temporal patterns over time can then be achieved using cluster analysis (Perez-Quezeda *et al.*, 2003). Cluster analysis allows for the grouping of fields showing similar responses over time into distinct classes (Fridgen *et al.*, 2004), and was used effectively to identify various classes of nutrient response patterns in smallholder farming systems in SSA (Kihara *et al.*, 2016).

The specific objectives of this study were to: (i) assess the magnitude and spatial-temporal patterns of maize yield responses to N, P and K application; (ii) identify and characterize clusters of farms with similar yield response patterns to N, P and K; (iii) assess the utility of soil chemical properties in predicting maize responses to N, P and K application. We hypothesize that patterns of crop responses to N, P and K fertilization over a combination of space and time in heterogeneous farms provide an important basis for developing site-specific fertilizer recommendations.

2. Materials and methods

2.1 Study Site

The study was conducted in Sidindi, western Kenya. A 10 km by 10 km site previously used to collect soil mapping data under the African Soil Information Services (AfSIS) project was selected (AfSIS, 2016). The site is centred at a latitude of 0.15 ^{o}N, a longitude of 34.4^{o}E and at about 1240 metres above sea level. Annual rainfall ranges from 1600 – 2000 mm and is distributed over two distinct seasons with a long rains (LR) season from March to July and short rains (SR) season from September to December. Maize is the main staple food crop and is cultivated on more than 80% of the crop area in western Kenya (Place *et al.*, 2006). Despite water limited yields (Yw) which refers to the yield achievable in farmer's fields with best nutrient, pest, and crop management practices under rainfed conditions (Van Ittersum *et al.*, 2013) of 12 t ha^{-1} and 8 t ha^{-1} in the long and short rains seasons respectively, actual maize yields on majority of smallholder farms in western Kenya are low at about 1.9 t ha^{-1} (Van Ittersum *et al.*, 2016). The area is also characterized by large within and between farm heterogeneity in soil fertility (Tittonell *et al.*, 2005).

2.2 Selection of trial sites

On-farm nutrient omission trials were established in 2013 across 24 sites representative of major soil units in the study area. Selection of trial sites was conducted on the basis of a previous survey conducted by the AfSIS project (AfSIS, 2016) that collected socio economic and agronomic data from 300 farmers within the study site (data not shown). From this survey, stratified random sampling was conducted to select an initial sample containing 48 farms representative of the study area based on land size, socio-economic characteristics and soil type.

From this sample, eight fields within each of the three sub-locations in the study area namely Sirembe, Malanga, and Ndere were selected based on the availability of land for trial set-up to make a total of 24 fields.

Seasonal rainfall data in each of the sub-locations was collected using rain gauges located at each of the sub-locations. The experiments were conducted for six consecutive cropping seasons in 2013 – 2015.

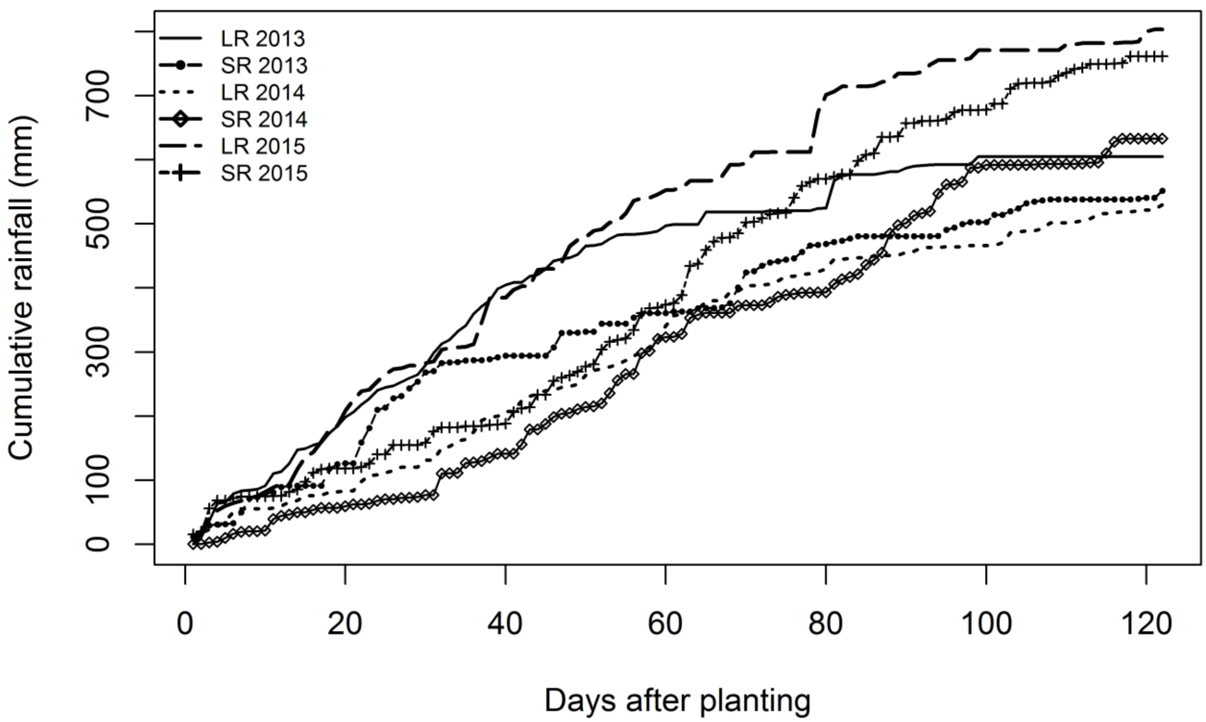

Figure 1: Cumulative average rainfall in the long rain (LR) and short rain (SR) seasons of 2013 - 2015.

2.3 Site characterization

Prior to the establishment of the trials, the position of each field was determined using a Global Navigation Satellite Systems receiver (Etrex 20, Garmin Limited, Chicago USA). Soil samples were collected from four points within each field using a 'Y frame sampling approach' at a 0-20 cm depth. Collected samples were then placed in a basin, thoroughly mixed and a composite sample obtained. Composite samples from each field were then air dried and passed through a 2 mm sieve before chemical analysis at Crop Nutrition Laboratories in Nairobi. Available P and exchangeable bases (calcium, magnesium, K and sodium) were determined after a

Mehlich 3 extraction (Mehlich, 1984), while soil organic matter (SOM) was determined using the Walkley-Black method (Robinson, 1993). Soil pH was determined in water, while soil texture was determined using the hydrometer method after adding a dispersing solution to a 50 g sample of soil (Bouyoucos, 1962).

2.4 Experimental treatments and management

The first set of nutrient omission experiments was established in early April 2013 at the onset of the long rains season. The experiment included a set of five treatments to assess maize response to N, P and K application including a control, P+K, N+K, N+P and N+P+K treatments established in plots measuring 10 m by 10 m (Table 1) replicated in 24 farms with each farm serving as a complete block. N was applied in the form of urea in three equal splits; at planting, at three weeks after emergence and at six weeks after emergence. The P and K fertilizers were applied at planting in the form of triple super phosphate (TSP) and muriate of potash (KCl) respectively. Trial plot locations and allocated treatments remained the same throughout the study period.

Each season, fields were prepared about two weeks before seeding by tilling to a depth of approximately 20 cm using hand hoes. Remaining crop residues from the previous season were removed prior to tilling, reflecting normal farmer practice. Throughout the experimental period, the short-season maize variety DK8031 was planted at the recommended spacing (75 by 25 cm) to give 53,333 plants ha^{-1} after thinning. Two seeds were planted per planting station and thinned to one at two weeks after emergence. All plots were manually weeded at three and six weeks after emergence.

Table 1: Treatment structure for nutrient omission trials in Sidindi, western Kenya.

Treatment	Nutrient		
	N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}
Control	0	0	0
PK	0	40	60
NK	150	0	60
NP	150	40	0
NPK	150	40	60

2.5 Yield data collection

At physiological maturity, all maize plants were harvested within a net plot of 2.25 m by 3 m including three centre rows in each plot, leaving at least 2 m on each side of the center rows to minimize edge effects. The exact location of the net plot was chosen such that the net plot was visually representative of general growth conditions within the centre rows. After harvesting, total plant and cob numbers were recorded, and total cob weight determined in the field using a digital scale accurate to 2 decimal places. Grain moisture content was determined using a moisture tester (Dickey John Mini GAC, Minneapolis USA). Grain yield in each plot was then expressed in 88% dry matter.

2.6 Relative yield

Relative yield (RY) was used as a measure of the yield responses to N, P and K and was determined as the ratio between nutrient limited yield and yield in the NPK plot (equation 1). Relative yield values <1 indicate response to the applied nutrient, while values >=1 indicate no response to the applied nutrient.

$$RY_{i,j,s} = \frac{GY_{i,j,s}}{GY_{npk,j,s}} \qquad (1)$$

Where;

$RY_{i,j,s}$ = Relative yield in treatment plot *i* at field *j* in season *s*

$GY_{i,j,s}$ = Grain yield in treatment plot *i* at field *j* in season *s*

$GY_{npk,j,s}$ = Grain yield in the NPK treatment plot at field *j* in season *s*

2.7 Normalized yield

Yield normalization was conducted to enable comparisons of plot performance with other plots that received the same treatment in the same season, i.e. highlighting spatial differences. It allows evaluation of the resilience of plot nutrient stocks over time. It also allows evaluation of changes in ranking of plots over time, enabling understanding of key factors that may identify better performing plots. Normalized yield (NY) was determined as the ratio between the yield for a particular treatment and season in a particular field and average treatment yield for that treatment across all fields in a particular season (Equation 2). When normalized yields are trending downwards, this reflects a smaller resilience when compared to other plots and when trending upwards it reflects a larger resilience, both indications of changing spatial patterns.

$$NY_{i,j,s} = \frac{GY_{i,j,s}}{\overline{GY_{i,s}}} \quad (2)$$

Where;

$NY_{i,j,s}$ = Normalized yield in treatment plot *i* at field *j* in season *s*

$GY_{i,j,s}$ = Grain yield in treatment plot *i* at field *j* in season *s*

$\overline{GY_{i,s}}$ = Overall mean grain yield in treatment plot *i* across all fields in season *s*

2.8 Statistical analysis

The final dataset used in the analysis comprised of data from 23 fields after one field was excluded due to lack of yield data in the fifth and sixth season following farmer withdrawal from the study. The effect of treatment on grain yield in the 23 fields was analysed at seasonal level using a generalised linear model with grain yield as response variable and treatment as explanatory factor with the LME4 package available in R software (www.r-project.org). Differences in treatment means were then evaluated for significance using a Tukey HSD test with the package 'agricolae' in R and reported at a significance level of 0.05. To evaluate the differences in yield variation between and within treatments, the coefficient of variation (CV) was calculated for each treatment in each season (using the 'raster' package in R). Scatter plots of CV values and seasons were then constructed and regression lines fit for trend assessment.

To assess differences in response to N, P and K, a Student t-test was used to evaluate if seasonal relative yield values were different from a value of 1.0. Evaluation of differences in response to N, P and K over time was conducted using a GLM model with treatment relative yield as response variable and season as explanatory factor. Frequency distribution plots were then used to show trends in relative yield at field level over seasons.

Cluster analysis was used to identify groups of fields with similar trends in yield responses to N, P and K based on Euclidian distances between paired vectors including intercept and trend values. These were based on 6 season relative yield values for PK, NK, and NP treatments per field, and was conducted with the 'GMD' package in R software. This clustering method starts with one cluster per field and merges clusters based on squared dissimilarities between fields, using the Ward criterion (Murtagh and Legendre, 2014). The clustering algorithm was set to identify the number of clusters which explained at least 70% of the total variation, and additional variation explained by adding one extra cluster was less than 10%.

To evaluate the relationship between initial soil fertility and observed responses to N, P and K, seasonal RY_{PK}, RY_{NK}, and RY_{NP} values were plotted against soil organic matter (SOM), soil available P (mg kg^{-1}), and soil exchangeable K (cmol kg^{-1}) respectively. Ensuing scatter plots were then split into four quadrants by drawing a horizontal line at RY= 0.95 (where values >0.95 represented no response to the nutrient under evaluation), and vertical lines drawn at 3%, 10 mg kg^{-1}, and 0.2 cmol kg^{-1}, representing average critical values of SOM, soil available P, and soil exchangeable K respectively, for soils in the region (Okalebo *et al.*, 1993).

3. Results

3.1 Maize yields

Maize yields increased significantly with nutrient application including N in all six seasons (Table 2). In all seasons, maize yield in the control treatment was similar to that in the PK treatment, but significantly ($P<0.05$) less than that in the NK, NP and NPK treatments. Yields in the NK, NP and NPK treatments were not significantly different in the first season. However, NK treatment yields were significantly smaller than NPK treatment yields in all five subsequent seasons and in the last season for the NP treatment (Table 2). Yields in the NK treatment declined over the seasons from 5.1 to 2.9 ton ha^{-1}. In the NPK treatment, yields in the long rains seasons were at least 0.4 ton ha^{-1} higher than in corresponding short rains seasons (Table 2).

Table 2: Average maize grain yield in t ha^{-1} at 88% dry matter for nutrient omission trials conducted on 23 farms in Sidindi, western Kenya.

Treatment	Season[†]					
	LR 2013	SR 2013	LR 2014	SR 2014	LR 2015	SR 2015
Control	2.8^{b}	2.1^{c}	2.2^{c}	1.8^{c}	2.2^{c}	1.1^{c}
PK	3.2^{b}	2.8^{c}	2.7^{c}	2.6^{bc}	2.6^{c}	1.4^{c}
NK	5.1^{a}	3.7^{b}	3.7^{b}	3.3^{b}	4.0^{b}	2.9^{b}
NP	5.1^{a}	4.1^{ab}	4.6^{b}	4.4^{a}	4.6^{ab}	3.6^{b}
NPK	5.5^{a}	4.9^{a}	5.6^{a}	5.2^{a}	5.7^{a}	5.3^{a}
HSD	**1.2**	**1.2**	**1.4**	**1.3**	**1.6**	**1.2**

Grain yield values in the same column followed by a different superscript are significantly different at P<0.05)

[†]*LR and SR refer to long and short rains seasons respectively*

3.2 Variability in grain yield responses

On average, variability was greatest in the control treatment followed by the NK treatment and least in the NPK treatment (Fig. 2). Variability remained constant for NPK but increased significantly (*P*<0.05) for only Control and NP. A decrease in variability in season five when compared to the trend was observed for all treatments except NPK which showed an increase in variability (Fig. 2).

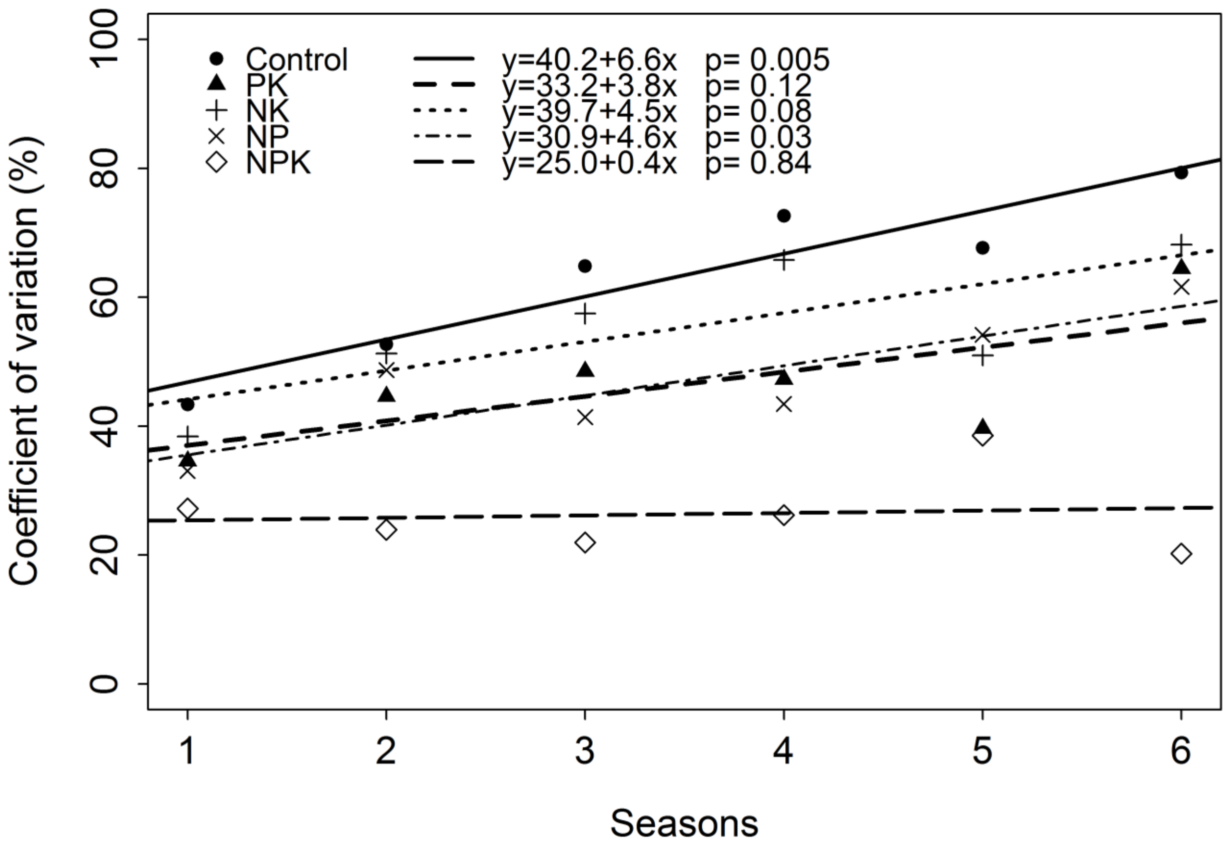

Figure 2: Scatter plots of coefficient of variation in treatment maize grain yield and seasons in nutrient omission trials conducted with a single complete replicate block per farm (*n* = 23) in Sidindi, western Kenya. Solid and dashed lines are fitted linear regression lines. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015 respectively.

3.3 Maize grain yield responses to N, P and K applications

Evaluation of mean RY values in the first season showed that only $RY_{PK,}$ was significantly less than 1 (Table 3), indicating a strong response to only N. However, in subsequent seasons responses to N, P and K were all significant as indicated by $RY_{PK,}$ RY_{NK} and RY_{NP} values significantly less than 1 (Table 3), demonstrating increasing yield limitations with continued cropping without application of P and K. In all six seasons, mean RY was in the order $RY_{PK}< RY_{NK}< RY_{NP}$, indicating that N was the most limiting nutrient in the study area followed by P and K respectively.

Seasonal trends within RY showed that only in the last season was the RY_{PK} value significantly smaller than that observed in the first season, indicating minimal change in response to N over time (Table 3). RY_{NP} values in the third, fourth and sixth seasons were significantly ($P<0.05$) smaller than for the first season, while decreases in RY_{NP} were not significant over time (Table 3), illustrating significant temporal differences in P availability.

Table 3: Within and between season differences in relative maize grain yields for nutrient omission trials conducted on 23 farms in Sidindi, western Kenya.

Relative Yield†	Season‡						
	LR 2013	SR 2013	LR 2014	SR 2014	LR 2015	SR 2015	**HSD**
RY_{PK}	0.61[a]	0.60[a]	0.48[a]	0.53[a]	0.49[a]	0.25[b]	**0.20**
RY_{NK}	**0.93[a]**	0.73[ab]	0.64[b]	0.59[b]	0.70[ab]	0.52[b]	**0.28**
RY_{NP}	**0.94**	0.80	0.79	0.84	0.80	0.68	**0.27**

Values in bold are not significantly different from a value of 1

Values in the same row followed by a different superscript are significantly different at P<0.05

†*RY_{PK}, RY_{NK} and RY_{NP} are the ratios between mean PK, NK and NP treatment yield, and mean NPK treatment yield in a particular season respectively.*

‡*LR and SR refer to long and short rains seasons respectively*

The frequency distribution of relative yield over the four cropping seasons is shown in Figure 3. Differences in responses to N, P and K between fields in a season were observed as well as differences in field's responses to a particular nutrient across seasons (Fig. 3). In the first season, strong responses to N (RY_{PK} <0.5) were observed in 29% of fields. In the subsequent five seasons, the percentage of fields strongly responsive to N (RY_{PK} <0.5) increased to 48, 57, 57, 61 and 96% respectively. For P, only 4% of fields showed a strong response to P (RY_{NK} <0.5) in the first season. In the subsequent five seasons, 22, 30, 35, 26 and 43% of fields were strongly responsive to P (RY_{NK} <0.5) respectively. RY_{NP} values in the first season indicated that only 4% of fields where strongly responsive to K (RY_{NP} < 0.5). The proportion of fields showing strong response to K (RY_{NP} < 0.5) in subsequent seasons was 17, 13, 9, 13, and 30%. Although the proportion of fields responsive to P and K were comparatively smaller than those responsive to N, the effects of P and K omission in deficient fields were very strong with yields losses of up to 80% relative to the NPK treatment in some of these farms, particularly from the second cropping season onwards (Fig. 3b, 3c, 3d, 3e and 3f).

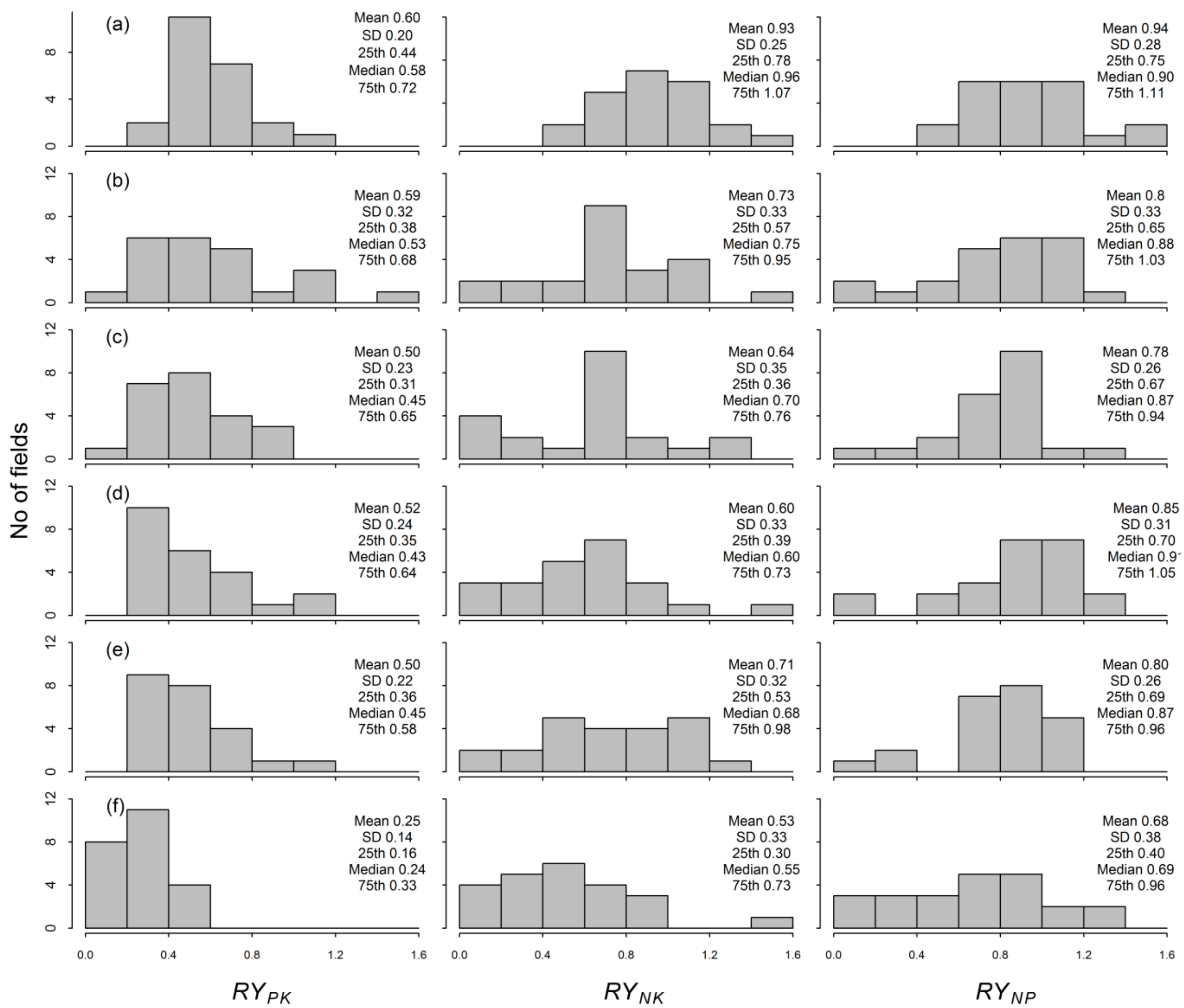

Figure 3: Frequency distribution plots showing relative maize grain yield RY_{PK}, RY_{NK} and RY_{NP} in nutrient omission trials conducted with a single complete replicate block per farm (n = 23) in Sidindi, Western Kenya in; (a) long rains 2013 (b) short rains 2013 (c) long rains 2014 (d) short rains 2014 seasons (e) long rains 2015 and (f) short rains 2015 seasons respectively. RY_{PK}, RY_{NK} and RY_{NP} are the ratios between PK, NK and NP treatment yields and NPK treatment yield respectively.

3.4 NPK response clusters

Six clusters with high internal homogeneity explaining 75% of total variation in yield trends (not shown), were identified to categorize fields in the study area into N, P and K response classes (Fig. 4). Clusters clearly differed in RY of control plots and NPK response (Fig. 4). Overall, RY_{PK} declined over time for all clusters, while RY_{NK} declined over time in 5 out of 6 clusters indicating increased deficiency of N and P due to nutrient mining (Fig. 4b and 4c). However, clusters RY_{PK} converged, while RY_{NK} diverged over time (Fig. 4b and 4c), indicating differences in response patterns between nutrients over time. Negative trends in RY_{NK} for clusters 2, 3, 4 and 6 indicated limited P stocks (Fig. 4c). However, declines for clusters 2 and 4 stabilised from season 3 onwards (Fig. 4c). RY_{NK} for cluster 1 did not show strong trends at levels of about 0.75, indicating P deficient conditions with resilient P stocks (Fig. 4c). A negative RY_{NP} trend in cluster 1 indicates an increasing K deficiency, while clusters 1 and 4 were somewhat deficient, although deficiency did not increase much over the seasons (Fig. 4d). The strongest response to K supply was observed for fields in cluster 6, and fields in clusters 1, 2 and 4 also benefited from K supply, as shown by RY_{NP} values below 1.0 for most seasons (Fig. 4d). Cluster 5 included four farms with low relative yield values for the control and PK treatments, while relative yields in the NK and NP treatments were around 1.0 in all seasons indicating N deficiency while P and K supply was sufficient for all seasons (Fig. 4a, 4b, 4c and 4d).

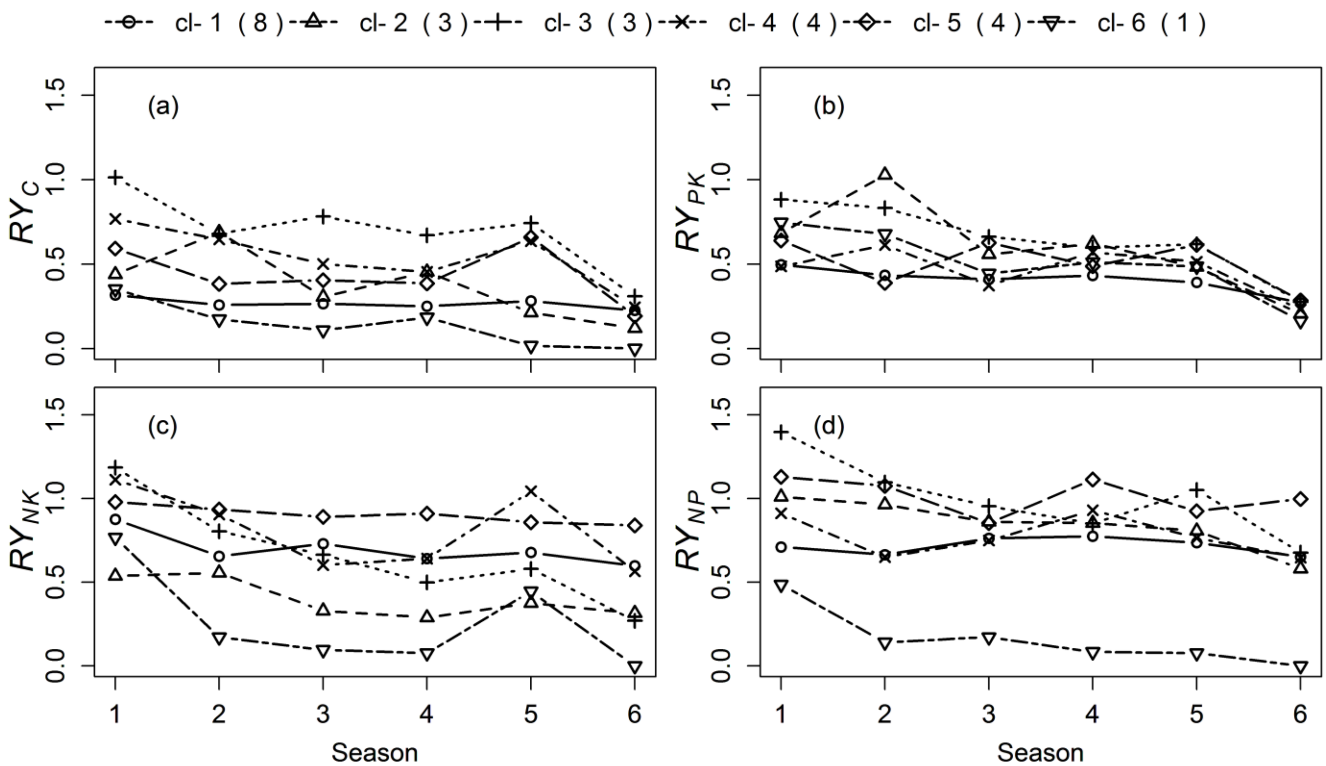

Figure 4: Seasonal trends in relative yields (RY) per cluster for (a) control (b) PK (c) NK and (d) NP treatments respectively. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015 respectively. 'RY_C', 'RY_{PK}', 'RY_{NK}' and 'RY_{NP}' are the ratios between control, PK, NK and NP treatment yields and NPK treatment yield respectively.

Consistency of spatial patterns was evaluated using normalized treatment yields (Fig. 5). A large range in NY values and consistent differences between clusters were observed for control, PK and in particular NK and treatment yields, indicating strong and persistent spatial yield patterns. The range in NY values for the NPK treatments was much smaller (Fig. 5b). This illustrates that spatial differences between trend clusters were mainly driven by differences in field P availability (Fig. 5a, 5c, 5d and 5e), and amendments with NPK reduce spatial variability.

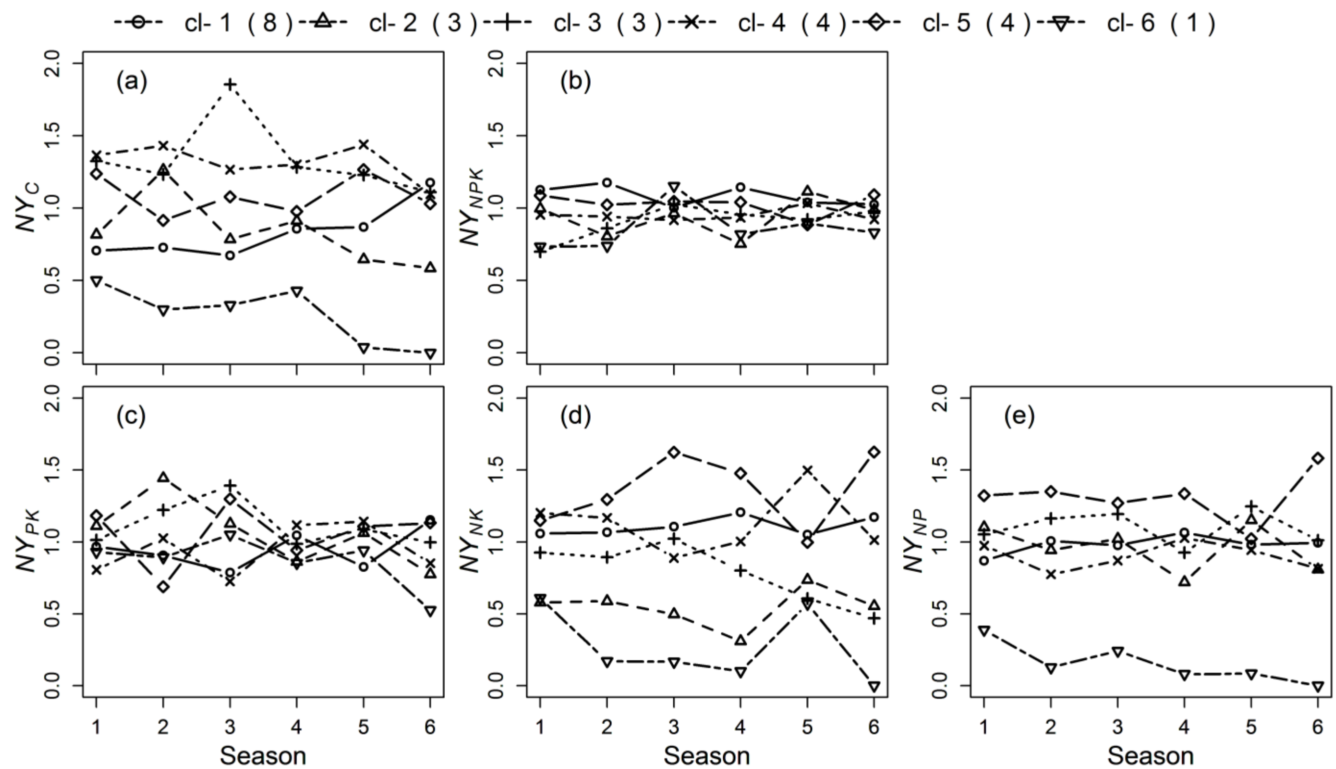

Figure 5: Seasonal trends in normalized yields (NY) per cluster for (a) control (b) NPK (c) PK (d) NK and (e) NP treatments respectively. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015 respectively. *'NY_C', 'NY_{PK}','NY_{NK}', 'NY_{NP}'* and *'NY_{NPK}'* are the ratios between field level control, PK, NK, NP and NPK yield and seasonal means of control, PK, NK,NP and NPK yield respectively.

To assess if yields in unfertilized plots would be a good predictor for the response to NPK, seasonal relative control, PK, NK and NP treatment yields were plotted against seasonal normalized control yields (Fig. 6). Normalized control treatment yields were shown to provide a good indicator of the response to combined NPK application, with farms with high control yields showing a weaker response to combined NPK application (Fig. 6). Control yields were however less informative for responses to other treatments. The range of normalized control yields increased over time indicating increasing differences in nutrient depletion rates in the various fields over time (Fig. 6).

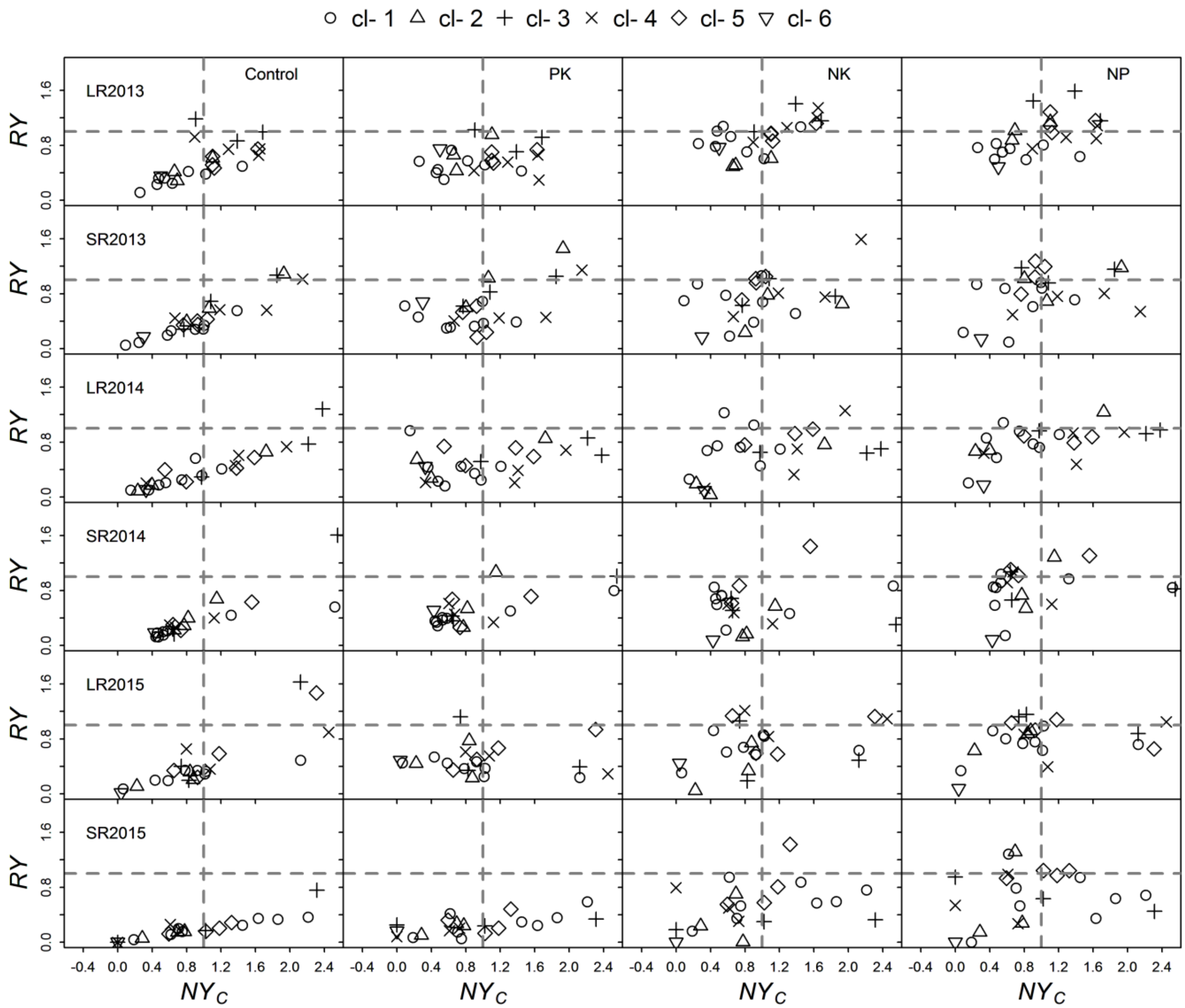

Figure 6: Relative yields (RY) of control, PK, NK and NP treatments versus normalized control treatment yields (NY_c) for fields in the identified clusters. LR and SR refer to long and short rains seasons respectively.

3.5 Relationships between soil fertility and responses to NPK

All fields in the experiment had a sandy loam, sandy clay loam or sandy clay texture, with contents ranging from 16.5 – 38.5 % clay, 6.2 – 19.8 % silt and 48.0 – 77.2% sand. Response to N was weakly related to soil SOM content (Fig. 7a). The majority of RY_{PK} values were within the N deficiency range across the extent of soil organic matter values (Fig. 7a). At low available P values (<10 mg kg^{-1} P) response to P was weakly related to available P with low and high RY_{NK} values observed across the range of available P values (Fig. 7b). However, at larger available P values (>10 mg kg^{-1} P) RY_{NK} values indicated minimal P deficiency across the six seasons study period (Fig. 7b). Responses to K varied greatly over the range of exchangeable K values measured, with some high RY_{NP} values observed at low exchangeable K values, and low RY_{NP} values observed at higher exchangeable K values (Fig. 7c). However, the majority of RY_{NP} values indicated K sufficiency conditions. Mean soil properties did not show significant differences between clusters (not shown).

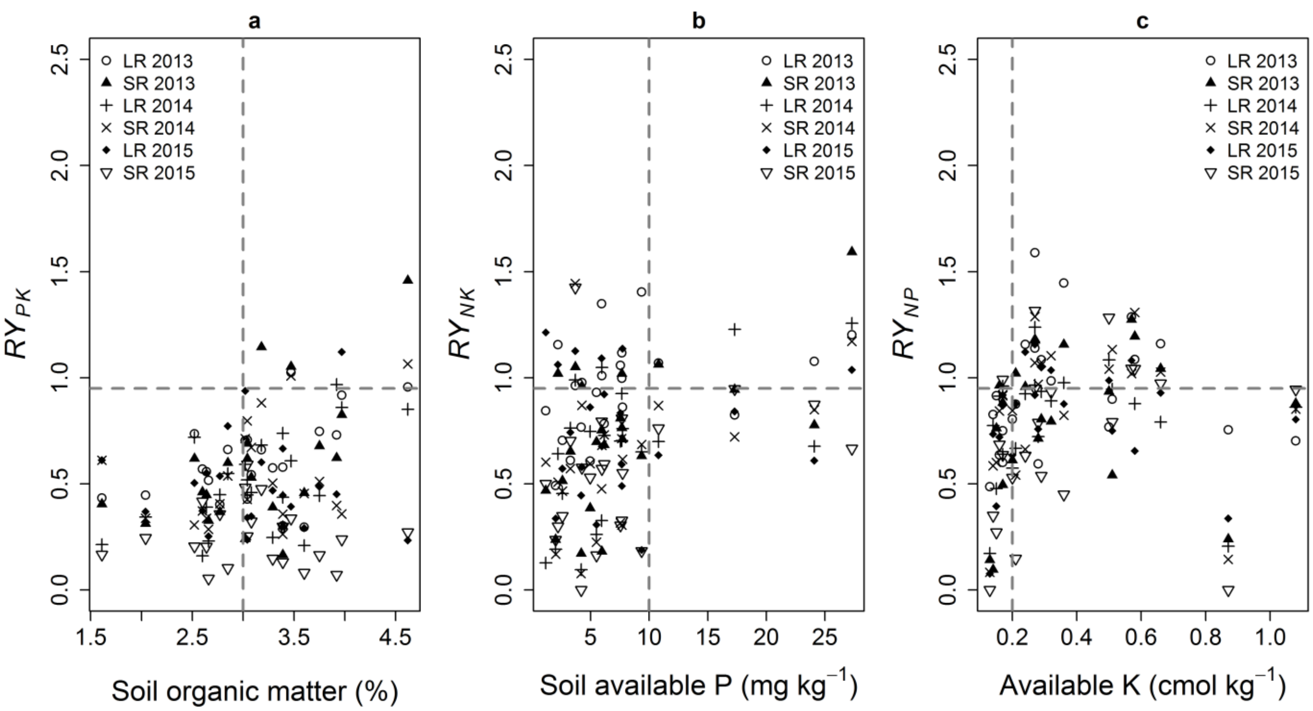

Figure 7: Relationships between, a) soil organic matter content (%) and relative PK treatment yield (RY_{PK}) ; b) soil available P (mg kg^{-1}) and relative NK treatment yield (RY_{NK});and c) soil exchangeable K (cmol kg^{-1}) and relative NP yield (RY_{NP}) across 23 fields in four consecutive cropping seasons in Sidindi, Western Kenya. Horizontal dotted lines represent relative yield = 0.95, while vertical dotted lines represent critical values for respective soil properties.

4. Discussion

The observed maize yield responses to the applied N, P and K combinations were highly variable over space and time, confirming the strong effects of the variability in soil fertility on maize productivity and nutrient requirements. N was deficient on most farms, while the responses to P and K application varied strongly across farms. Temporal differences in response to N were weak as illustrated by the minimal change in mean RY_{PK} over time, and the gradual decline in RY_{PK} observed for most clusters. Spatial differences in response to N also decreased over time as illustrated by the observed convergence in RY_{PK} for the different response clusters over time. The widespread N deficiency can be linked to the relatively low soil organic matter contents resulting from continuous cropping without legumes and very limited application of fertilizer N or manure (Shepherd and Soule, 1998; Tittonell *et al.*, 2005). Combined application of fertilizer N with organic resources (Vanlauwe *et al.*, 2011) and rotation of cereal crops with legumes (Tully *et al.*, 2015) can help farmers in this region improve the N status of their farms across the response clusters. Given the minimal spatial-temporal differences in response to N observed, we expect minimal improvements in nitrogen use efficiency when accounting for differences in spatial temporal responses to N between farms in the Siaya region.

Large relative NK yields indicated that maize yield response to applied P was not significant in the first season. This was likely due to some residual effect of P applied in previous seasons, as P applied as fertilizer or manure that is not taken up by the crop is released slowly to succeeding crops (Janssen *et al.*, 1987; Kifuko *et al.*, 2007). The presence of clusters with large differences in the response to applied P, and the large variability in NK treatment maize yields that we observed indicates differences in P fertility status of the soil, reflecting differences in historical field management and farmer resource endowment (Vanlauwe *et al.*, 2006). However, residual P was only effective over a short period of time, with more farms showing stronger responses to P over time. This shows that resilience of soil P stocks in these fields is limited. Omitting P for more than one season resulted in significant and progressively smaller yields when compared to P fertilized plots. The small rates of fertilizer applied by smallholder farmers in western Kenya are insufficient to build P soil availability that can support high maize yield for multiple seasons (Kamiri *et al.*, 2011; Kihara and Njoroge, 2013). Judicious and regular application of P, whether seasonally or every second season based on observed response clusters can therefore assist farmers to sustain productivity.

Strong spatial-temporal patterns in response to K were observed. Two out of 23 fields showed very strong response to K, while declining relative yields for the NP treatment were observed in Clusters 1, 2 and 4 which included 65% of fields in the study area. Further, K deficiencies are expected to become more pronounced at higher N and P application rates. These findings are in contrast to current fertilizer recommendation for the Siaya region which assume sufficient K reserves (FURP, 1994), and could be related to the presence of localized K deficiency hotspots (Kihara *et al.*, 2016), and continuous removal of harvest products without application of mineral K (Chianu and Mairura, 2012; Zörb *et al.*, 2014). Crop productivity intensification strategies based on increased fertilizer application should therefore be cognisant of the need to supply K in combination with N and P, even in regions that are traditionally considered to be mainly deficient in N and P, such as western Kenya. Targeted application of K fertilizer to K deficiency hot spots is also recommended (Kihara *et al.*, 2016).

The assessment of soil nutrient status has been identified as a key starting point in the process of restoring and managing soil fertility (Sanginga and Woomer, 2009). Soil available P following Mehlich-3 extraction has been found to reliably estimate plant available soil P levels (Mehlich, 1984), while soil exchangeable K is usually used as the basis for K fertilizer recommendations (Madaras and Koubová, 2015; Zörb *et al.*, 2014). However, soil organic matter, soil available P, and soil exchangeable K related weakly to responses to N, P and K respectively. Weak relationships were previously reported by Vanlauwe *et al.* (2006), with soil total N explaining only 27% - 44% of the response to N, while crop yield response to P did not increase beyond an Olsen-P value of 8 mg kg^{-1}. In the same study area, Tully *et al.* (2015) observed large variation in maize yields between 24 farms despite largely similar soil physical and chemical properties between farms. Working across various sites in SSA, Kihara *et al.* (2016) reported minimal variation in exchangeable Mehlich K despite strong responses to K in some sites, while soil organic carbon (SOC) was not a defining factor for different nutrient response classes observed. Given that soil analysis data was weakly related to the observed differences in responses to applied N, P and K, the merit of deriving fertilizer recommendations based solely on field-level soil analysis can be questioned. It is noted that soil analysis was only conducted at the start of the experiment and hence did not allow for a detailed analysis of the dynamics of soil nutrient changes and responses to nutrients. However, this analysis provides a fair evaluation of the value of soil analysis for majority of smallholder farmers as for practical reasons, most farmers will assess the soil P and K fertilizer status only once every few years. Results from this study indicate that while soil analysis may be helpful to monitor soil nutrient stocks, it does not provide sufficiently reliable quantitative information that can be used to adjust required inputs. A strategy to fertilize the soil to maintain moderate P and K stocks, balancing in- and outputs, while fertilizing the plant with minimum side-dress PK mix at planting and top-dressing of N would be recommended. In addition, the restoration of soil P and K stocks based on the field history, including socio-economic and rock mineralogical factors is recommended as these factors have previously been identified as drivers of variability in yield response (Tittonell *et al.*, 2008a; Zingore *et al.*, 2011).

Cluster analysis allowed identification of distinct N, P and K response categories that differed in response to fertilizer application and the resilience of soil nutrient stocks. All fields in this study were responsive to combined NPK fertilizer (Kihara *et al.*, 2016; Zingore *et al.*, 2007b), where the response was strongly related to yield in control plots. The presence of distinct N, P and K response clusters calls for site specific nutrient recommendations that address the observed variability. For example, based on observed N, P and K response patterns, improved nutrient allocation strategies based on differential N, P and K rates and combinations can be formulated to meet either short or long term crop productivity intensification objectives at the farm level. Such strategies can be designed using tools such as Nutrient Expert (Pampolino *et al.*, 2012) and FIELD (Tittonell *et al.*, 2010).

A major challenge exists in the identification of response patterns at scale. Recent developments in the use of satellite data offer an opportunity to assess and quantify spatial heterogeneity at regional scales (Lobell, 2013; Shanahan *et al.*, 2001). At the local level, farmers have shown the ability to categorize their farms into relatively homogenous entities using criteria such as crop performance, ease of tillage, soil moisture retention, soil colour and presence of weeds and soil invertebrates (Murage *et al.*, 2000), and this has being suggested as key for designing strategies for improved crop productivity in the region (Tittonell *et al.*, 2013).

The consistently higher average NPK treatment yields relative to other treatment yields observed, coupled with the lowest variability in yield observed for this treatment indicates that amendment with NPK helps to reduce observed spatial-temporal variability. This highlights the importance of balanced nutrient management to increase and stabilize yield across wide-ranging soil fertility conditions. The NPK treatment yielded on average 0.5-1.7 t ha^{-1} more than the NP treatment, a significant difference in 2 out of the 6 seasons. The main current mineral fertilizer use recommendation in the Siaya region of 55 kg N and 25 kg P ha^{-1} (FURP, 1994) needs to be revisited. Results in this experiment indicate that yields above 5 tha^{-1} can be sustained using the short season cultivar, where nutrient use efficiency can be further improved when accounting for comparative yield levels in control plots without fertilizer application. Results in this study further indicated that maize yield response to combined NPK application was higher in long rains seasons, illustrating that there may be room for farmers to further improve the efficiency of fertilizer use through fertilizer application rates based on in-season rainfall (Kurwakumire *et al.*, 2014; Van Ittersum *et al.*, 2016). There is therefore potential for majority of farmers in the Siaya region to surpass the initial target of 3 t ha^{-1} set towards achieving the African Green Revolution (Sánchez, 2010) in the face of variable responses to N, P and K.

5.0 Conclusions

We conclude that strong spatial temporal differences in responses to N, P and K exist in smallholder farming systems in western Kenya. It is clear that current blanket fertilizer application rates result in low nutrient use efficiencies and may not achieve the desired sustainable crop productivity improvement in the region. We further conclude that current soil analysis techniques were not able to adequately predict the crop response that can be expected from N, P and K fertilizers. This raises questions whether investing in soil analysis alone results in better fertilizer recommendations for smallholder farmers, and urges for a new, more cost effective approach. The strong spatial-temporal patterns observed indicate that characterization of soil, lithological and landscape characteristics in combination with management history may result in a much cheaper and more cost effective methodology for assessing the required N, P and K fertilizer applications, when mapped at the appropriate scale. Decision support tools may offer a feasible and cheaper alternative for the development of site specific nutrient recommendations using information readily available at the farm level. In the absence of such strategies, balanced nutrition including N, P and K offers farmers in heterogeneous landscapes a lower risk intensification option that results in yields that can be sustained during a much longer period of time, evidenced by the relatively small variations in yield for the NPK treatment across fields and seasons.

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References

Adediran, J.A., Banjoko, V.A., 1995. Response of maize to nitrogen, phosphorus, and potassium fertilizers in the savanna zones of Nigeria. Communications in Soil Science and Plant Analysis 26, 593-606.

AfSIS. (2016). Africa Soil Information Service. Retrieved September 8, 2016, from http://africasoils.net/

AGRA. (2016). AGRA. Retrieved October 11, 2016, from http://agra.org/

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., Thiombiano, L., Waswa, B., 2012. Knowing the African Soils to Improve Fertilizer Recommendations. In: Kihara, J., Fatondji, D., Jones, J.W., Hoogenboom, G., Tabo, R., Bationo, A. (Eds.), Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer Netherlands, pp. 19-42.

Bouyoucos, G.J., 1962. Hydrometer Method Improved for Making Particle Size Analyses of Soils. Agronomy Journal 54, 464-465.

Byerlee, D.R., Kelly, V.A., Kopicki, R.J., Morris, M., 2007. Fertilizer Use in African Agriculture. The World Bank.

Chianu, J.N., Mairura, F., 2012. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agronomy for Sustainable Development 32, 545-566.

Chikowo, R., Zingore, S., Snapp, S., Johnston, A., 2014. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutr Cycl Agroecosyst 100, 1-18.

Deckers, J., 2002. A systems approach to target balanced nutrient management in soilscapes of sub-saharan Africa. In: Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. (Eds.), Integrated Plant Nutrient Management in Sub-Saharan Africa. CAB International, Wallingford, pp. 47-61.

Diao, X., Hazell, P., Thurlow, J., 2010. The Role of Agriculture in African Development. World Development 38, 1375-1383.

Fridgen, J.J., Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Wiebold, W.J., Fraisse, C.W., 2004. Management Zone Analyst (MZA): Software for Subfield Management Zone Delineation. Agronomy Journal 96, 100-108.

FURP, 1994. Fertilizer Use Recommendations. Fertilizer Use Recommendation Project. Kenya Agricultural Research Institute, National Agricultural Research Laboratories, Nairobi, Kenya.

Giller, K.E., Rowe, E.C., De Ridder, N., Van Keulen, H., 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. Agricultural Systems 88, 8-27.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'Ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agricultural Systems 104, 191-203.

Janssen, B.H., Lathwell, D.J., Wolf, J., 1987. Modeling Long-Term Crop Response to Fertilizer Phosphorus. II. Comparison with Field Results1. Agronomy Journal 79, 452-458.

Kamiri, W.M.H., Pypers, P., Vanlauwe, B., 2011. Residual Effects of Applied Phosphorus Fertilizer on Maize Grain Yield and Phosphorus Recovery from a Long-Term Trial in Western Kenya. In: Bationo, A., Waswa, B., Okeyo, M.J., Maina, F., Kihara, M.J. (Eds.), Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts. Springer Netherlands, Dordrecht, pp. 717-727.

Kifuko, M.N., Othieno, C.O., Okalebo, J.R., Kimenye, L.N., Ndung'u, K.W., Kipkoech, A.K., 2007. Effect of combining organic residues with Minjingu phosphate rock on sorption and availability of phosphorus and maize production in acid soils of western Kenya. Experimental Agriculture 43, 51-66.

Kihara, J., Huising, J., Nziguheba, G., Waswa, B.S., Njoroge, S., Kabambe, V., Iwuafor, E., Kibunja, C., Esilaba, A.O., Coulibaly, A., 2015. Maize response to macronutrients and potential for profitability in sub-Saharan Africa. Nutr Cycl Agroecosyst, 171-181.

Kihara, J., Njoroge, S., 2013. Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field Crops Research 150, 1-8.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agriculture, Ecosystems & Environment 229, 1-12.

Kurwakumire, N., Chikowo, R., Mtambanengwe, F., Mapfumo, P., Snapp, S., Johnston, A., Zingore, S., 2014. Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. Field Crops Research 164, 136-147.

Lobell, D.B., 2013. The use of satellite data for crop yield gap analysis. Field Crops Research 143, 56-64.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review of Environment and Resources 34, 179-204.

Madaras, M., Koubová, M., 2015. Potassium availability and soil extraction tests in agricultural soils with low exchangeable potassium content. Plant, Soil and Environment 61, 234-239.

Mehlich, A., 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 15, 1409-1416.

Minot, N., Benson, T., 2009. "Fertilizer subsidies in Africa: Are Vouchers the Answer?". IFPRI Issue Brief No 60. International Food Policy Research Institute, Washington, DC.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254-257.

Murage, E.W., Karanja, N.K., Smithson, P.C., Woomer, P.L., 2000. Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. Agriculture, Ecosystems and Environment 79, 1-8.

Murtagh, F., Legendre, P., 2014. Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion? Journal of Classification 31, 274-295.

Nziguheba, G., Palm, C.A., Berhe, T., Denning, G., Dicko, A., Diouf, O., Diru, W., Flor, R., Frimpong, F., Harawa, R., Kaya, B., Manumbu, E., McArthur, J., Mutuo, P., Ndiaye, M., Niang, A., Nkhoma, P., Nyadzi, G., Sachs, J., Sullivan, C., Teklu, G., Tobe, L., Sanchez, P.A., 2010. The african green revolution. Results from the millennium villages project. Advances in Agronomy, pp. 75-115.

Okalebo, J.R., Gathua, K.W., Woomer, P.L., Tropical Soil, B., Fertility, P., 1993. Laboratory methods of soil and plant analysis : a working manual. Tropical Soil Biology and Fertility Programme, Nairobi.

Pampolino, M.F., Witt, C., Pasuquin, J.M., Johnston, A., Fisher, M.J., 2012. Development approach and evaluation of the Nutrient Expert software for nutrient management in cereal crops. Computers and Electronics in Agriculture 88, 103-110.

Perez-Quezeda, J.F., Pettygrove, G.S., Plant, R.E., 2003. Spatial-temporal analysis of yield and the influence of soil factors in two four-crop rotation fields in the Sacramento Valley, California. Agronomy 95, 676-687.

Place, F., Njuki, J., Murithi, F., Mugo, F., 2006. Agricultural enterprise and land management in the highlands of Kenya. In: Pender J, Place F, SJ, E. (Eds.), Strategies for sustainable land management in the East African highlands. International Food Policy Research Institute (IFPRI), Washington, DC, pp. 190-216.

Robinson, J.B.D., 1993. Tropical Soil Biology and Fertility: A Handbook of Methods. CAB International, Wallingford, Oxfordshire.

Sanchez, P., Palm, C., Sachs, J., Denning, G., Flor, R., Harawa, R., Jama, B., Kiflemariam, T., Konecky, B., Kozar, R., Lelerai, E., Malik, A., Modi, V., Mutuo, P., Niang, A., Okoth, H., Place, F., Sachs, S.E., Said, A., Siriri, D., Teklehaimanot, A., Wang, K., Wangila, J., Zamba, C., 2007. The African millennium villages. Proceedings of the National Academy of Sciences of the United States of America 104, 16775-16780.

Sanchez, P.A., 2002. Soil Fertility and Hunger in Africa. Science 295, 2019-2020.

Sánchez, P.A., 2010. Tripling crop yields in tropical Africa. Nature Geoscience 3, 299-300.

Sanginga, N., Woomer, P.L., 2009. Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Process. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture, Nairobi.

Shanahan, J.F., Schepers, J.S., Francis, D.D., Varvel, G.E., Wilhelm, W.W., Tringe, J.M., Schlemmer, M.R., Major, D.J., 2001. Use of remote-sensing imagery to estimate corn grain yield. Agronomy Journal 93, 583-589.

Sheahan, M., Barrett, C.B., 2014. Understanding the agricultural input landscape in Sub-Saharan Africa : recent plot, household, and community-level evidence. World Bank Group, Washington, DC.

Shepherd, K.D., Soule, M.J., 1998. Soil fertility management in west Kenya: Dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture, Ecosystems and Environment 71, 131-145.

Smaling, E.M.A., Nandwa, S.M., Prestele, H., Roetter, R., Muchena, F.N., 1992. Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. Agriculture, Ecosystems & Environment 41, 241-252.

Smaling, E.M.A., Stoorvogel, J.J., Windmeijer, P.N., 1993. Calculating soil nutrient balances in Africa at different scales. Fertilizer Research 35, 237-250.

Summit, A.F., 2006. Africa fertilizer summit proceedings. IFDC, Muscle Shoals 182.

Tittonell, P., Corbeels, M., van Wijk, M.T., Giller, K.E., 2010. FIELD—A summary simulation model of the soil–crop system to analyse long-term resource interactions and use efficiencies at farm scale. European Journal of Agronomy 32, 10-21.

Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research 143, 76-90.

Tittonell, P., Muriuki, A., Klapwijk, C.J., Shepherd, K.D., Coe, R., Vanlauwe, B., 2013. Soil Heterogeneity and Soil Fertility Gradients in Smallholder Farms of the East African Highlands. Soil Sci. Soc. Am. J. 77, 525-538.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008a. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya-An application of classification and regression tree analysis. Agriculture, Ecosystems and Environment 123, 137-150.

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2008b. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313, 19-37.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture, Ecosystems and Environment 110, 166-184.

Tully, K.L., Wood, S.A., Almaraz, M., Neill, C., Palm, C., 2015. The effect of mineral and organic nutrient input on yields and nitrogen balances in western Kenya. Agriculture, Ecosystems and Environment 214, 10-20.

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—A review. Field Crops Research 143, 4-17.

Van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52, 197-208.

Van Ittersum, M.K., Van Bussel, L.G.J., Wolf, J., Grassini, P., Van Wart, J., Guilpart, N., Claessens, L., De Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., Van Oort, P.A.J., Van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences of the United States of America 113, 14964-14969.

van Keulen, H., Breman, H., 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? Agriculture, Ecosystems and Environment 32, 177-197.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. Outlook on Agriculture 39, 17-24.

Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. SOIL 1, 491-508.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339, 35-50.

Vanlauwe, B., Tittonell, P., Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr Cycl Agroecosyst 76, 171-182.

The R Project for Statistical Computing. https://www.r-project.org/

Xu, X., He, P., Qiu, S., Pampolino, M.F., Zhao, S., Johnston, A.M., Zhou, W., 2014. Estimating a new approach of fertilizer recommendation across small-holder farms in China. Field Crops Research 163, 10-17.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007a. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agriculture, Ecosystems & Environment 119, 112-126.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007b. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Research 101, 296-305.

Zingore, S., Tittonell, P., Corbeels, M., van Wijk, M.T., Giller, K.E., 2011. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Nutr Cycl Agroecosyst 90, 87-103.

Zörb, C., Senbayram, M., Peiter, E., 2014. Potassium in agriculture – Status and perspectives. Journal of Plant Physiology 171, 656-669.