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RESEARCH ARTICLE

Sorghum yield response to NPKS and NPZn nutrients along sorghum-growing landscapes‡

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Summary

Grain sorghum [Sorghum bicolor (L.) Moench] is the major cereal crop used as staple crop in the arid and semi-arid regions of Ethiopia. Low sorghum yields are attributed to soil, climate and topographic factors. We investigated sorghum yield response to factorial combination of nitrogen and phosphorous (NP) as well as potassium (K), sulphur (S) and zinc (Zn), and how the position of farmers' fields belonging to different landscape positions (i.e., upslope, mid-slope, and foot slope) could explain fertilizer response and yield variability. The analysis in this study made use of dataset from two sets of on-farm experiments where trials were set at two farmers' fields for NPKS and three farmers' fields for NPZn experiments in each landscape position. The experiments were implemented at two sorghum-growing locations (i.e., Hayk and Sirinka) in parts of the north-eastern Amhara region in Ethiopia. Sorghum yield response to fertilizer application was strongly linked to the spatial variation along landscape positions and varied over locations. Fertilizer response was significantly higher at foot slopes compared to mid-slopes and upslope positions, where fields at foot slopes exhibited relatively homogeneous responses. Application of combined nitrogen (N) and phosphorus (P) fertilizers, landscape position and the interaction of fertilizer application and landscape positions strongly affected sorghum yield. There was a linear and significant increase in sorghum yield with the increase in the NP rates. The combined application of NP with different levels of KS as well as NP with Zn fertilizer rates did not result in significant yield difference. The results indicated that local factors were much more influential when accounting for the heterogeneity in sorghum yield response to fertilizer. This further acknowledges the importance of a landscape-based fertilizer management approach to respond yield potential variability related with the farmers' fields and landscape environment. Further investigation is needed to develop homogeneous fertilizer response units based on spatial variability of soil and topographic attributes along the landscape.

Keywords: Landscape position; yield response; yield variability; sorghum; Ethiopia

Introduction

Agriculture in Ethiopia is the foundation of the country's economy, accounting for 41.4% of gross domestic product (GDP), 83.9% of exports and 80% of total employment (Matouš *et al.*, 2013). However, the agriculture production and food systems are facing challenges due to fast-growing population, increasing soil depletion and land degradation, and changing climate. Agricultural

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production is primarily characterized by low input and output smallholder farming. This is mainly associated with mountainous topography, subsistence smallholder farming systems and fragmented landholdings (van Beek *et al.*, 2016). The consistent increase in rural population has forced smallholder farmers to cultivate on steep slopes and marginal areas, characterized by degraded and low fertile soils which are less responsive to fertilizer application (Tamene *et al.*, 2017). Sorghum (*Sorghum bicolor* (L.) Moench) is one of the important food crops growing in semi-arid areas under marginal rainfall and soil conditions. Sorghum grain is the fifth major staple cereal after wheat, rice, maize and barley in terms of total production (Heuze *et al.*, 2015). By area, it is the fourth most important crop after teff (*Eragrostis tef*), maize (*Zea mays*) and wheat (*Triticum asetivum*), covering 1.83 million ha. But the national average yield is low at 2.8 t ha^{-1} (Affholder *et al.*, 2013; CSA, 2019) due to moisture stress and low soil fertility.

There is a wide variability in actual crop yields (Affholder *et al.*, 2013) within smallholder agricultural landscapes attributed to soil and topographic variations (Amede *et al.*, 2020; Diarisso *et al.*, 2016; Tamene *et al.*, 2017). The yield variability is also associated with resource availability and nutrient use efficiency (Tittonell *et al.*, 2008). For instance, fields near the homesteads that receive high organic matter tend to exhibit better soil fertility indicators (Amede and Diro, 2005; Tittonell *et al.*, 2008). Some studies have documented the relevance of slope position in determining the variability of crop yield response to fertilizer. For instance, (Moorman *et al.*, 2004; Pierson and Mulla, 1990) concluded that soils formed in foot slopes contained higher organic carbon and aggregate stability compared with those formed at upper slopes and resulted in higher crop yield response.

Despite the Ethiopian government's efforts to invest in accelerating fertilizer usage and creating soil maps with recommendations to guide farmers, low adoption and crop response to fertilizer applications are still a major concern (Amede *et al.*, 2020). For instance, in 2019–2020 only 18–20% of sorghum producer farmers used urea and the blend NPS fertilizer with an average application rate of 165 kg ha^{-1} (CSA, 2020). Although farmers are aware of the benefits of fertilizer application, many have financial constraints on the use of fertilizers, and they also avoid the risk of fertilizer use due to drought. Moreover, farmers are reluctant to apply the required or the recommended rates because of the risks of unknown fertilizer response at their locality. To avoid risks, farmers traditionally classify their fields based on the fertility and topographic variations and can vary the amount of fertilizer applied with respect to the fertility status and slope position. Farmers realize that the use of the same amount of fertilizer for different landscape positions could result in different responses and lead to unnecessarily cost increase (Amede *et al.*, 2020). In addition, one of the reasons for the low adoption of fertilizer at the required rate is the blanket nutrient application that may result in non-uniform and limited response of crops to fertilizer at different topographic and farming systems (Tamene *et al.*, 2017). High degree of variability in crop response to application of nutrients could be associated with variability in soil properties, landscape positions and soil water regimes (Liu *et al.*, 2020; Tamene *et al.*, 2017). The effectiveness of fertilizer application to respond to a specific soil fertility problem and its positive economic return depends on the identification of production constraints and targeting specific niches (Tamene *et al.*, 2017). Thus, efforts to increase crop productivity through fertilizer application and to narrow the yield gaps in smallholder farming require stratified fertilizer management in agricultural landscapes (Diarisso *et al.*, 2016).

Crop yield variability in response to fertilizer application is largely associated with the spatial distribution of nutrients in soils and soil water content further dictated by landscape positions (Amede *et al.*, 2020; Liu *et al.*, 2020). Owing to their influence on the shape of land surface, topographic positions dictate the distribution of some important soil properties and significantly control the movement and distribution of water and soil particles in a landscape (Liu *et al.*, 2020). In addition, change in slope position has a major impact on soil erosion that may cause loss of fine particles with high content of organic carbon, soil total nitrogen and shallow soil depth on steeper slopes. Benoît *et al.* (2012) referred to a 'landscape agronomy' approach as targeting multiple crop yield-limiting factors that are operating in homogenous landscape positions. Previous studies thus showed that coupling information on soil variability and topographic factors can inform targeted fertilizer management and improve crop productivity under smallholder farming. Targeting homogenous landscape position to fertilizer management is believed to increase the certainty of fertilizer management decisions and reduce risks of adoption by farmers.

Given the diverse rainfall regimes, farming systems and topographic conditions, the low level of fertilizer use and the high level of nutrient mining in Ethiopia, it is increasingly realized that achieving the national Growth and Transformation Plan objectives could be difficult (van Beek *et al.*, 2016). Hence, site-specific fertilizer management practices have been proposed and are being implemented targeting landscape positions (Amede *et al.*, 2020). For testing these hypotheses, on-farm experiments were conducted on farmers' fields with three landscape positions (i.e., upslope, mid-slope and foot slope) in the dry lowlands of sorghum-growing areas in north-eastern Ethiopia. We hypothesized that it is necessary to select the most appropriate fertilizer management for each landscape position to optimize sorghum grain yield under these heterogeneous environments. But interactions among the topography, soil and fertilizer on sorghum grain yield are not widely studied. A landscape position-based homogenous response unit approach is necessary to understand the underlying mechanisms of these interactions. Thus, this paper aims to determine the response of sorghum yield to locations, landscape position and fertilizer rates and estimate the relative contribution of other limiting factors.

Materials and Methods

Description of the study area

The study area represents dry agro-ecosystems in the north-eastern parts of the Amhara region of Ethiopia where sorghum is the major crop in the farming system. The study was conducted at Hayk and Sirinka in South and North Wollo administrative zones, respectively. The elevation range of locations is 1800–2200 m asl. The range of annual mean rainfall is 900–1200 mm, adding up rainfalls occurred in bimodal rainfall seasons. Depending on the occurrence of rainfall, the sorghum-growing period varies from April to November or from June/July to November. Farmers usually prefer to grow long-maturing sorghum varieties under long and normal rainfall seasons (April–November); however, they are forced to use short-maturing varieties when there is late onset of rainfall in July. The soils of the locations are characterized by Vertisols in the lower slope positions and shallow Regosols in the upper slopes.

Experimental setup

On-farm experiments which were the basis for this study were conducted in 2017 cropping season. The on-farm experiments were implemented along three landscape positions (i.e., upslope, mid-slope and foot slope) (see Figure 1). Although landscape position is a compound feature representing slope, slope shape and altitudinal differences, for simplicity to define landscape positions, we used slope gradient as criteria to classify topographical zones. Thus, landscape positions were divided based on the topographic zone in the topo-sequence, with slope ranges of 0–5%, 5–15% and 15–30%, respectively (Amede *et al.*, 2020). In each landscape position, two farmers' fields for NPKS set of experiment and three farmers' fields for NPZn were selected as replicates, considering certain distances between the fields in order to capture variations in the landscape.

The experiment was conducted to investigate the response of combination of nutrients – nitrogen (N), phosphorous (P), potassium (K), sulphur (S) and zinc (Zn) on sorghum yield at two locations, Hayk and Sirinka, in the 2017 cropping season. Two sets of on-farm experiments were conducted. The first set of treatments included four levels of N/P_2O_5 (0/0, 46/23, 92/46 and 138/69 kg ha^{-1}) combined with nine levels of K_2O SO_4 (0, 40 and 80 kg ha^{-1} K_2O and 0, 20 and 40 kg ha^{-1}

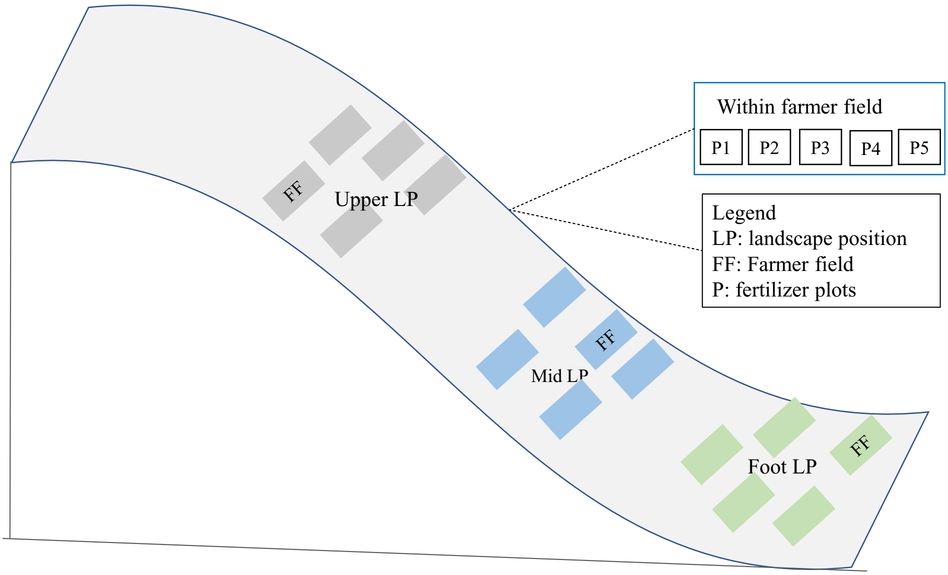

Figure 1. Schematic layout of within farmers' fields, between farmers' fields and between landscape positions along the landscape.

SO_4). The experiment was conducted at two locations (Sirinka and Hayk), three landscape positions in each location, and two farmers' fields in each landscape ($n = 36 \times 2 \times 3 \times 2 = 432$ plots). The second set of treatments were four levels of N/P_2O_5 combined with four levels of Zn (0, 4, 8 and 12 kg ha^{-1}) laid at two locations, three landscape positions and three farmers' fields in each landscape resulting in 288 plots ($n = 16 \times 3 \times 3 \times 2 = 288$ plots). Zero fertilizer was taken as a control treatment for both sets of experiments. Each of the treatments was placed in two or three farmers' fields as replicates at each landscape position, and each treatment had a plot area of 25 m^2 (5 x 5 m). To reduce the variability of the experimental area, plots were folded along the length of the field. All the nutrients and half of N were applied as basal application at planting, and the remaining half of N was applied 45 days after planting during the first weeding, approximately mid to end of August. Other agronomic practices were applied uniformly for all plots during the crop growth period as per the recommended on-farm practices. Farm operations were conducted using manual labour.

We used 'Girana 1' sorghum variety, a most adaptable, short-maturing variety with a seeding rate of 12 kg ha^{-1} at 75 cm row spacing and 10 cm spacing between plants. For the two sets of experiments, planting and harvesting dates were between 5–12 July and 8–25 November, respectively. At a later stage of sorghum, cultivation (locally named as *shilshalo*) and then thinning was carried out.

Data collection and analysis

Agronomic data such as biomass yield, grain yield, average head weight and plant counts were collected in each farmer's field. To measure total biomass and grain yield of sorghum, the entire plot was manually harvested at maturity. After threshing, the head weight and stover were weighed. The grain samples were dried and adjusted at 13% moisture level. To understand spatial patterns of landscapes in terms of soil water characteristics, topsoil (at 20 cm depth) moisture content was measured at three spots per farmers' fields belonging to the three landscape positions. Soil moisture was measured using calibrated time domain reflectometer (TDR 300) portable probe with a 20 cm rod size. The yield data were subject to analysis of variance using the Generalized

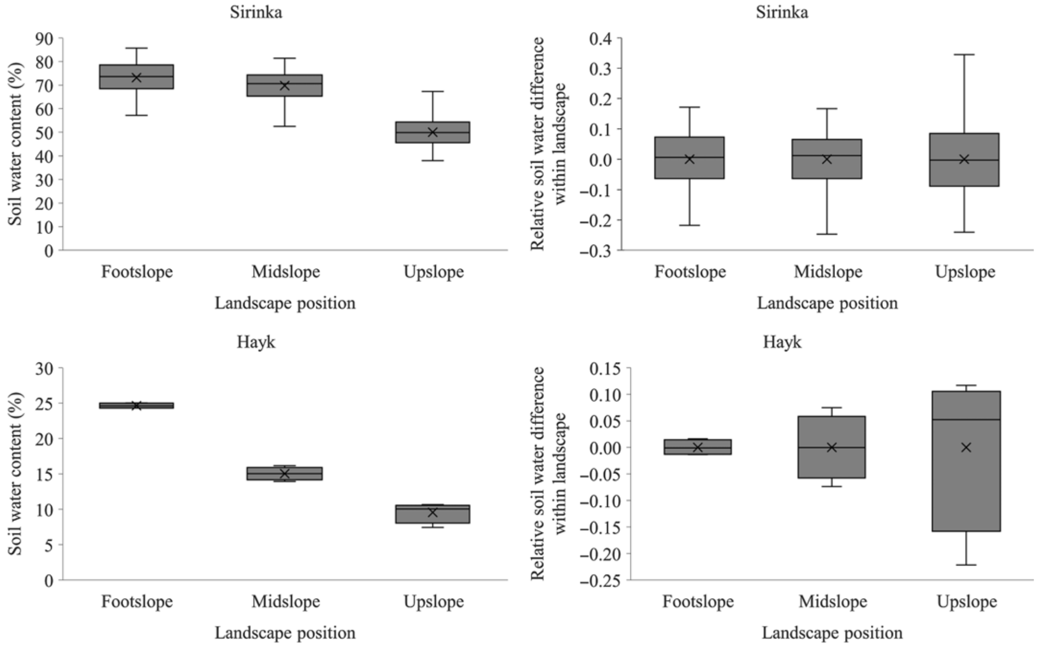

Figure 2. Soil water content and relative soil water difference of farmers' fields within each landscape position.

Linear Model (GLM) of SAS statistical package version 9.2. Using the GLM, the treatment means and total variability of factors were quantified. Means for the effects of the location, landscape positions, fertilizer rates and their interactions were compared using Tukey's pairwise comparison test at 5% probability level. To determine the relative effects of landscape positions on yield and soil moisture, we performed orthogonal contrast analysis using Scheffe's F test. Coefficients of variation of sorghum yield computed per fertilizer rate were applied to evaluate the yield variability between farmers' fields.

We used multivariate regression models to test whether the landscape position, farmers' fields and fertilizer factors can predict yield differences, and assess the importance of factors explaining variations in sorghum yield. Multivariate regression models were used to determine relative importance of the three factors (i.e., landscape position, farmer's field and fertilizer rates). Model I considered the three factors, whereas Model II explained sources of variation by excluding farmers' fields. In addition to the experimental factors, the sources of variations of soil and topographic variables on sorghum yield were modelled.

Results

Characterizing soil water content along landscapes

Figure 2 depicts the amount of soil water content (at 20 cm soil depth) of landscape positions and the relative difference in soil water content of farmers' fields within each landscape position. The soil water content was measured three weeks after the average cessation of seasonal rainfall considering the relative importance of soil water for crop growth until maturity stage of crops. The soil water variability (assessed by coefficient of variation, CV in %) was high at upslope and low at foot slope. The CV at Sirinka was 8.9, 8.5 and 11.9% at foot slope, mid-slope and upslope positions, respectively. Similarly, the CV increased from foot slope to upslope in the order of 1 1.5, 6.1 and 15.2% at Hayk. It indicates that slope positions in the landscape had a strong effect on the soil water variations.

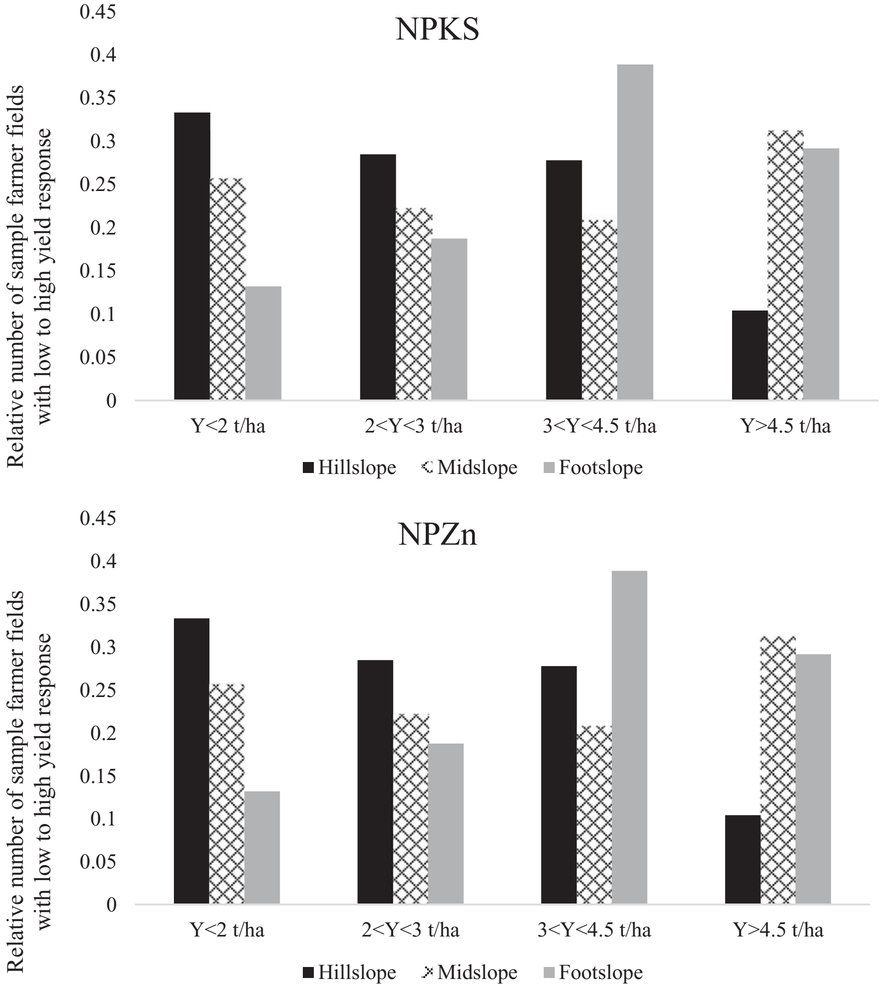

Figure 3. Proportion of experimental fields with relative occurrence of ranges of grain yield at the three landscape positions for the two sets of fertilizer experiments.

The respective interquartile range (IQR) values of soil water content of upslope, mid-slope and foot slope were 0.264, 0.116 and 0.027% at Hayk and 0.174, 0.129 and 0.137% at Sirinka. The larger range of IQR soil water values among the landscape positions at Hayk clearly indicated the high variability of farmers' fields in the upslope landscape position, which may be attributed to variations in slope gradient, soil depths and less fertility. Landscape positions at Sirinka did not exhibit high variability in soil water content. The lower IQR at foot slopes implies a relatively spatially homogenous response unit. Similarly, considering the relative soil water content of all farmers' fields across the three landscape positions at Sirinka, higher soil water variability was observed at upslope landscape position than the mid-slope and foot slope positions.

Effects of landscape positions on sorghum yield

In the NPKS experiment, of the total farmers' fields belonging to foot slopes, 29 and 39% of fields provided high (>4.5 t ha^{-1}) and medium yield (3–4.5 t ha^{-1}). 31 and 21% of fields belong to the mid-slope and 10 and 27% belong to the upslope represented high and medium yield, respectively (Figure 3). The proportion of fields with very low yield (<2 t ha^{-1}) were 13, 25.7 and 33%

Table 1. Mean effect of location and landscape position interaction on sorghum yield parameters

	Grain yield (kg ha^{-1})		Biomass yield (kg ha^{-1})		Stover yield (kg ha^{-1})		Average head weight (g per plant)	
Landscape position	Sirinka	Hayk	Sirinka	Hayk	Sirinka	Hayk	Sirinka	Hayk
NPKS								
Foot slope	3870.9	3565.4	17 687	14 671	13 816	11 106	81.9	97.4
Mid-slope	3751.9	3096	16 301	12 590	12 549	9494	82.5	78.8
Hillslope	2310.6	3186.9	11 324	17 113	9013	13 926	98.3	73.8
SE	125.74		366.12		398.2		4.1	
SE diff	177.83		517.78		563.13		5.7	
NPZn								
Foot slope	4049.2	4146.4	16 850	15 954	12 800	11 807	79.8	95.2
Mid-slope	4171.2	3703.9	13 986	12 000	9815	8296	72.1	71.5
Hillslope	2557.1	3103.9	10 410	15 181	7853	12 077	84.4	69.6
SE	145.71		510.03		513.08		4.5	
SE diff	206.07		721.29		725.6		6.3	

NPKS – factorial combination of nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) nutrients; NPZn – factorial combination of nitrogen (N), phosphorus (P) and zinc (Zn) nutrients. SE = Standard error of mean; SE diff = Standard error of mean difference.

corresponding to foot slope, mid-slope and upslope positions, respectively. In general, one-third (32%), half (48%) and two-thirds (62%) of farmers' fields belonging to foot slope, mid-slope and upslope landscape positions produced below median yield (3 t ha^{-1}), whereas, in the NPZn experiment, 23, 33 and 55% of farmers' fields belonging to foot slope, mid-slope and hillslope resulted in grain yield below median yield (3 t ha^{-1}) and vice versa.

The statistical results showed that the interaction effect of location by landscape positions was significant ($p < 0.001$) on sorghum yield parameters (Table 1). However, location alone has non-significant effect on sorghum yield parameters. In both sets of fertilizer treatments, at Sirinka site, foot slopes had significantly higher sorghum yield than the mid-slope and hillslope positions. There is decrease in yield when moving from foot slopes to upslopes. However, at Hayk, the hillslopes showed more yield response than the mid-slopes. At Sirinka, foot slopes and mid-slopes showed respective increments of 68 and 62% grain yield and 53 and 39% stover yield over the hillslopes with the application of NPKS nutrients. Similarly, grain yield increments of 58 and 63% were recorded from foot slope and mid-slope compared to hillslopes with the application of NPZn nutrients. At Hayk, foot slopes recorded 12 and 34% grain yield increase over hillslope positions with the application of NPKS and NPZn, respectively. However, at Hayk, the mid-slope and hillslopes had comparable yield response. The non-linear yield response over landscapes at Hayk is likely attributed to other non-experimental factors. The contrast analysis also revealed that the three landscape positions had a significant sorghum yield difference among each other (Table 2). Thus, the interaction effect explained the non-uniform fertilizer response of landscape positions over different locations which is attributed to spatial variation of soil nutrients, soil water content, geomorphologic and climatic features. This difference of yield response among landscape positions across locations explained the need for designing location specific fertilizer experiments to capture different environmental domains. This entails that fertilization recommendation would have to take into account this yield potential variability related to the landscape position.

Effects of fertilizer on sorghum yield

The effects of fertilizer rates were significant ($p < 0.001$) for both grain and stover yield of sorghum. The relative contribution of factorial NP nutrients on grain yield increased with an increase

Table 2. Orthogonal contrasts between landscape positions

Contrast		NPKS Grain yield (kg ha^{-1})	NPKS Biomass yield (kg ha^{-1})	NPZn Grain yield (kg ha^{-1})	NPZn Biomass yield (kg ha^{-1})
Contrast 1 (FS:MS:HS = 2:-1:-1)	Variance ratio (F)	17.09	19.48	16.14	37.77
	p	0	0	0	0
	SE	216.12	591.92	251.27	807.09
Contrast 2 (FS:MS:HS = 1:-1:0)	Variance ratio (F)	30.18	16.46	38.16	29.95
	p	0	0	0	0
	SE	124.78	341.75	145.07	465.97

NPKS – factorial combination of nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) nutrients; NPZn – factorial combination of nitrogen (N), phosphorus (P) and zinc (Zn) nutrients. FS = Foot slope; MS = Mid-slope; HS = Hillslope; SE = Standard error of mean.

of both N and P rates. Results from this study showed higher grain yields resulting from the use of N and P. The mean grain yield effect increased significantly with an increase in NP nutrient levels (Figure 4). Averaged across nine levels of K and S nutrients, sorghum grain yield response to four rates of N and P nutrients revealed a significant grain yield increase. Within NP levels, there was no significant grain yield difference at the different K (0, 40 and 80 kg ha^{-1}) and S (0, 20 and 40 kg ha^{-1}) levels (Figure 4a). This shows that application of either K (40 and 80 kg ha^{-1}) or S (20 and 40 kg ha^{-1}) did not result in significant sorghum yield difference compared to without applying K and S nutrients. Application of N0P0-K80S0 and N138P69-K80S0 produced the lowest (1615 kg ha^{-1}) and highest (4906 kg ha^{-1}) yield of sorghum, respectively. The negative control treatment (N0P0-K0S0) provided grain yield of 1942 kg ha^{-1} which had no statistically significant difference with N0P0 and N46P23 levels at all levels of K and S, while it had significant grain yield difference with N92P46 and N138P69 levels. Compared to zero fertilizer treatment, yield increases due to increased levels of N and P nutrients were 450 to 2965 kg ha^{-1} regardless of landscape positions. Application of higher levels of K (80 kg ha^{-1}) without N and P fertilizer produced significantly higher stover yield while comparable stover yield was gained by applying both 40 and 80 kg ha^{-1} K in combination with N46P23. As the levels of N and P increase, high stover yield effect was obtained by applying 40 kg ha^{-1} K (Figure S1). Like the grain yield, S application did not show any significant effect on stover yield.

The combined application of NP and Zn resulted in significant ($p < 0.001$) sorghum yield difference. Application of highest rates of N and P (N92P46 and N138P69) resulted in significant yield variation (Figure 4b). The lowest (1997 kg ha^{-1}) and highest (5173 kg ha^{-1}) yield of sorghum was obtained with the application of N0P0-Zn8 and N138P69-Zn8, respectively. Application of N46P23 combined with all levels of Zn did not show significant grain yield of sorghum compared to the control treatment (N0P0-Zn0). However, the control treatment had statistically significant yield difference with N92P46 (90–105% yield increase) and N138P69 (135–140% yield increase) levels combined with all levels of Zn. Thus, application of Zn nutrients (4, 8 and 12 kg ha^{-1}) did not result in significant sorghum yield difference within NP levels while there was numerical yield increase of 150–700 kg ha^{-1} with the application of Zn nutrients. Numerically high stover yield was recorded by applying Zn without N and P or high rates of N and P (N92P46 and N138P69) without Zn (Figure S1).

The response of sorghum yield to fertilizer was evaluated under different topographic positions – hillslope, mid-slope and foot slope. There was a statistically significant interaction effect of landscape position and fertilizer rates on sorghum grain yield and stover yield (Figure 5). Simple effect analysis of fertilizer rates within a landscape position also revealed a significant ($p < 0.001$) effect of fertilizer rates on total biomass, grain and stover yields as well as on average head weight per plant. Despite extremely high spatial variability in yields (see Figure 6, varying with a CV of 4–70%), a significant interaction effect of

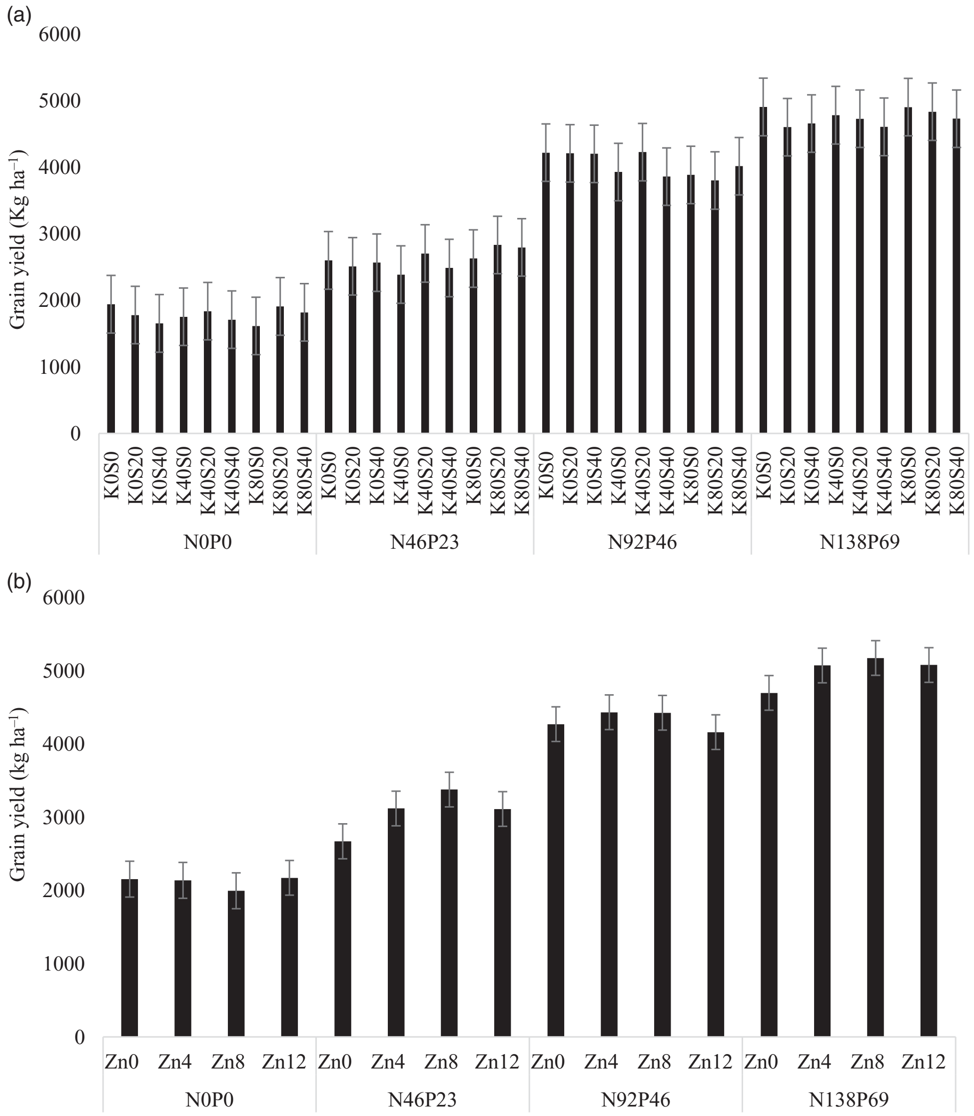

Figure 4. Mean grain yield of sorghum at different levels of N, P, K and S fertilizers (a) and N, P and Zn fertilizers (b) combined over Sirinka and Hayk sites.

fertilizer and slope position was observed, of progressively increasing yields when moving downslope.

Relative importance of factors to sorghum yield variability

The analysis for sorghum yield variability between farmers' fields considered yield data of the fertilizer rates within each landscape position. As displayed in Figure 6, the coefficient of variation of grain yield for each fertilizer treatment depicts the general patterns of yield variability explained between farmers' fields. The yield variation between farmers' fields is highly pronounced at hill-slopes and mid-slopes except inconsistency at low NP application. Interestingly, yield variability between fields reduced with increased fertilizer application rates (Figure 6). High variability was

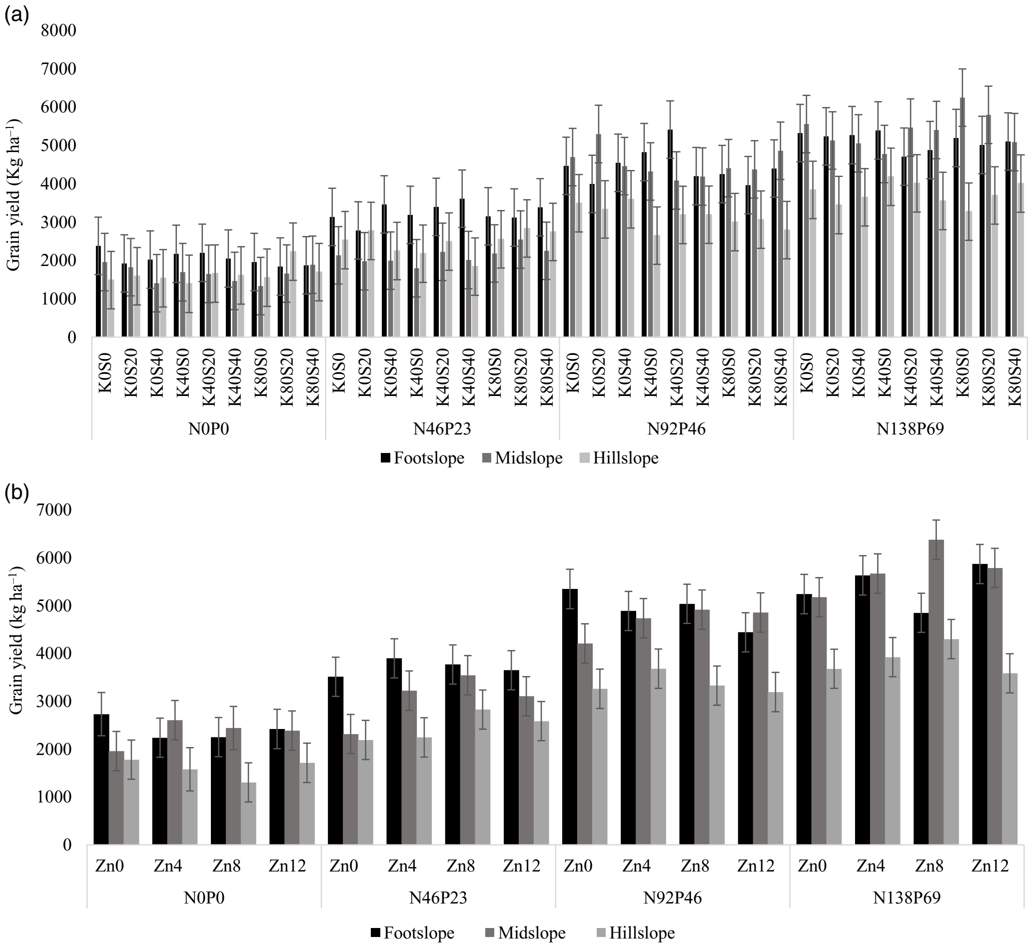

Figure 5. Interaction effects of landscape position and fertilizer rates: (a) for NPKS set of experiment; and (b) for NPZn set of experiments implemented at Sirinka and Hayk sites.

obtained without NP fertilizer application (N0P0). This implies that application of fertilizers could be used to minimize yield gradients at a specific location.

Crop yields were highly variable across fields because of interactions among different factors, such as soil properties, topography and management factors (Huang *et al.*, 2008). In this study, the variations of sorghum yield were modelled in relation to three factors: fertilizer application, landscape position and farmers' fields. As shown in Table S1, model I explained the combined effects of fertilizer application, farmers' fields and landscape position on grain and stover yield. Model II explained the effects on sorghum yield by excluding farmers' fields. The models revealed that there was a strong effect of fertilizer rates as the most influential factor (74–100% of relative influence) explaining differences in grain yield (Table S1). Landscape position is the second most important factor that contributes to yield variations. The root mean square error (RMSE) was about 0.74–0.92 and 0.58–1.00 for the NPKS and NPZn set of experiments. The contribution of farmers' fields for the yield variability was found negligible. The proportion of explainable variance in grain and stover yield (R^2 of 0.48–0.73 for grain yield and 0.25–0.39 for stover yield) was relatively low, indicating that other factors such as soil and topographic factors that had a relatively large influence on the yield differences within farmers' fields were not considered yet. Interestingly, in addition to fertilizer rates (explaining 80% of variability), topographic and soil properties such as

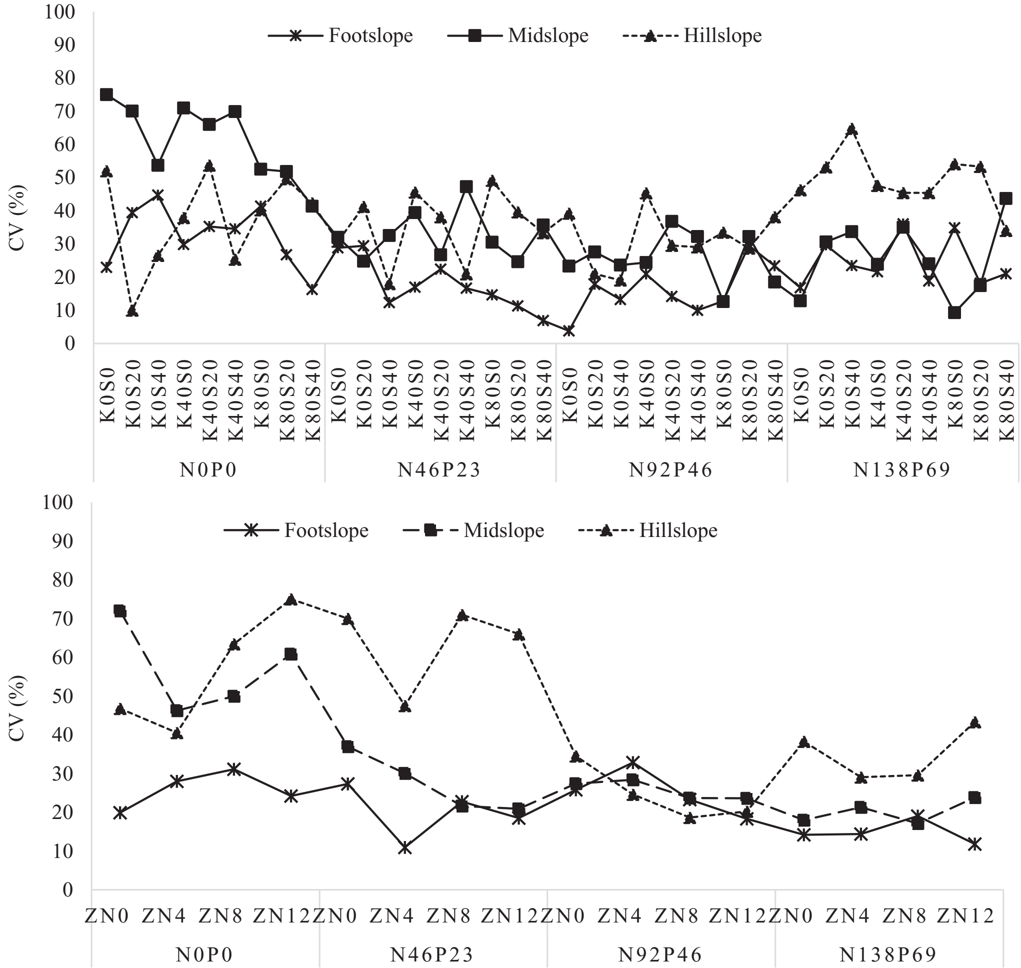

Figure 6. Coefficient of variation (CV, %) of grain yield between farmers' fields per each fertilizer treatment in each landscape position.

topographic wetness index, pH, bulk density, soil type, cation exchange capacity (CEC) and organic matter were identified as factors which had considerable effect explaining the fraction of sorghum grain yield variation (improved R^2 of 0.58–0.65 with RMSE of 0.63–0.67) within farmers' fields (Table S2).

Discussion

Grain sorghum is usually grown in stressful environments with high temperatures, lack of predictable water supply, fragile soils with low nutrient status and limited growing season length (Palé *et al*., 2009). Breman and Debrah (2003) indicated that improving the agricultural resource base of sorghum fields by increasing either nutrient availability or water availability can increase the efficiency of external inputs and make them an attractive option for African farmers. In line with these concepts, our study reported the roles of soil water content variation along landscape positions, fertilizer, interaction of fertilizer by landscape position on sorghum yields. Accordingly, the results showed that soil moisture content varied along the landscape positions. Lower soil moisture content and higher soil moisture variability were observed at the upslope landscape position than the mid-slope and foot slope positions. This implies that variability of soil water content within landscape position leads to inconsistent yield response to fertilizer and vice versa. The increase in soil water content down the slope is very much expected and an indication of fine soil texture as well as interflow and concentration of runoff from upslopes to foot slopes, which agrees with the findings of (Ofori *et al.*, 2013). Assefa *et al.* (2020) reported that the lower total porosity of the soil observed at upper slope positions may result in low soil water content, which could most likely be related to the high bulk density and shallow soil depths. Famiglietti *et al.* (1998) found that wetness index accounted for about half of the variability in soil depths and organic matter content. This, in turn, influences the crop yield variability in a landscape (Thelemann *et al.*, 2010). In general, the interaction of landscape position and soil water content influenced the variability in yield and the yield response to fertilizer. This implies that soil water content variations at landscape scale must be considered when determining factors that drive differences in crop yield.

In this study, application of combined rates of N and P nutrients resulted in a linear increase in sorghum yield while the efficiency of N and P utilization declined with increased N and P levels. Specifically, sorghum yield benefits over the zero fertilizer were increased for higher rates of N and P nutrients (25–150% yield increase for both NPKS and NPZn experiments). It was observed that applying K, S and Zn fertilizers, in combination with NP, resulted in non-significant sorghum yield compared with application of NP nutrients alone. The response to fertilizer is a much more important characteristic, especially in farming systems with low fertilizer application rates (Schut *et al.*, 2018). Bekunda *et al.* (2015), Bekunda *et al.* (2010) indicated that the two most limiting nutrients to food production in Africa are nitrogen (N) and phosphorus (P). A meta-analysis study in sorghum-cropping system in Africa concluded that application of N and P fertilizer resulted in 98% yield improvement (Tonitto and Ricker-Gilbert, 2016). Breman and Debrah (2003) indicated that improving the agricultural resource base by increasing either nutrient availability or water availability can increase the efficiency of external inputs and make them an attractive option for African farmers. In line with their reports, the positive effect of interaction of fertilizers with landscape position on sorghum yield while moving downslope is because of increased fertilizer use efficiency at downslopes leading to high sorghum yield. It is because the foot slopes enhanced soil water storage and thereby increase fertilizer use efficiency (Palé *et al.*, 2009). This indicates that applying fertilizers alone without considering soil water, soil depth and topographic positions in the landscape was not sufficient to enhance sorghum productivity. Consequently, stratified fertilizer targeting along landscape positions help to address issues of insufficient water or moisture stress conditions in semi-arid regions that limit fertilizer application.

Considering grain yield variability along the landscape, there were large differences in the observed yields along the landscape. Fields at the foot slope yielded higher and with less variability between fields compared with the upslopes, which showed low yield and high variability. The positive yield response of foot slopes to fertilizer application is related to better soil water content and soil quality over upslopes. However, foot slopes could result in lower yields when there is waterlogging under Vertisols and improper crop growth conditions. These yield variability patterns across the three landscape positions indicate the importance of a landscape-based fertilizer management approach to respond to yield variability according to the landscape environment. In this study, we found that fertilizer application and landscape positions were significant terms in the multivariate model estimating yield response to fertilizer application. Large differences in spatial variability between landscapes indicate that yield variability itself is an indicator of soil responsiveness and status of soil fertility (Schut *et al.*, 2018; Yao *et al.*, 2014). The results indicate that local factors are much more influential in explaining the heterogeneity in sorghum yield and yield response to fertilizer application.

These variations are attributed to highly diverse farming systems and the environmental factors such as soil, topography and water availability that vary strongly between farmers' fields and landscapes (Tittonell *et al.*, 2013, 2008; Yao *et al.*, 2014). The spatial variability is further compounded by heterogeneous management practices among farmers' fields, as the crop rotations, intercropping, crop residue, scattered trees and manuring are common (Amede *et al.*, 2020; Tamene *et al.*, 2017).

Fertilizer recommendations are commonly assumed similar response of all farmer fields in a landscape position to fertilizer application. But as demonstrated in the results, the actual yield response to fertilizer application varied significantly. This indicates that the interaction of landscape position with soil and topographic variables as well as farm management practices strongly affects yield response to fertilizer application. The attributions to the variations in the response are discussed and reported in several studies (Giller *et al.*, 2011; Kurwakumire *et al.*, 2014; Schut *et al.*, 2018; Zingore *et al.*, 2007). Thus, local scale assessment of the response to applied nutrients is much more important to capture field variations explained in soil fertility differences within short distances. The concept of site-specific fertilizer management is to identify and manage spatially coherent areas within the landscape that present homogenous combination of yield-limiting factors (Córdoba *et al.*, 2016; Schepers *et al.*, 2004). Thus, the largest spatial variation that was explained between landscape positions made it difficult to determine homogenous fertilizer response zones, as there are too many limiting factors. Thus, the need for understanding the relationship among spatial variability of farmers' fields and crop yields is getting increasingly important because of growing concern about the more efficient application of fertilizer (Yao *et al.*, 2014). Managing soil spatial variability by applying inputs according to site-specific requirements is the common approach for site-specific fertilizer management (Reyes *et al.*, 2019).

Overall, although topography determines general trends of crop performance, fertilizer recommendations should rather be field based than zone based, and farmers are probably able to evaluate the general fertility of their field. The relative yield pattern could highlight different yield response zones relative to the control fertilizer rate: (1) a landscape zone defined with negative yield response to fertilizer; (2) a landscape zone defined with low-yielding fields but positive yield response to fertilizer; and (3) a landscape zone defined with high-yielding fields and positive grain yield response to fertilizer. Besides, there were farmers' fields that uniquely exhibited yield variability differed from the general pattern described in the three landscape zones. For example, farmers' fields demonstrating lower yields at foot slopes indicated that other factors (e.g., low soil fertility, waterlogging, soil and crop management variations, improper crop growth, pests and diseases) had a relative influence on the yield differences. Thus, it is worth further investigation and identification of determinant factors at local scale that contribute to the yield variability among farmers' fields in a landscape. In general, relative yield variations demonstrated that sorghum yield was highly influenced both by the farmer's field conditions and other environmental and management factors along the landscape.

Conclusion

It was noted that increase in nitrogen and phosphorus fertilizer applications led to a significant increase in grain and stover yield of sorghum. Inherent soil fertility and topographic attributes contributed significantly to the grain and stover yields of sorghum irrespective of fertilizer rates applied. Fertilizer applications up to 138/69 kg N/P2O5 ha^{-1} were found to be the fertilizer rate leading maximum yield. Compared to zero fertilizer application, significant sorghum yield difference was observed by applying 92/46 and 138/69 kg N/P2O5 ha^{-1} while comparable yield with the 46/23 kg N/P2O5 ha^{-1}. However, application of K, S and Zn across all levels of N and P nutrient levels did not produce significant sorghum yield differences.

An understanding of sorghum yield response to fertilizer application along landscape positions is essential to realizing the goal of applying landscape-targeted fertilizer management and meeting a positive return to soil investment. Our research shows that sorghum yield is spatially variable and influenced by farmers' fields-scale variations in a landscape that could be associated with soil and topographic attributes. Crop yield response to fertilizer application is very much dictated by farmers' fields distributed along landscapes where the yield response was high at fields located at foot slopes due to higher soil water content and soil nutrients relative to upslope positions.

It is apparent that fertilizer alone, or as a single factor, cannot explain the spatial variability in sorghum yields along landscapes. More importantly, landscape positions consistently influenced yield variations. Consequently, many environmental factors explaining larger fraction of yield variation can be considered as an indicator to explain yield variability and the response to fertilizer application and thereby to delineate fertilizer response zones. Further investigations are needed to identify most influential factors and relationships among factors explaining yield variation and then define homogenous fertilizer response zones. This study provides first-hand information in identifying factors responsible for fertilizer response that deliver a knowledge-based approach to fertilizer application with the goal of fertilizer optimization. More work is needed to develop a general protocol on fertilizer response based on spatial variability of soil and topographic attributes and crop yield along the landscape.

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References

Affholder F., Poeydebat C., Corbeels M., Scopel E. and Tittonell P. (2013). The yield gap of major food crops in family agriculture in the tropics: assessment and analysis through field surveys and modelling. *Field Crops Research* **143**, 106–118.

Amede T. and Diro M. (2005). Optimizing soil fertility gradients in the enset (ensete ventricosum) systems of the Ethiopian highlands: trade-offs and local innovations. In Bationo A., Waswa, B., Kihara, J., and Kimetu, J. (eds), *Improving Human Welfare and Environmental Conservation by Empowering Farmers to Combat Soil Fertility Degradation*. Addis Ababa: Working Paper #15, African Highlands Initiative (AHI), pp. 1–11.

Amede T., Gashaw T., Legesse G., Tamene L., Mekonen K., Thorne P. and Schultz S. (2020). Landscape positions dictating crop fertilizer responses in wheat-based farming systems of East African Highlands. *Renewable Agriculture and Food Systems*, 1–13. https://doi.org/10.1017/S1742170519000504

Assefa F., Elias E., Soromessa T. and Ayele G.T. (2020). Effect of changes in land-use management practices on soil physicochemical properties in Kabe watershed, Ethiopia. *Air, Soil and Water Research* **13**, 1–16. https://doi.org/10.1177/1178622120939587.

Bekunda A.M., Bationo A. and Ssali H. (2015). Soil fertility management in Africa: a review of selected research trials. In Brush R.J., Sanchez P.A. and Calhoun F. (eds), *Replenishing Soil Fertility in Africa*. Madison: Soil Science Society of America, pp. 63–80.

Bekunda A.M., Sanginga N. and Woomer P.L. (2010). Restoring soil fertility in sub-Saharan Africa. *Advances in Agronomy* **108**, 183–236. https://doi.org/10.1016/S0065-2113(10)08004-1.

Benoît M., Rizzo D., Marraccini E., Moonen A.C., Galli M., Lardon S., Rapey H., Thenail C. and Bonari E. (2012). Landscape agronomy: a new field for addressing agricultural landscape dynamics. *Landscape Ecology* **27**, 1385–1394. https://doi.org/10.1007/s10980-012-9802-8.

Breman H. and Debrah S.K. (2003). Improving African food security. *SAIS Review* **23**, 153–170. https://doi.org/10.1353/sais.2003.0002.

Córdoba M.A., Bruno C.I., Costa J.L., Peralta N.R. and Balzarini M.G. (2016). Protocol for multivariate homogeneous zone delineation in precision agriculture. *Biosystems Engineering* **143**, 95–107. https://doi.org/10.1016/j.biosystemseng.2015.12.008.

CSA (2019). *Report on Area, Production and Yield of Crops for Private Peasant Holdings for Main Crop Season 2012–2013.* Addis Ababa: CSA.

CSA (2020). *Area and Production of Major Crops.* Addis Ababa: CSA.

Diarisso T., Corbeels M., Andrieu N., Djamen P., Douzet J.M. and Tittonell P. (2016). Soil variability and crop yield gaps in two village landscapes of Burkina Faso. *Nutrient Cycling in Agroecosystems* **105**, 199–216. https://doi.org/10.1007/s10705-015-9705-6.

Famiglietti J.S., Rudnicki J.W. and Rodell M. (1998). Variability in surface moisture content along a hillslope transect: rattlesnake hill, Texas. *Journal of Hydrology* **210**, 259–281. https://doi.org/10.1016/S0022-1694(98)00187-5.

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. and 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. https://doi.org/10.1016/j.agsy.2010.07.002.

Heuze V., Tran G. and Lebas F. (2015). *Sorghum Grain*. Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO. https://feedipedia.org/node/224

Huang X., Wang L., Yang L. and Kravchenko A.N. (2008). Management effects on relationships of crop yields with topography represented by wetness index and precipitation. *Agronomy Journal* **100**, 1463–1471. https://doi.org/10.2134/agronj2007.0325

Kurwakumire N., Chikowo R., Mtambanengwe F., Mapfumo P., Snapp S., Johnston A. and 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. https://doi.org/10.1016/j.fcr.2014.05.013

Liu R., Pan Y., Bao H., Liang S., Jiang Y., Tu H., Nong J. and Huang W. (2020). Variations in soil physico-chemical properties along slope position gradient in secondary vegetation of the hilly region, Guilin, southwest China. *Sustainability* **12**, 1303. https://doi.org/10.3390/su12041303.

Matouš P., Todo Y. and Mojo D. (2013). Roles of extension and ethno-religious networks in acceptance of resource-conserving agriculture among Ethiopian farmers. *International Journal of Agricultural Sustainability* **11**, 301–316. https://doi.org/10.1080/14735903.2012.751701.

Moorman T.B., Cambardella C.A., James D.E., Karlen D.L. and Kramer L.A. (2004). Quantification of tillage and landscape effects on soil carbon in small Iowa watersheds. *Soil and Tillage Research* **78**, 225–236. https://doi.org/10.1016/j.still.2004.02.014.

Ofori E., Atakora E.T., Kyei Baffour N. and Antwi B.O. (2013). Relationship between landscape positions and selected soil properties at a Sawah site in Ghana. *African Journal of Agricultural Research* **8**, 3646–3652. https://doi.org/10.5897/AJAR12.150.

Palé S., Mason S.C. and Taonda S.J.B. (2009). Water and fertilizer influence on yield of grain sorghum varieties produced in Burkina Faso. *South African Journal of Plant and Soil* **26**, 91–97. https://doi.org/10.1080/02571862.2009.10639939.

Pierson F.B. and Mulla D.J. (1990). Aggregate stability in the Palouse region of Washington: effect of landscape position. *Soil Science Society of America Journal* **54**, 1407–1412. https://doi.org/10.2136/sssaj1990.03615995005400050033x.

Reyes J., Wendroth O., Matocha C. and Zhu J. (2019). Delineating site-specific management zones and evaluating soil water temporal dynamics in a farmer's field in Kentucky. *Vadose Zone Journal* **18**, 1–19. https://doi.org/10.2136/vzj2018.07.0143.

Schepers A.R., Shanahan J.F., Liebig M.A., Schepers J.S., Johnson S.H. and Luchiari A. (2004). Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. *Agronomy Journal* **96**, 195–203. https://doi.org/10.2134/agronj2004.0195.

Schut A.G.T., Traore P.C.S., Blaes X. and de By R.A. (2018). Assessing yield and fertilizer response in heterogeneous smallholder fields with UAVs and satellites. *Field Crops Research* **221**, 98–107. https://doi.org/10.1016/j.fcr.2018.02.018.

Tamene L., Amede T., Kihara J., Tibebe D. and Schulz S. (2017). *A Review of Soil Fertility Management and Crop Response to Fertilizer Application in Ethiopia. Towards Development of Site- and Context-Specific Fertilizer Recommendation.* Addis Ababa: CIAT.

Thelemann R., Johnson G., Sheaffer C., Banerjee S., Cai H. and Wyse D. (2010). The effect of landscape position on biomass crop yield. *Agronomy Journal* **102**, 513–522. https://doi.org/10.2134/agronj2009.0058.

Tittonell P., Muriuki A., Klapwijk C.J., Shepherd K.D., Coe R. and Vanlauwe B. (2013). Soil heterogeneity and soil fertility gradients in smallholder farms of the East African highlands. *Soil Science Society of America Journal* **77**, 525–538. https://doi.org/10.2136/sssaj2012.0250.

Tittonell P., Vanlauwe B., Corbeels M., Giller K.E. and Corbeels M. (2008). Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya Editorial Responsibility: len Wade. *Plant Soil* **313**, 19–37. https://doi.org/10.1007/s11104-008-9676-3.

Tonitto C. and Ricker-Gilbert J.E. (2016). Nutrient management in African sorghum cropping systems: applying meta-analysis to assess yield and profitability. *Agronomy for Sustainable Development* **36**, 10. https://doi.org/10.1007/s13593-015-0336-8.

van Beek C.L., Heesmans Alterra Á.H., Elias E., Yihenew Á.M., Tolla G.S., Tsegaye A., Feyisa H., Melmuye M., Gebremeskel Y. and Mengist S. (2016). Soil nutrient balances under diverse agro-ecological settings in Ethiopia. *Nutrient Cycling in Agroecosystems* **106**, 257–274. https://doi.org/10.1007/s10705-016-9803-0

Yao R.J., Yang J.S., Zhang T.J., Gao P., Wang X.P., Hong L.Z. and Wang M.W. (2014). Determination of site-specific management zones using soil physico-chemical properties and crop yields in coastal reclaimed farmland. *Geoderma* **232–234**, 381–393. https://doi.org/10.1016/j.geoderma.2014.06.006.

Zingore S., Murwira H.K., Delve R.J. and Giller K.E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems and Environment* **119**, 112–126. https://doi.org/10.1016/j.agee.2006.06.019.

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