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Full Length Research Paper

Geo-spatial analysis of factors constraining the productivity of common bean in small holder systems in western Kenya

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Bean (*Phaseolus vulgaris*) productivity is low in smallholder systems in SSA due to numerous constraints, including low soil fertility, high pest and disease pressure, and low use of purchased inputs. This has resulted in food and nutritional insecurity, and low household income. Localized geo-spatial analyses of these factors to visualize their spatial and temporal distribution was conducted. Bean experimental plots were set up in 66 farms in Nandi County, during the short rains 2016, and the long rains 2017 seasons. Data was collected on pests and diseases, rainfall and temperature. GPS coordinates were recorded and soil samples taken for determination of pH, organic carbon, texture, and micronutrients. Bean grain yield was assessed and data subjected to statistical evaluation, including correlation, ANOVA, and regression analyses. Geo-spatial analysis of bean fly, root rot and bean common mosaic virus (BCMV) was conducted to assess their distribution in time and space, and influence on bean productivity. Results showed large spatial and temporal variations in the distribution of pests and diseases, creating possible hotspots with significantly decreased bean productivity. Rainfall was negatively correlated with bean fly, BCMV and angular leaf spot, while a positive correlation was observed between rainfall and bean root rot. Iron and manganese had the largest effect on bean productivity. This study indicates that important bean production constraints have spatial and temporal distribution and technology testing and dissemination of production options should be informed by this knowledge in order to match the options to biophysical contexts to improve bean productivity in smallholder systems.

Keywords: smallholder systems; common bean; production constraints; geo-spatial analysis; western Kenya.

1. INTRODUCTION

1.1 Importance of beans in smallholder systems

Common bean (*Phaseolus vulgaris* L.) is an important grain legume in sub-Saharan Africa (SSA), particularly in Eastern, Central and Southern Africa, where its consumption per capita exceeds 50 kg yr⁻¹, and is perhaps the highest in the world, particularly in western Kenya (Wortmann et al., 1998). However, its productivity is low in much of SSA (Ojiem et al., 2006), leading to food and nutritional insecurity. Beans in this region are grown primarily by smallholder, resource-poor farmers and provide essential dietary protein, fiber and income for at least 100 million people in Africa (Kimani et al., 2001).

1.2 Constraints to bean productivity

Numerous factors constrain bean productivity, especially in western Kenya and much of the highlands of East Africa, where smallholders face a myriad of challenges in improving land productivity. The major constraints to bean production include land scarcity, low soil fertility, prevalence of pests and diseases, and variability in weather conditions (e.g. rainfall and temperature). The western Kenya region is generally characterized by wet and humid climatic conditions and because of this, high incidences of a range of fungal, bacterial and viral bean diseases are often observed (Wortmann et al., 1998). Similarly, damage by insect pests constitute a major constraint to bean productivity (Allen et al., 1996). Low soil fertility is generally accepted to be an important limitation to crop productivity in many parts of SSA (Sanchez et al., 1997). In western Kenya in particular, widespread soil degradation and nutrient depletion, along with inadequate fertilizer and organic matter inputs have been identified as the major causes of declining food production in smallholder farms (Stoorvogel *et al.*, 1993).

Important soil-related bean production constraints in western Kenya and most of the tropical bean production regions include N and P deficiencies, and Al and Mn toxicities in acid soils (Smithson and Sanchez, 2001). Biological N fixation rates and tolerance to P deficiency are already low in common bean in comparison to other legumes (Broughton *et al.*, 2003). Soil acidity and P deficiency, which combine to adversely affect root nodulation, survival of rhizobia and biological nitrogen fixation, seriously lower bean yields.

1.3 Analyzing bean production constraints

The complex variability in biophysical factors such as, soil fertility, rainfall, altitude and pests and diseases in smallholder systems offer challenges in identifying the major constraints to increased bean production. Geospatial data plays an important role in decision-making in agricultural activities, particularly in response to the impacts and vulnerability of agricultural productions to variability (Ayanlade et al., 2013). A good understanding of

the spatial and temporal distribution of productivity limiting factors is necessary to establish the biophysical and socio-economic contexts of the production environment. Spatial analysis can be used to guide where to test and disseminate agricultural production technologies. Although a systematic sampling of test sites can be done to ensure coverage of diverse range of testing environments, without spatial analysis it is possible to miss areas where a cultivar might produce high yields (Hyman et al., 2013). Utilization of geo-spatial analysis in sub-Saharan Africa has lagged behind because of limited development of geospatial data infrastructure to enhance agricultural practices especially agricultural risk management in this age of climate change (Ayanlade et al., 2013). Where such data is available, the spatial resolution is often too large to allow application in specific smallholder situations like western Kenya. This study conducted a geospatial analysis of the major biophysical factors influencing bean productivity in smallholder farms in western Kenya to facilitate matching bean production options to contexts to improve productivity.

2. MATERIALS AND METHODS

2.1 Description of study area and sampling design

This study was carried out at three sites (Kapkerer, Kiptaruswo and Koibem) in Nandi County, western Kenya. Kapkerer is located at latitude 0° N and longitude 34.7833° E, Kiptaruswo 0° N, 34.5602° E, and Koibem 0° N, 34.9667° E. The area receives bimodal rainfall, with short rain season that is between September and December (the main bean growing season in western Kenya), and long rains season that is between January and August. A total of 66 farms were sampled for this study, 22 in each of the three study sites. A systematic sampling procedure was applied to ensure even spatial distribution of data points, taking into consideration the heterogeneity of observations. This procedure involved random selection of 22 farms from each site at a sampling interval of 1 km. The sampling interval of 1 km was determined by dividing the total area under agricultural use in each site (approximately 22 km²) by 22 farms, which the resources available could allow. GPS coordinates and altitude were recorded for all selected farms.

2.2 Establishment of bean plots and data collection

Common bean (variety KK8, bush type of medium maturity) was planted in unreplicated 9 m² experimental plots in each of the farms to assess the variation in grain yield between farms. The plots were established at the beginning of the short rain season in September 2016. Spacing was at the recommended spacing of 50 cm inter-row and 10 cm intra-row. Fertilizer Triple Super Phosphate (TSP) was applied at 30 kg P ha⁻¹ in planting holes. Weeding was done twice, first weeding 21 days after planting (DAP) and the second one 42 DAP. The trial was

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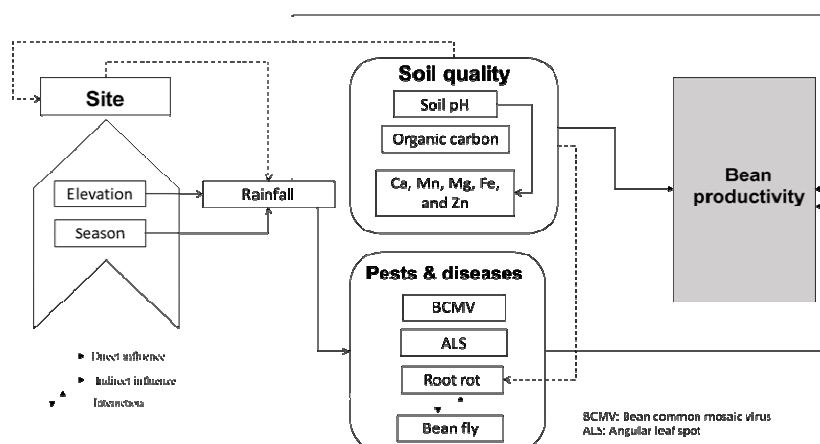


Figure 1 Conceptual framework for assessment of factors influencing bean productivity, and data analysis

repeated in the same farms but different plots during the long rains season-March to July 2017. Prior to planting, composite soil samples (0 to 20 cm) were taken from the trial plots in each of the 66 farms for determination of soil factors important for legume growth. Soil pH, organic carbon, exchangeable calcium, magnesium and potassium, and soil texture were determined at the Kenya Agricultural & Livestock Research Organization laboratory based in Nairobi, Kenya. In addition, soil concentrations of important micro-nutrients (Fe, Zn, Mb, and Mn) were analyzed by Ethylenediamine-tetraacetic acid (EDTA) extraction and measurements using Atomic Absorption Spectrometer (AAS).

Weather data (rainfall and temperature) was collected every growing season. 12 rain gauges and thermometers were placed in each site at strategic locations to provide even coverage of the entire study site. Daily rainfall was recorded at each of the locations. Morning, mid-day and evening temperatures were recorded at each location using the installed thermometers. Morning temperature was recorded at 9 am, mid-day temperature at noon, while evening temperature was recorded at 6 pm. From these three readings, an average daily temperature was calculated for each location.

Emergence of bean plants was assessed 10-14 days after planting (DAP) by counting the number of plants that had emerged and expressing this as a percentage of the seeds that were planted in each plot. Pest and disease damage was assessed and scored based on symptoms that were observed at various stages during the growing season. Plant fatality due to bean root rot and bean fly were recorded cumulatively at 14, 21 and 28 DAP and percent plants dying determined based on emerged plants. Bean common mosaic virus (BCMV), anthracnose, angular leaf spot (ALS), and common bacterial blight (CBB) were

scored on a scale of 1-5, where 1 represents least diseased and 5 represents most diseased. The scoring was based on CIAT bean program standard evaluation scale (CIAT, 1985). In addition to scores, plant samples were taken to University of Nairobi plant pathology laboratory for isolation of pathogens and culturing to facilitate positive identification of the fungal, bacterial and viral diseases, whose symptoms were observed during the growing season. This was used to validate the disease-related mortalities reported. Damage by aphids was also scored on a scale of 1-5, as explained above. Bean plots were harvested at the end of each growing season, pods removed and threshed for determination of grain yield. Grain moisture content was measured using an electronic moisture meter, grain weighed and grain yield expressed in t ha^{-1} at 13% moisture content.

2.3 Data analysis

Grain yield data was subjected to visual evaluation of boxplots using Stata software, to assess the variability of bean performance between and within sites, over the long and short rain seasons. Statistical analysis was conducted by assessing factors that directly influence bean productivity, and those whose influence is indirect. Figure 1 gives the conceptual framework that guided the analysis. Correlation analysis was conducted to determine how the soil quality parameters, pests and diseases, and rainfall relate with bean grain yield, and with each other. This was followed by development of visual correlation diagrams to show the relationship between grain yield and rainfall, elevation, soil pH, root rot, and bean fly. A second correlation diagram was constructed to show the relationship between rainfall and percentage of plants dying due to root rot and bean fly. The diagrams were

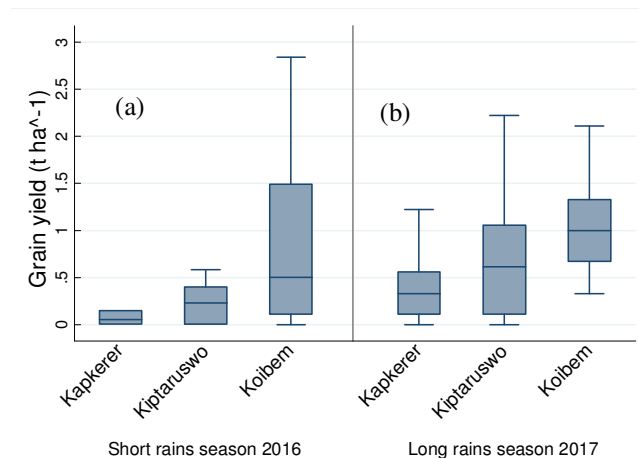


Figure 2. Bean grain yield performance at Kapkerer, Kiptaruswo and Koibem sites in Nandi County: (a) short rains 2016, and (b) long rains 2017.

made using R statistical package version 3.4.0. Data was then subjected to ANOVA to identify the variables with significant influence on bean grain yield. The variables that were included in the ANOVA model were selected based on the output of correlation analysis to avoid multicollinearity. The ANOVA output informed the regression analysis which was conducted to determine the variables with significant contribution to bean grain yield. Linear mixed model (fixed and random effects) was fitted using both forward and back ward selection of variables to get the model best fitting the data. The ANOVA and regression analyses were conducted on data combined over seasons and sites.

Spatial analysis was conducted to establish the spatial and temporal distribution of the key factors affecting bean productivity in the three study sites. Variables which showed correlation with grain yield and had significant effect on grain yield, according to the regression analyses, were considered within the spatial analysis. Quantum GIS (QGIS) version 2.8.2 was used to analyze and map the spatial information of selected variables from the above analyses. GIS overlay maps showing the interaction of bean fly, root rot, and BCMV with grain yield were done for each study site for both the long and the short rains growing seasons. Inverse Distance Weighting (IDW) interpolation method was used in the development of the maps. Variogram models were fitted in R using the gstat libraries to analyze the spatial relationship between data points.

3. RESULTS AND DISCUSSIONS

3.1 Grain yield

Bean grain yield varied with site and season (Fig. 2). During the short rains season in 2016, the range in grain

yield at Kapkerer was 0.00 to 0.20 t ha⁻¹, with 75% of the observations falling between 0.00 and 0.18 t ha⁻¹. At Kiptaruswo, the range was 0 to 0.58 t ha⁻¹ with 75% of the observations falling between 0 and 0.40 t ha⁻¹, whereas at Koibem, the range was 0 to 2.84 t ha⁻¹, with 75% of the observations falling between 0 and 1.5 t ha⁻¹. Similarly, during the long rains season 2017, Kapkerer had the lowest grain yield performance, ranging from 0.00 to 1.20 t ha⁻¹ with 75% of the observations falling between 0 and 0.59 t ha⁻¹. Kiptaruswo had a highest grain yield range of 0 to 2.21 t ha⁻¹, with 75% of the observations falling between 0 and 1.08 t ha⁻¹. The grain yield range at Koibem was 0.31 to 2.15 t ha⁻¹, with 75% of the observations falling between 0.31 and 1.35 t ha⁻¹. The observed yields of bean at Kiptaruswo and Koibem sites compare favorably with national mean yields of 0.5 t ha⁻¹. However, the yields at Kapkerer are far below the national mean yields as well as the mean yield eastern Africa highlands (Katungi et al., 2010), which include Kenya, Uganda, Tanzania, Burundi and Rwanda.

3.2 Environmental factors influencing grain yield

The variations in grain yield as determined by correlation and regression are partly attributable to rainfall, incidences of pests and diseases, and micro-nutrient deficiencies, especially Fe. Negative correlation was observed between a number of pests and diseases, particularly bean fly (correlation coefficient (r)= -0.278**), BCMV (r= -0.228), and root rot (r= -0.228).

3.2.1 Rainfall

Rainfall was significantly correlated with grain yield (r= 0.291). Rainfall was variable between the study sites both during the short rains 2016 and the long rains 2017 growing seasons (Fig. 3). At Kapkerer, total monthly rainfall

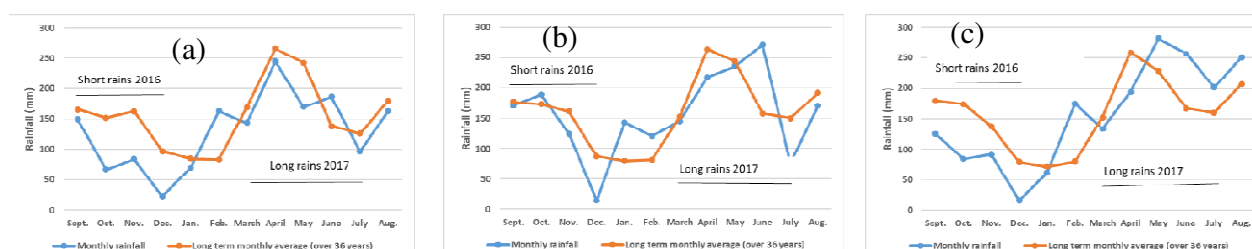


Figure 3. Rainfall distribution during the short rains 2016 and the long rains 2017 growing seasons at Kapkerer (a), Kiptaruswo (b) and Koibem (c) sites.

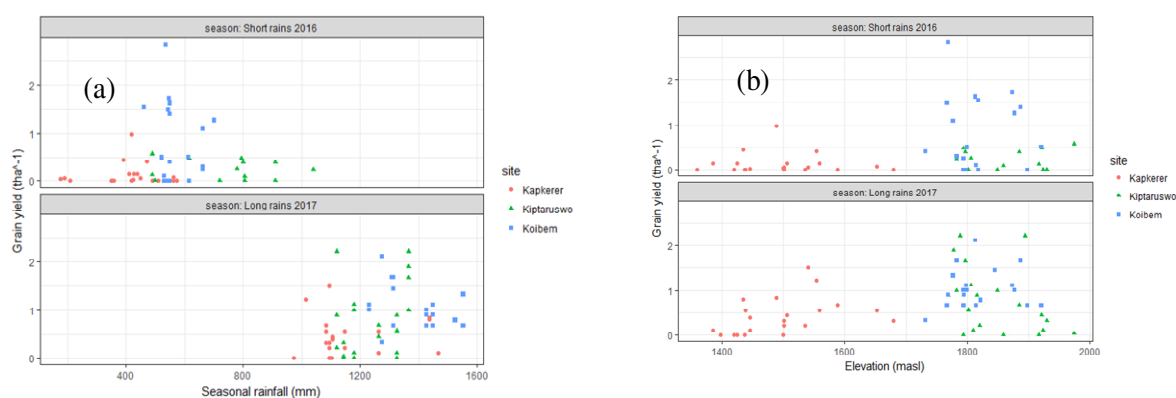


Figure 4. Relationship between bean grain yield performance and seasonal rainfall (a), and elevation (b) at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

was much below the long term average during the short rains 2016 growing season (Fig. 3a). During the subsequent growing season (long rains 2017), the total monthly rainfall was much higher than the previous season, and closely mirrored the long term average. The higher rainfall received at Kapkerer during the long rains growing season resulted in increased grain yield performance (see Fig. 2). At Kiptaruswo site however, the short rains season 2016 started with fairly good rainfall amounts, which was followed by a sharp decline during the month of November (Fig. 3b). This sharp decline in rainfall occurred during flowering stage, and the relatively poor grain yield observed during this season is partly due to poor podding and grain filling as a result of this drought. Rainfall was adequate during the long rains growing season resulting in much higher grain yield performance compared to the short rains growing season. Similar to Kiptaruswo, rainfall declined sharply between November and December during the short rains 2016 growing season at Koibem (Fig. 3c). This coincided with the podding and grain filling growth stages when moisture availability is critical. Bean grain yield performance was therefore relatively lower during the short rains season 2016 than the long rains season 2017 (Figure 2), when soil moisture was adequate.

There was variation in rainfall both within and between seasons (Fig. 4 a). During the short rains 2016 growing season when seasonal rainfall was low, bean grain yield was correspondingly low and no clear relationship observed between bean grain yield and rainfall. Insect pests and viral outbreaks tend to increase during dry seasons (Katsaruware-Chapoto et al., 2017), hence contributing to low bean productivity. This was also observed in our study during the short rains 2016 growing season. Aphids, BCMV, and bean fly infestations were higher during the season. Conversely, during the long rains 2017 growing season when seasonal rainfall was high, grain was also high.

Successful bean production requires between 200 to 400 mm of rain during the growing season (Broughton et al., 2003), and the distribution over the growing season is an important consideration. In addition, climate change is an emerging challenge that is likely to negatively influence bean productivity especially in the predominantly rainfed smallholder production systems of SSA.

3.2.2 Elevation

Significant variation in altitude was recorded both within and between the study sites. Farms that were sampled at Kapkerer were at the lowest altitude (1350 – 1680 masl),

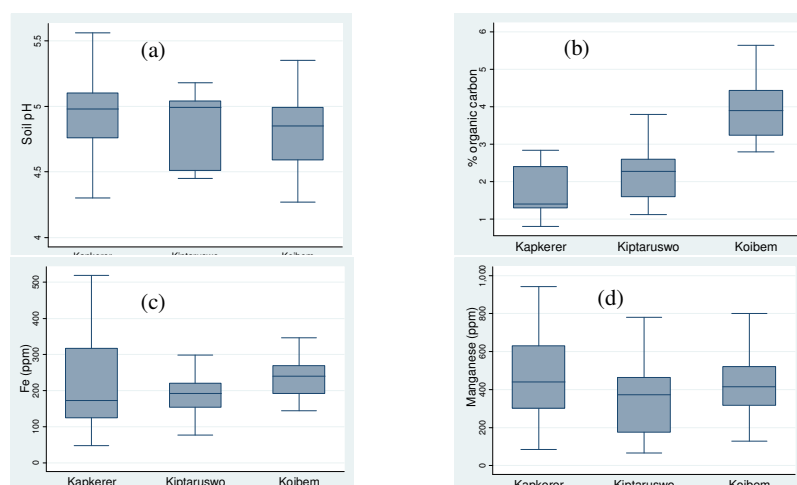


Figure 5. Variations in soil pH (a), soil organic carbon (b), and levels of selected micronutrients: Iron (c) and Manganese (d) in the soil at Kapkerer, Kiptaruswo and Koibem.

while those sampled at Kiptaruswo and Koibem were at about 1700-1980 masl (Figure 4b). Altitude did not have a clear effect on grain yield (Figure 4b). However, altitude modifies factors such as rainfall and temperature, which directly impact pests and diseases. This relationship has been taken into account in our data analysis conceptual frame work (Figure 1). In addition, altitude affects days to maturity and rates of evapotranspiration (Wortmann et al., 1988), thus influencing grain yield. Beans are grown in a wide range of agro-ecological zones in Kenya, with altitudes ranging from 800 Masl (medium) to 2000 Masl (high) (Wortmann et al., 1998), and the yields realized in these different agro-ecological conditions vary.

3.2.3 Soil quality

A variety of soil quality factors influence the productivity of beans, and indeed, the vulnerability and resilience of cropping systems (Smaling and Dixon, 2006). These factors include soil pH, organic C content, available P and N, and a number of micro-nutrients. Variations were observed in soil pH, organic carbon, iron, and manganese contents within and between study sites (Fig. 5). Across the sites, pH ranged from 4.2 to 5.5, with 75% of the observations falling between 4.2 and 5.1 (Fig. 5a), which is strongly acidic and likely to inhibit bean root growth (Yang et al., 2012). Organic C is an important indicator of soil health. In this study, organic C content was significantly correlated with grain yield ($r = 0.363^*$). However, levels of organic C were lowest at Kapkerer, ranging from 0.8% to 2.9%, and highest at Koibem, ranging from 2.9% to 5.8% (Figure 5b) with most of the observations falling above 3%, which is considered adequate for maintaining good soil

health. Iron and manganese contents were also variable within and between study sites (Fig. 5 c and d). Generally, greater variability was observed in iron and manganese at Kapkerer, relative to Kiptaruswo and Koibem sites (Figs. 5c and d).

3.2.4 pests and diseases

Bean fly and aphids were the only pests of bean observed in this study. However, only bean fly had a significant correlation with grain yield ($r = -0.278^{**}$). Bean diseases observed were root rot, BCMV, ALS, anthracnose, and CBB. Nevertheless, root rot and BCMV were the ones that had major effect on grain yield. Root rot was more severe during the long rains season across the sites, while BCMV was generally more prominent during the short rains season at Kapkerer and Kiptaruswo. Incidences of ALS, anthracnose and CBB were relatively minor across the sites and seasons.

Bean fly, also known as bean stem maggot, is the most important field pest of beans in smallholder systems in Africa. In Kenya, it causes grain yield losses of between 30% and 100% (Ampofo, 1993; Mwanauta et al., 2015). A negative relationship was observed between bean fly and bean grain yield across the sites during the short rains and the long rains growing seasons (Fig. 6a). Greater damage by bean fly was observed during the short rains season than the long rains season, especially at Kapkerer. Bean fly damage was negatively correlated with seasonal rainfall (Figure 6b). During the short rains season, when seasonal rainfall was up to 900mm, plant death per plot ranged from 0-70%, compared to plant death rate of about 0-8% during

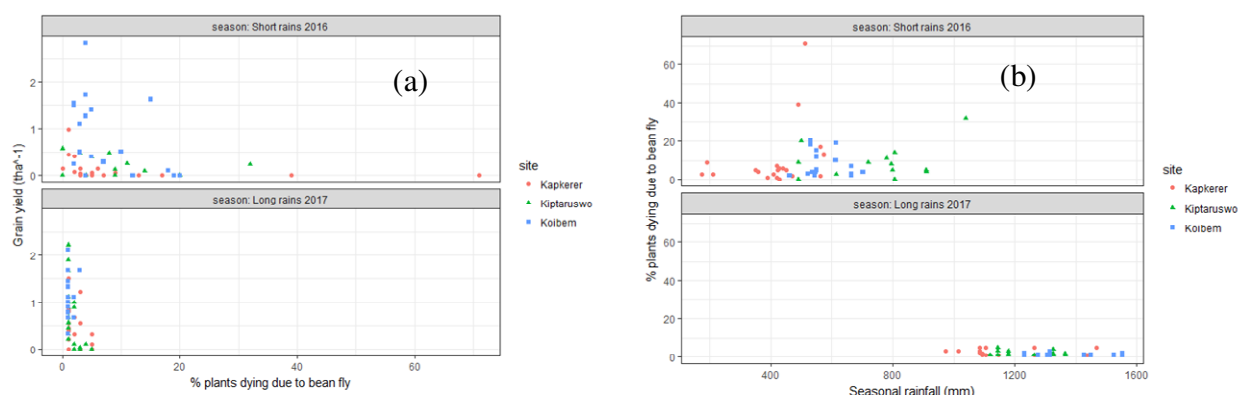


Figure 6. Relationship between grain yield and bean fly (a), and bean fly and rainfall (b), at the three study sites during the short rains 2016 and the long rains 2017 growing seasons

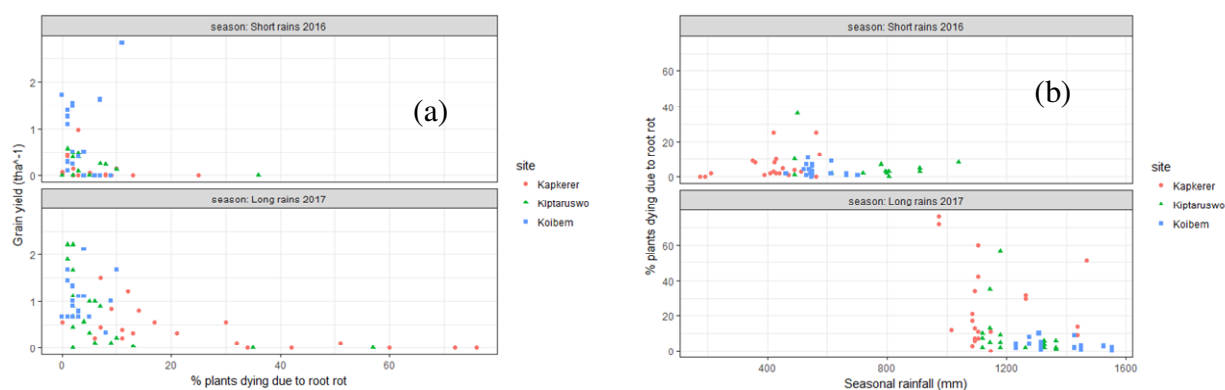


Figure 7. Relationship between grain yield and root rot (a), and root rot and rainfall (b), at the three study sites during the short rains 2016 and the long rains 2017 growing seasons

the long rains season when seasonal rainfall was upto 1580 mm.

Incidences of root rot were observed at all the sites during the short and the long rain growing seasons. However, severity varied within and between sites, causing grain yield losses (Fig.7a). Damage by root rot was more severe during the long rains than the short rains, and Kapkerer and Kiptaruswo were more affected than Koibem. Root rot was also correlated with seasonal rainfall ($r=0.10$) (Fig. 7b). The relatively lower seasonal rainfall observed during the short rains 2016 growing season was associated with lower rate of root rot damage. During the long rains 2017 growing season, when higher rainfall was received, a higher rate of root rot damage was observed. Root rot severity tends to be more in smallholder farms where soils have been degraded, coupled with low soil pH, low K, and continuous bean cultivation (Kimani et al., 2001)

3.3 Multivariate analysis

The outputs of linear mixed effect regression show that several factors had significant influence on the productivity of beans (Table 1). Season had the greatest influence on bean productivity, accounting for an increase in bean grain yield by 0.35 t ha^{-1} moving from short rains season 2016 to long rains season 2017. The analysis also show that BCMV and root rot had significant negative influence on bean productivity. A decrease in grain yield by 0.14 t ha^{-1} was observed for every unit increase in the score of BCMV. Relative to BCMV, the influence of root rot on bean grain yield was relatively minor, a reduction of 0.018 t ha^{-1} for every one percent increase in plant mortality. Iron and manganese also had significant influence on bean productivity, with grain yield increase of 0.003 t ha^{-1} for every unit increase of iron and reduction of grain yield by 0.0002 t ha^{-1} for every unit increase in exchangeable manganese. Wortmann et al. (1998a) reported that

Table 1. Regression analysis output showing major factors having significant influence on bean productivity in smallholder systems, Nandi County

	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	0.3339	0.2639	100	1.265	0.208629
Season	0.3510	0.0983	54	3.572	0.000752 ***
BCMV	-0.1363	0.0674	97	-2.022	0.045921 *
Root rot	-0.0184	0.0052	99	-3.531	0.000629 ***
Iron (Fe)	0.0034	0.0008	80	4.021	0.000129 ***
Manganese (Mn)	-0.0002	0.0001	56	-4.146	0.000115 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

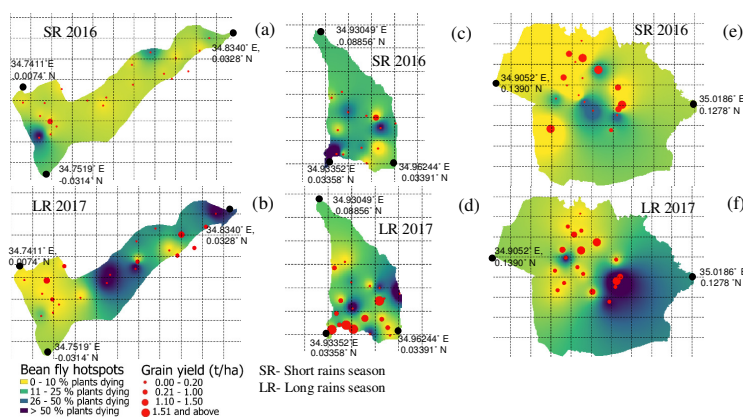


Figure 8. The distribution of bean mortality due to bean fly at kapkerer (a, b), Kiptaruswo (c, d), and Koibem (e, f) during the short rains 2016 and the long rains 2017 growing seasons

manganese toxicity is an important constraint that can cause up to 200 kg ha^{-1} loss for a sole crop if soil pH is 4.5 to 5.0 and 100 kg ha^{-1} if soil pH is 5.0 to 5.5.

3.4 Geospatial distribution of bean pests and diseases

3.4.1 Bean fly

Bean fly had a variable spatial and temporal distribution (Fig.8). During the short rains season 2016 at Kapkerer, bean mortality rates of 0-10% and 11-25% (% of plants dying per hectare) covered about 90% of the area of the study site (Fig.8a). However, high mortality rate of > 50% covered only about 4% of the site. These areas recording >50% of plants dying can be regarded as possible bean fly hotspots. Since this study was conducted for two growing seasons only, it is not possible to confirm the hotspots as more temporal data would be required for this confirmation. However, further analysis conducted by fitting variogram model indicated high correlation between farms close to each other hence the high mortality rates can be generalized for a cluster of farms in a particular location.

In the long rains 2017 season (Figure 8b), bean mortality distribution was more variable. Higher mortality rates of between 26-50% and > 50% were observed in about 60% of the site, and the possible hotspot observed at $34.74828^\circ \text{ E}, -0.01257^\circ \text{ S}$ in the previous season shifted to $34.77384^\circ \text{ E}, -0.00544^\circ \text{ S}$ and increased six fold in size. In addition, a new possible hotspot emerged at $34.82195^\circ \text{ E}, 0.02752^\circ \text{ N}$. Mortality was generally correlated with grain yield. Overall, bean fly hotspots were associated with low bean grain yield.

Similar to Kapkerer, bean mortality due to bean fly showed a spatial and temporal distribution at Kiptaruswo. However, there was generally more mortality at Kiptaruswo (Figures 8c and d) compared to Kapkerer. The low mortality rates of 0-10% and 11-25% were recorded in only about 25% of the study site during the short rains season (Figure 8c), while possible hotspots, observed at $34.93352^\circ \text{ E}, 0.03358^\circ \text{ N}$ and $34.95442^\circ \text{ E}, 0.04653^\circ \text{ N}$ increased in coverage to about 10%. Mortality slightly reduced during the long rains 2017 season (Figure 8d), although possible hotspots still covered about 10% of the site, but were observed in different locations.

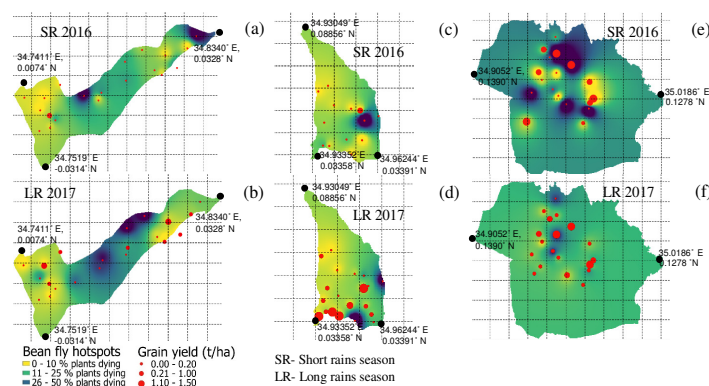


Figure 9. The distribution of bean mortality due to root rot at Kapkerer (a,b), Kiptaruswo (c,d), and Koibem (e,f) during the short rains 2016 and the long rains 2017 growing seasons

One was at 34.94136° E, 0.04225° N, and the other at 34.96209° E, 0.05202° N.

Bean fly pressure was much lower at Koibem than Kapkerer and Kiptaruswo during the short rains season 2016, with about 90% of the site recording a mortality rate of 25% and below (Figure 8d). The highest mortality recorded was 26-50% at 34.9606° E, 0.1228° N and 34.9741° E, 0.1191° N, and covered about 3% of the study site. Similar to observations at Kiptaruswo and Kapkerer, bean grain yield at Koibem generally decreased with increasing mortality rating. During the long rains season 2017, bean mortality significantly increased (Figure 8e). About 25% of the site suffered a mortality rate of at least 50%, with possible hotspots (>50% mortality) having an area coverage of about 5%. A large possible hotspot was observed at 34.9776° E, 0.1225° N.

3.4.2 Root rot

Similar to bean fly, bean mortality due to root rot had a variable spatial and temporal distribution (Figure 9). Generally, a close association between bean fly (Figure 8) and root rot was observed ($r = 0.382^{**}$) at Kapkerer and Kiptaruswo, but not at Koibem. Similar findings have been reported by CIAT (1992) and Ampofo (1993) where soil fertility is low. Similarly, a close correlation between root rot mortality and bean grain yield was observed at Kapkerer and Kiptaruswo, especially during the long rains season. No clear relationship was observed at Koibem. The lower mortality rates of 0-10% and 11-25% were recorded in about 50% of the area of Kapkerer site in the short rains season 2016 (Figure 9 a). However, possible root rot hotspots (mortality rate of > 50%) were recorded in an area of about 4% of the site, at 34.76951° E, 0.00351° N and 34.82579° E, 0.03141° N. Mortality increased considerably during the long rains season, with about 30% of the area of the site recording up to 25% of bean plants dying per hectare (Figure 9b). Similarly, area under

possible hotspots increased substantially. There were slight to big changes in the location of these possible hotspots. One that was at 34.76951° E, 0.00351° N shifted slightly to 34.7745° E, 0.00356° N, and nearly doubled in size. A new possible hotspot was observed at 34.79121° E, 0.01920° N, which covered nearly 4% of the site.

Root rot mortality at Kiptaruswo was slightly lower compared to Kapkerer both during the short and the long rains seasons. About 90% of the study site recorded mortality rates of up to 25% during the short rains season (Figure 9c). A single small possible root rot hotspot (> 50% mortality) was observed at 34.95909° E, 0.04984° N. Overall, bean root rot mortality during the long rains season followed a similar distribution to that of the short rains season. Mortality rates of up to 25% covered about 90% of the area of the site (Figure 9d). Possible hotspots were however recorded in two locations, at 34.96209° E, 0.05202° N and 34.95062° E, 0.03667° N.

There was relatively more root rot mortality at Koibem compared to Kapkerer and Kiptaruswo, with a slightly different spatial and temporal distribution (Figure 9). While there were several possible root rot hotspots (at 34.9602° E, 0.1506° N; 34.9732° E, 0.1187° N; 34.9603° E, 0.1218° N; and 34.9387° E, 0.1290° N) during the short rains season (Figure 9d), none was observed during the long rains season (Figure 9e).

3.4.3 Bean common mosaic virus (BCMV)

The distribution of BCMV varied spatially and temporally across the study sites (Figure 10). Generally, the disease covered most of the land area of each site, with the exception of a few scattered spots where no visible symptoms of disease were observed. Only a slight difference in the distribution of the disease was observed at Kapkerer between the short and the long rains seasons (Figures 10 a and b). Generally, there were no major changes in the location of possible BCMV hotspots (50%

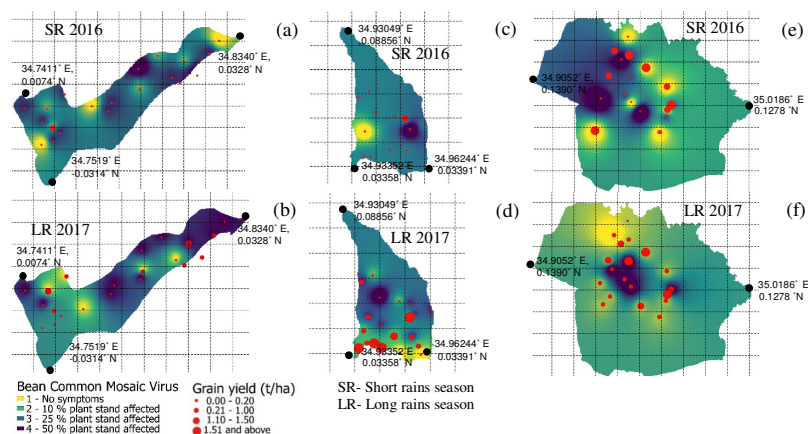


Figure 10. The distribution of BCMV hotspots in kapkerer (a, b), Kiptaruswo (c, d), and Koibem (e,f) during the short rains 2016 and long rains 2017 growing seasons

plant stand showing foliar damage) at Kapkerer, with the exception of the north-east tip of the site, which was a major possible hotspot during the second season. Similar to Kapkerer, there were only minor changes in the distribution of BCMV at Kiptaruswo between the short rains (Figure 10 c) and the long rains (Figure 10 d) growing seasons. Most of the area of the site showed at least 25% plant stand damage during the two seasons, with possible hotspots appearing at 34.95916° E, 0.04831° N, and 34.94341° E, 0.05677° N during the short rains and the long rains seasons, respectively. Grain yield was better correlated with disease rating during the long rains season. Grain yield was generally higher where foliar damage by BCMV was lower. The distribution of BCMV at Koibem followed a slightly different pattern than the other two sites. Serious damage was concentrated in the north-east corner of Koibem during the short rains season (Figure 10 e), while during the long rains season (Figure 10 f) the total area showing serious damage had shrank considerably and was located towards the centre of the site.

CONCLUSION

This study demonstrates that large spatial and temporal variations exist in the distribution of important biophysical factors that constrain the productivity of bean in smallholder systems in western Kenya. Bean productivity varies in relation to the spatial and temporal distribution of these constraints. The results indicate that root rot, bean common mosaic virus, and bean fly are among the most important pests and diseases whose variable spatial distribution creates high pest and disease pressure zones that significantly reduce bean productivity. Soil pH and micronutrients, particularly iron and manganese have significant impact on bean productivity. Knowledge of the

spatial and temporal distribution of bean production constraints, and their impact on bean productivity is critical for informed technology testing and the scaling out of production options that match biophysical contexts to improve bean productivity in the heterogeneous small holder systems. In addition, results of this study can inform the formulation of national policies seeking to increase agricultural productivity by availing spatial information to policy makers for integration into guide lines for the promotion of legumes to improve household nutrition and smallholder productivity. The results of this study can also be used to reform and improve the delivery of agricultural services. By incorporating spatial variability into technology dissemination frameworks, bean production technologies with the greatest potential to succeed in particular biophysical environmental contexts can be identified and disseminated. Further research is needed to generate more temporal data to confirm the existence of pests and disease hotspots in the study area.

Highlights

- Large geo-spatial variations of bean production constraints causes low productivity
- Root rot, common mosaic virus and bean fly major constraints to bean productivity
- Existence of zones of high pest and disease pressure associated with low yields
- Rainfall significantly correlated with root rot and bean fly, and low bean yields
- pH, iron and manganese among the major soil factors influencing bean productivity

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