FACTORS INFLUENCING MAIZE YIELD GAPS ON SMALLHOLDER FARMS IN VIHIGA AND KAKAMEGA COUNTIES OF WESTERN KENYA

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DEDICATION

I dedicate this work to my mother and my siblings for their ever continuous support through prayer and encouragement throughout the journey.

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GENERAL ABSTRACT

Despite decades of investment in new agricultural technologies, crop yields of main staple crops such as maize (*Zea mays*), rice (*Oryza sativa*) and wheat (*Triticum aestivum*) continue to stagnate in many parts of Sub Saharan Africa. As a result, there have been large yield gaps; the difference between potential and actual yield >50%. Research has shown that factors causing yield gaps ranging from biophysical, field management and socio-economic are studied in isolation. An inclusive approach is needed where biophysical, socio-economic and field management factors are studied to enhance yields. The overall objective was to provide insights into factors influencing yield gaps by studying socio-economic, management and biophysical variables on maize fields at a farmer level as a solution to enhancing yields. The specific objectives were: To assess biophysical factors influencing maize yield gaps; To determine the effect of farmer derived management on maize yield variability; To analyze the effect of the interrelationship between socio-economic, management and biophysical factors on maize yield gaps; To determine the effect of spatial arrangements (fields) differentiated by distance from the homestead on maize yield gaps.

The study was conducted in two contrasting sites; Mukuyu and Shikomoli of Western Kenya for a period of two years; 2016 and 2017. The sites contrast in agro-ecology, market access and population density. Multi-stage sampling design was adopted to select regions and villages followed by random selection of 70 households; 35 households in Mukuyu and 35 in Shikomoli. A total number of 170 maize fields which were the study units were identified and georeferenced from the 70 households. In the year 2016, soil sampling and analyses were done to characterize soil properties. Field measurements to determine within season biophysical variables were done at two key maize development stages; ear initiation (stage 1) and tasseling and silking (stage 3). Maize output was also collected and yield determined per hectare. Yield gaps were then computed at a farmer level by comparing the determined yields at the 90th percentile to other yields.

Household surveys were conducted to collect field management and socio-economic factors. Satellite imagery was acquired and processed to map yield gap variability at different spatial arrangements with respect to distance from the homestead. In the year 2017, on farm trial plots with best and average farmer derived management practices were laid out on 33 smallholder farms using the randomized complete block design. The management practices were based on survey findings from 2016 and included; nutrient supply, weed management and plant density. An integrated analysis comprising the Generalized Linear Mixed Model (GLMM), Classification and Regression Tree analysis (CART), Factor Analysis (FA), Linear Mixed Effects Model analysis (LMER) and Spatial Analysis Techniques was used to analyze the collected data.

Results showed that the average measured maize yield and yield gaps for Mukuyu were 3.8 t ha^{-1} and 1.8 t ha^{-1} while for Shikomoli they were 2.7 t ha^{-1} and 2.6 ha^{-1} respectively. This represented 35% and 54% of unachieved yields for Mukuyu and Shikomoli respectively. Factor Analysis showed socio-economic variables as the overarching factor influencing maize yield gaps over biophysical and management across the two sites. The GLMM identified education, age, membership to groups, access to markets, family labour, gender, credit facility, maize variety, crop residue utilization insitu, quantity of organic and inorganic fertilizer use, while CART identified maize density, chlorophyll values, maize height, and depth to compact layer as consistent factors affecting yield at both sites. Also, according to CART weed cover at early stages and maize density at late stages were the most limiting factors in maize production in Mukuyu and Shikomoli, respectively. The GLMM analysis also showed a two-way significant interaction effect between socio-economic, management and biophysical factors on maize yield gaps which was agro-ecology specific. In Mukuyu inorganic fertilizer use and gender of operator as female, weed coverage at early maize stages and crop residue utilization as animal feed, positively interacted to influence maize yield gaps. While low weed coverage at early maize stages and phosphorus, depth of compaction and crop residue use *insitu*, number of organic fertilizer and cation exchange capacity, negatively interacted to influence maize yield gaps. In Shikomoli, membership to groups and timeliness in execution of agronomic activities such as land preparation, planting and weeding negatively interacted to influence maize yield gaps. The LMER analysis on on-farm trial data revealed that highest yields were recorded on the best farmer derived management treatments and averaged 7.8 and 6.6 t ha^{-1} for Mukuyu and Shikomoli. These yields represented 45 and 35% between farm and inter-annual yield variation when compared to average-derived farmer practices and best farmer management practices from past surveys respectively. Spatial analysis techniques demonstrated that heterogeneous patterns of high, average and low yield gaps were found on fields closer to the homestead. While nearly homogenous yield gap patterns were found on fields further from the homestead. Factors such as inorganic fertilizer use, weed control, early land preparation, hired and family labour use and large land sizes were utilized on spatial arrangements further the homestead. Organic fertilizer and family labour use was utilized on fields closer to the homestead.

The findings indicate that large yield gaps > 30% exist on smallholder farms showing a scope for farmers to exploit the gap. The findings also demonstrate that an integrated approach can result in consistent, agroecology specific and interacting factors influencing yield gaps applicable at different scales of decision making; farmer, local, county, national and regional in improving yields. The high yields from the on-farm trial research (best management plots) demonstrate the potential to reduce maize yield gaps on smallholdings. Since maize is a staple crop in Kenya and in most parts across the globe, policy measures aimed at improving general soil fertility, market accessibility, relaying agricultural information and encouraging family involvement in agronomic activities are needed. Agro-ecology and field specific measures focused on improving particular

soil nutrient types and levels, weed management and plant density are also required. Delineating management zones based on yield gap patterns will also help promote field-specific land management to enhance yields. Further research in yield gap studies could focus on the effect of post-harvest handling practices in reducing yields and in using crowdsourcing methods via innovatively developed mobile applications to collect data.

CHAPTER ONE

INTRODUCTION

1.1 Background

Despite decades of investment in new agricultural technology, crop yields of main staple crops such as rice (*Oryza sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) continue to stagnate (Cassman et al., 2010; van Bussel et al., 2015). The problem is particularly acute in Sub-Saharan Africa where yields of cereal crops have stagnated at 1.1–1.5 MTH compared to world production of 3.2 MTH (AGRA, 2013). In Kenya, the actual yield of maize achieved by farmers is 1.8t ha^{-1} compared to a potential yield 6t ha^{-1} (Tittonell et al., 2008). The low yields have resulted in large yield gaps (the difference between potential and actual yield) of >50% in major staple food crops in Sub Saharan Africa leading to food insecurity (Lobell et al., 2009; Licker et al., 2010; Ray et al., 2013). In Kenya, for instance, approximately 1.5 million people are severely food insecure (FAO, 2015).

The present human population in Sub Africa will likely grow by 50% in 2050 UNDP, (2012) and this will increase the average daily calorie intake per capita demand from the current 2360 Kcal to 3050 Kcal (Alexandratos and Bruinsma, 2012). To sustain adequate food production for the growing population, there have been calls to intensify analysis of the causes of crop yield gaps in order to adjust crop and soil management for increased yields in areas with agricultural intensification potential (van Ittersum et al., 2013). Subsequently, numerous studies focusing on analysis of biophysical, socio-economic and management factors influencing maize yield gaps have emerged (Affholder et al., 2013; Beza et al., 2016; Poeydebat et al., 2013; Tittonell et al., 2006; Yengoh, 2012). More often, these factors are studied in isolation (Beza et al., 2016). Yields of crops on smallholder farming systems are affected by a combination of soil, socio-economic and management factors (Sumberg, 2012). Contingent on utilization of these factors, yields in a certain area within a given time could be higher or lower resulting in yield gaps. For these reason, analysis of factors influencing yield gaps ought to take an inclusive approach where soil, socio-economic and agronomic factors are studied in detail using different methodologies (Ciampitti and Vyn, 2014; Fan et al., 2012; Meng et al., 2013).

Smallholder farming systems are diverse regarding agro-ecological and socio-economic conditions (Tittonell et al., 2010). Considering the diversity that exists on smallholder farming systems, it is important to design site specific crop management strategies, that also recognizes the fact that farmers operate under constrained resource conditions (Banerjee et al., 2014; van Ittersum et al., 2013) . However, most existing studies on yield gap analysis have been done either at global, regional or national level. Such studies are often associated with methodological assumptions and overly aggregated data estimates that prevent findings from being used to derive location specific crop and management strategies for narrowing of yield gaps (van Bussel et al., 2015). There is growing interest to provide findings on factors influencing yield gaps having relevance both at large and small spatial scales (Ittersum et al., 2013). Shifting focus from a universal to site specific analysis of factors influencing yield gaps is therefore required (FAO and DWFI, 2015).

1.2 Statement of the problem

Large yield gaps in staple crops of more than 50% exist especially in developing countries resulting in food insecurity (Licker et al., 2010; Ray et al., 2013). Studies on factors influencing yield gaps have been done (Tittonell et al. 2008; Yengoh 2012; Affholder et al. 2013; Poeydebat et al. 2013). Often, socio-economic, soil and management factors influencing maize yield gaps have been studied singly. However, yields and yield gaps are affected by the interaction between soil, socio-economic and management factors (Spiertz, 2012). As such, these factors cannot be disentangled; requiring a multi-disciplinary approach where soil, socio-economic and management factors are studied using different data collection and analysis methods to provide insights into causes of yield gap. Furthermore, studies on factors influencing yield gaps exist at a national or regional level resulting in generalized findings and recommendation with low local applicability (van Ittersum et al., 2013). There is growing interest to provide findings on factors influencing yield gaps having relevance both at large and small spatial scales (Ittersum et al., 2013). Shifting focus from a universal to site specific analysis of factors influencing yield gaps is therefore required (FAO and DWFI, 2015).

1.3 Justification for the study

Yield gap analysis is required to identify socio-economic, soil and crop management factors limiting crop productivity, prioritize research and initiate measures to improve yields and food security globally. The African continent has prioritized research to improve crop yields and enhance food security as its key objective, to ensure the current and future food demands for the growing human population are met according to Sustainable Development Goals. In Kenya, measures to improve crop yields and sustain food security is among the key pillars of the Vision 2030. Given the food security concerns and the gap in knowledge, insights into factors influencing yield gaps will help adjust soil and crop management practices at different levels at local, national and regional levels to enhance yields and improve food security. Results showing important factors influencing maize development and yield will inform the Government of Kenya to prioritize site-specific research, development and extension in certain areas. Measuring yield gaps at a farmer level presents an opportunity for smallholder farmers to understand site specific socio-economic, biophysical and field level management practices causing yield gaps. This information will be useful to **s**mallholder farmers as it will aid in adjusting soil and crop management practices that will improve yields.

1.4 Objectives of the Study

The main objective of the study was to provide insights into factors influencing maize yield gaps by studying socio-economic, management and biophysical variables on farmers fields as a solution to enhancing yields.

The specific objectives were:

i. To assess biophysical (soil and management-related) factors at different maize development stages influencing maize yield gaps on smallholder farms

ii. To investigate the effect of farmer-derived management practices at different maize development stages on maize yield variability on smallholder farms

iii. To analyze the effect of the interrelationship between socio-economic, management and soil factors on maize yield gaps on smallholder farms

iv. To determine the effect of the spatial arrangements found on smallholder farms on maize yield gaps

1.5 Hypotheses

i. There are significant variation in maize yield gaps between fields on smallholder farming systems caused by differences in soil and management-related factors occurring at different maize development stages
ii. There are significant variation in maize yields on smallholder farms caused by farmer-derived management practices occurring at different maize development stages
iii. There are significant differences in maize yield gaps resulting from the interaction between soil, management and socio-economic factors
iv. There are patterns of low, average and high yield gaps caused by spatial arrangement of fields on smallholder farms

CHAPTER TWO

LITERATURE REVIEW

2.1 The yield gap concept

Recent advances in agricultural technology across the world such as the introduction of new crops; adoption of improved germplasm; improved management practices relating to crops; mechanisation; infrastructural development and use of external inputs resulted in improvement in agricultural productivity thus contributing to increased farm production over the past half-century (George, 2014). For instance, substantial yield gains were observed between 1980's, 1990's through to 2000 as a result of crop genetic improvement (Cassman et al., 2010; Ittersum *et al.*, 2013). However, crop yields have plateaued in many regions around the world. This is because in some regions average yields have approached the ceiling and in others, crop response to additional inputs exhibits a diminishing marginal yield benefit. As a result, large yield gap of crops have been observed (Beza et al., 2016).

Yield gap is the difference between potential yield versus actual yield achieved over some specified spatial and temporal scales under certain limitations for a particular crop (Lobell et al., 2009). Yield potential of a crop can be obtained in a suitable environment of adequate moisture and nutrients, without pest and disease problems and also depends on sunshine intensity, temperature, crop-sowing date, plant population and light-use efficiency (Lobell et al., 2009). While actual yield is obtained under limited conditions of management, biophysical and socio-economic factors (Silva et al., 2017). Depending on the scale of estimation, different types of yield gaps can be computed. These include model, experimental, exploitable and farmer based yield gaps. Modelled yield gaps can be estimated using crop growth models with input data from weather, soil, crop management and actual yield (Licker et al., 2010; LIU et al., 2014; Schulthess et al., 2013; van Ittersum et al., 2013; Wart et al., 2013). Experimental yield gaps are estimated by comparing highest yields obtained from research stations, where limitations related to agronomic factors have been controlled, and yields at the farmer level (Meng et al., 2013). Farmer-based yield gaps are obtained at the farm level by measuring or recording reported farmer yields and identifying the highest yield as a reference against which to compare other yields (Lobell et al., 2009). This can be done using the boundary function method with the aim of capturing local variability in yield gaps and the associated causal factors among the highest and lowest yields achieved by farmers (João et al., 2018). Exploitable yield gap is the difference between yield potential and the actual yield achieved by farmers (Cassman et al., 2003). Understanding yield potentials and exploitable gaps on smallholder farms is essential to ensure national food security (Meng et al., 2013).

2.2 Relevance of yield gaps analysis

Yield gap analysis is required to identify soil and crop management factors limiting crop productivity, prioritize research and development and initiate measures to improve agricultural intensification (Ittersum et al., 2013). Knowledge of yield gap can also assist in crop yield predictions, since yield potential shows the probable future productivity to be achieved and this information can be used for policy interventions to improve crop production (Sumberg, 2012). For instance, in Australia, recognition of water limiting factors as the main cause of yield gap led to improvement of management practices that have narrowed the yield gap (Hochman et al., 2012). Yield gap analysis for Southeast Asia helped explain yield trends in irrigated rice and revealed that nitrogen management had to be improved to increase yields (Kropff et al., 1993).

Globally, the human population will likely increase from the current to 7.6 to 9 billion by 2050 (Tilman et al., 2011). This will increase food requirements to about 60%, requiring doubling in agricultural production from 2.7% to meet the food demands (Oborn et al., 2013; Tilman et al., 2011; van Bussel et al., 2015). Sub-Saharan Africa displays the greatest gaps of more than 30% between potential yields and realized yields for a number of crops such as maize and rice (Licker et al., 2010; Ray et al., 2013). For example average maize yields of countries in Sub-Saharan Africa remained at around one-third to one-half of the world's average (1.1–1.5 metric tons per hectare versus 3.2 metric tons per hectare) between 2000 and 2010 (AGRA, 2013). Maize being one of the most important crop in Kenya owing to its use both for subsistence and commercial production exhibits yield gap of >60%, that is, the potential maize yield per ha is 6t ha^{-1} and the actual yield attained by farmers is 1.8t ha^{-1} (Tittonell et al., 2008). Expansion of agricultural land to increase production could be one way of meeting the future food demands and reducing the yield gaps. However, agricultural land is scarce and is also demanded by other non-agricultural uses (Defries et al. 2015). Hence there is need to intensify yield gap studies in order to adjust soil and crop management measures especially in areas with agricultural intensification potential.

2.3 Methods for analyzing yield gaps analysis

Yield gaps have been studied using different methods such as simulation models, experimental stations (research stations and on farm trials), surveys and remote sensing. By simulating crop yields, yield gaps for maize have been measured at different levels; potential yield, experimental and at farmer level (Ittersum et al., 2013; Liu et al., 2016; Schulthess et al., 2013). Simulation models are able to reproduce genotype*environment*management (G*E*M) interactions, therefore they capture spatial-temporal variations in potential and water limited yield. However, these yield gaps are limited by non-controllable factors and heterogeneity in climate data (Ittersum et al., 2013). Using research stations, Sileshi et al. (2010) assessed experimental yield gaps at different fertilizer levels and soil types. Controlled experiments assume perfect conditions in management and biophysical factors which may not represent the ideal smallholder farmers' situation. On farm trial research has also been used to assess yield gaps on smallholder farming systems. Kravchenko et al. (2017) revealed persistent yield gaps in low input and organic cropping systems using on farm trial designs demonstrated on farmers' fields. Yield gaps assessed on farms are subjected to significant soil and topographic diversity, and hence can better explain spatial and temporal causes of yield variation (Florin et al., 2009; Kravchenko et al., 2005). Household surveys have long been used to study yield gaps and the causes. Hall et al. (2013) used survey data on crop yields collected from districts and individual farms to quantify yield gaps for sunflower, and found that there were large variation between reported yield gaps at farmer level. Large differences in farmers' yields have also been observed within small areas such as villages (Dzanku et al., 2015). Although survey and experimental methods have proved reliable and easily comprehensible in estimation of yield and understanding yield gap, in most cases, this information is only available after a crop has been harvested. Thus, any anomalies in crop development resulting within the crop production period cannot be alleviated. They are also costly and time consuming (Reynolds et al., 2000). On the other hand, simulation models have challenges in terms of availability of weather data especially in developing countries which are characterized by heterogeneous climate and farming systems (Ittersum et al., 2013).

As efforts to understand yield gap intensify, new approaches such as remote sensing with the capability of providing timely information on crop status are needed to complement the existing conventional methods that have been used by agronomists, soil scientists and socio-economists (Lobell, 2013). Remote sensing has played a significant role in crop classification, Dhumal et al.

(2013) and crop area estimation (Qinghan et al., 2007). A new area of interest in research using remote sensing, is focusing on characterization of plant biophysical properties and crop yield (Nellis et al., 2009). The application of remote sensing in agriculture is based on the reflectance and transmittance of the red, infra-red and visible spectral wavelengths during the process of photosynthesis (Casady and Palm, 2000). The basic principle is that plants absorb light differently depending on the photosynthetic activities. Photosynthetically active plants absorb most of the visible light (blue and red) and reflect a large portion of the infrared light. For photosynthetically less active plants, the near-infrared light makes a small portion of the reflected light (Duncan et al., 2015). Using various derived vegetation indices; Normalized Difference Vegatation Indices (NDVI) and Generalized Difference Vegetation Indices (GDVI), the spectral wavelengths (visible and infrared lights) can be analysed to indicate the phenological stages of a plant (Martinez and Gilabert 2009). These stages include; vegetative and reproductive (Duncan et al., 2015). These Vegetation indices can also correlate well with green biomass, crop vigour, height and hence can be used to indicate crop development status and detect plant stress (Casady and Palm, 2000; Pinter et al., 2003). With regard to biophysical plant properties, remote sensing has been used in studying fraction vegetation cover, chlorophyll content and green leaf area index (Schlemmera *et al.*, 2013; Gitelson *et al .*, 2005; Daughtry *et al.*, 2000). These parameters can be used to predict crop yields and show crop yield variability (Wart *et al.*, 2013; Prasad *et al.*, 2006; Piwowar, 2010; Sibley *et al.*, 2014). Yield prediction using remote sensing has largely been done on homogenous fields globally (Battude et al., 2016; David, 2014; Sayago and Bosco, 2018). However, application of remote sensing on heterogeneous farms is constrained by the diverse farming systems, with just few studies having reported using the technology in yield and yield gap analysis (Burke and Lobell, 2017; Jin et al., 2017).

2.3.1 Comparison of statistical analysis methods used in yield gap studies

There is growing interest for yield gap studies to produce findings applicable both at small and large spatial scales. Hence the methods used should be able to capture differences between fields and within villages and simultaneously provide a general overview of the findings applicable on a larger scale (Sibley et al., 2014). Parametric methods such as linear regression and correlation methods have been widely used in yield gap studies (Krupnik et al., 2015; Mackay et al., 2011; Neumann et al., 2010; Sawasawa, 2003). Linear regression models are able to predict and show significant results between variables. Nonetheless the following assumptions that have to be met; independence, linearity, normality and homoscedasticity (Hastie et al., 2008). However, questions arise when the dataset being used is non-linear which is a likely scenario with many farm surveys and even experimental designs (Banerjee et al., 2014). A comprehensive determination of causes of yield gaps ought to include many and different variables, with linear and non- linear relationships. The integration of the different variables from soil, agronomic and socio-economic factors is likely to generate interactions requiring the application of linear and multivariate regression methods to unravel the interrelationships (Tittonell et al., 2008).

Multivariate analysis methods such as the Generalized Linear Mixed Model (GLMM), Classification and Tree Analysis (CART) and Linear Mixed Effects Model (LMER) are gaining interest in analysis of field surveys and experimental designs owing to the ability to handle highly skewed and unbalanced data which is common with participatory research (Yang, 2010). The GLMM and LMER have the advantage of including random effects as a predictor and they describe an outcome as the linear combination of fixed effects and conditional random effects associated with subjects and items resulting in more informative findings (Hui et al., 2016). While the advantages of CART includes; the gaussian distribution of predictor variables need not be satisfied; easy visualization of results as they are presented in form of a tree showing important variables and the interaction towards a response variable thus satisfying the parsimony rule of a model (Koon, 2015).

Multivariate methods have been applied in agricultural studies to unravel the relationships and interactions between different factors in causing yield variability. Banerjee et al. (2014a) used CART analysis to study the biophysical and socio-economic causes of low yields of maize in India. In analysis of infield variability of rice yields in Uruguay, Roel et al. (2007), was able to isolate management practices associated with farmers who had high and low yields of rice as a basis for recommending site specific farming. Tittonell et al. (2008) explored maize yield variability on smallholder farming systems in Kenya using CART and found that variability was caused by interaction of field management practices and soil fertility. Ronner et al. (2018) used LMER to show the effect of fixed and random effects on climbing beans on farmer managed trials.

For studies to be most useful in yield gap analysis, it is important that they also use methods that regroup and summarize measured variables to provide an overview of the underlying causes of low yields. Such methods include factor analysis. Factor analysis has mostly been used in clinical studies to provide a general conclusion of clinical conditions (Oh et al., 2016; Ohshiro and Ueda, 2018). Factor analysis loads variables together based on shared variance. This can help summarize the clustered variables into one composite factor which will describe a general overview of the most important factors influencing maize yields gaps. Description of factor analysis method is described by Yong and Pearce, (2013). CART, GLMM, LMER and Factor Analysis present findings from different viewpoints. Hence the applicability of different regression methods can result in complementary findings which can aid in unraveling causes of yield gaps and inform decisions at different levels.

2.4 Multi-disciplinary assessment of factors influencing yield gaps

To a large extent, there exists literature on explanatory factors ranging from soil, agronomic to socio-economic influencing yield gap in staple crops like maize (Affholder et al., 2013; Beza et al., 2016; Poeydebat et al., 2013; Tittonell et al., 2006; Yengoh, 2012). More often, these factors are studied singly with a certain component of factors being left out (Beza et al., 2016). For instance, the search for reasons behind yield gaps has been limited to soil factors such as N and P availability, and to growth reducing factors such as Striga infestation (Tittonell et al.,2006). Yengoh, (2012) investigated the relationship between socio-economic and field level management practices causing crop yield differences on smallholder farming systems. Other studies have reported biophysical factors as major causes of yield variations within different fields (Affholder et al., 2013; Keating et al., 2010; Poeydebat et al., 2013). In Western Kenya, for instance, agronomic factors have been shown to be responsible for causing maize yield variability at farm level (Tittonell et al., 2006). However, yield gap is a context-dependent variable affected by soil, socio-economic and field level management factors requiring a multi-disciplinary understanding of its causes among the disciplines of plant science, agronomy, soil science, agro-ecology and socio-economy (Ciampitti and Vyn, 2014; Fan et al., 2012; Meng et al., 2013).

Soil physical and chemical properties are vital in determining soil fertility. Soil physical properties such as texture influence the organic matter of soil and are important for water retention and availability, soil workability, soil trafficability, and supply of nutrients to the plants (Sherpherd, 2010). Soil nutrients such as nitrogen (N), phosphorus (P) and potassium (K) are macro elements that are taken up by the maize plant in large amounts during the critical yield determination stages namely; the ear initiation, ear determination and silking and tasseling (O'Keeffe, 2009). These stages occur during the maize development period and are characterized by important physiological processes which determine maize yield. The ear initiation stage occurs at the 3rd or 4th week after germination of maize and is characterized by start in ovule formation, determination of rows around the ear and initiation of tassel nodes. The ear determination stage happens around the 6th to 9th week after seed emergence and is described by determination of the ear length, start of pollen grain formation and tasseling. The silking and tasseling stage is the most critical phase and takes place at the start of 10th or 12th week is characterized by emergence of silks and tassels, formation of pollen grain and kernels and determination of number of grains. There is also partitioning of photosynthetic products (carbohydrates) to reproductive organs namely; ovules and silks during these stages (Fischer et al., 2014). Sufficient soil nutrition is required for successful development of maize through the critical yield stages (Fischer et al., 2014). Deficiency of nitrogen can cause irreversible decrease in ear diameter, ear length and number of kernels (O'Keeffe, 2009). Insufficient supply of phosphorus results affects root growth and slows down the growth of photosynthetic products (O'Keeffe, 2009). Low supply of potassium results in small grains (O'Keeffe, 2009). Carrying out soil sampling and testing at the start of the maize production season can indicate nutrient status and inform on the amount of fertilizer to apply.

Field management practices such as weed control, plant density and fertilizer application also influence maize growth at key maize stages. Weed control beyond the sixth week of maize development was found to influence leaf area development and anthesis, (Ghanizadeh et al., 2014). At the fourth week of maize growth, weeding was found to increase maize growth and lessened the silking and tasseling periods resulting in high maize yields (Reid et al., 2014). High leaf area index and dry matter was recorded on maize fields with high plant densities (Sharifi, 2016). Increased light interception resulted in increased kernel number per plant on maize fields with high plant population. Other studies have shown increased maize yield gaps on fields with low plant densities (Banerjee et al., 2014; Tamene et al., 2016). Yields of maize improved by 9.25% when nitrogen application was done at the knee height, pre-tasseling and silking stages (Ghosh et al., 2016). Other Management-related variables such as chlorophyll values, height, crop vigour and weed incidences taken during the critical yield determination periods are good indicators of crop health status (Duncan et al., 2015). These variables can be compared across different fields to assess spatial variability in crop development (Magney et al., 2016). This information can be related to socio-economic factors so as to provide within season comprehensive diagnosis of the causes of maize yield gaps and subsequently lower yield gaps. Management factors can be collected using field measurements and household surveys.

Socio-economic factors operate both at micro and macro level to influence management and soil factors. Takele et al. (2015) found the decision to use inorganic fertilizer and price to influence soil fertility. In addition, the educational background of the farmers may influence the manner in which the limited resources are allocated to farm management activities. Access to market and capital by the smallholder maize producers directly affect farmers' ability to acquire and use inorganic and certified seeds (Salami et al., 2010). Farmer characteristics such as availability of labour, determine the timing and frequency of agronomic operations such as weeding (Banerjee et al., 2014). At a macro level inadequate information, poor market accessibility, lack of credit facilities, land tenure insecurity and weak access to research and education have been shown to cause low crop productivity (Oluoch-Kosura, 2010). Narrowing the high yield gaps of maize in developing countries therefore requires strategies that adjust the existing socio-economic, biophysical and management constraints. Realization of this goal relies on understanding of the socio-economic background, their existing agronomic management and how these factors interact to influence maize productivity.

2.5 Assessing yield gaps at a local level

Yield gaps have been assessed on global and regional scales (Licker et al., 2010; Lobell et al., 2009; Sileshi et al., 2010; van Ittersum et al., 2013). Global and regional yield gap analyses are associated with methodological assumptions and overly exaggerated data estimates that prevent findings from being used to derive location specific crop and management strategies for narrowing of yield gaps (van Bussel et al., 2015). The diversity that exists on smallholder farms makes it difficult to decide the potential yield that can be used as a reference yield against which to calculate yield gaps (Poeydebat et al., 2013). What is known to be potential yield in one region/location might not possibly apply in another region (Poeydebat et al., 2013). A key decision however, is to make yield gap estimates that can be closed cost effectively considering the heterogeneity in agro-ecological conditions (Tittonell et al., 2010). The existing diversity on smallholder farming systems needs to be considered, requiring studies to approach the quantification of yield gap at a local level to help design location specific crop management strategies that also recognize the fact that farmers operate under constrained resource conditions (Banerjee et al., 2014). This will result in findings that can be applied both locally and in areas with wider spatial scales (Ittersum et al., 2013). Most important is to identify the factors that cause these variations and the prospects that are there in narrowing the yield gaps that exist between and within farms, villages and regions.

CHAPTER THREE

SOIL AND MANAGEMENT-RELATED FACTORS CONTRIBUTING TO MAIZE YIELD GAPS IN WESTERN KENYA

Abstract

The solution to reducing existing yield gaps on smallholder farms lies in understanding factors limiting yield in areas with agricultural intensification potential. This study applied an integrated analysis approach comprising Classification and Regression Tree (CART), Generalized Linear Mixed Model (GLMM), and Factor Analysis (FA), to explain soil and management-related factors influencing maize yield gaps, in order to enhance yields. The study was conducted in Mukuyu and Shikomoli in western Kenya, sites with, respectively, high and low agroecological potential regarding soil fertility. Maize yield gaps were computed by comparing yields at the 90th percentile to other yields (not in the 90th percentile) determined in 170 fields on 70 randomly sampled smallholdings. Soil and management-related factors were also determined at early and late maize development stages.

Maize yield on the 90th percentile of farms in Mukuyu and Shikomoli was 5.1 and 4.8 t ha^{-1}, respectively, and the average yield gap was 1.8 and 2.6 t ha^{-1}, representing 35% and 54% unachieved yield for Mukuyu and Shikomoli, respectively. In FA, soil was revealed to be the main factor influencing maize yield gaps at both sites, rather than management-related variables. The CART method identified maize density, chlorophyll values, maize height, and depth to compact layer as consistent factors affecting yield at both sites, while GLMM identified soil texture (silt content) as important. According to CART, weed cover at early stages and maize density at late stages was the most limiting factor in maize production in Mukuyu and Shikomoli, respectively. GLMM analysis identified agroecology-specific factors influencing maize yield gaps as soil-available phosphorus and zinc, plus weed pressure at early maize stages in Mukuyu and plus soil cation exchange capacity and exchangeable magnesium in Shikomoli. Through an integrated approach, it was possible to identify both consistent and agroecology-specific factors limiting crop yields. This can increase the applicability of the findings to smallholder farms.

Key words: Critical yield periods, intensification potential, integrated approach, soil, management, yield gap

3.1 Introduction

Despite decades of investment in new agricultural technologies, yield gaps (the difference between potential and achieved yield) for major staple food crops such as maize persist globally. The problem is particularly acute in areas of the world dependent upon rain-fed agriculture and especially in sub-Saharan Africa, where agricultural productivity has stagnated (Ray et al., 2013). As a result, maize yield gaps exceeding 90% have been reported (Ray et al., 2013). In Kenya, maize yield is as low as 1.8 t ha^{-1} on smallholder farmers, compared with potential yield of 6.0 t ha^{-1}, resulting in yield gaps greater than 50%. This makes many households food insecure (Oloo et al., 2013). Socio-economic, biophysical, soil, and management-related factors causing yield gaps have been identified (van Ittersum et al., 2013). However, there is a growing need to advance understanding of soil and management-related factors directly influencing maize yield (Beza et al., 2016; Cassman, 2003).

Soil factors are vital for growth and development of maize during critical yield determination stages (Fischer et al., 2014). Soil nutrient uptake and accumulation in maize plants starts after seedling emergence and increases as the plants advance through the critical yield determination stages, i.e., ear initiation, ear determination, silking, and tasseling (O'Keeffe, 2009). Soil physical properties such as clay, silt, and sand content affect soil organic matter content and are important for water retention and availability, soil workability, soil trafficability, and nutrient supply to plants (Sherpherd, 2010). Field measurements of chlorophyll content, crop height, and crop vigor are good indicators of crop status, and can be related to soil properties to identify within-field management practices limiting yield (Duncan et al., 2015). Weed cover and weed height are indicators of field nutrient status, water availability, and radiation use efficiency, and can be related to weed management measures (Reid et al., 2014b; Sherpherd, 2010). Soil factors influencing maize yield gaps have been widely studied (Affholder et al., 2013; Fermont et al., 2009; Okumu et al., 2011). However, only a few studies have examined the effect on crop yield of e.g., rooting depth (depth to compact layer) (van Bussel et al., 2015), which is important as it determines availability of water and nutrients (Sherpherd, 2010). Furthermore, the links between soil factors and crop status indicators such as chlorophyll content, weed height, crop vigor, and weed pressure as within-season constraints to crop yield have not been fully explored.

Many soil and management-related factors associated with maize yield gaps on smallholder farms are affected by high spatial variability in agroecological and economic conditions (Sultan et al., 2005). It is therefore important to design site-specific soil and crop management measures which recognize that farmers operate under diverse soil and climate conditions and are resource-constrained (Banerjee et al., 2014; van Ittersum et al., 2013). However, most existing studies on factors influencing yield gaps have been performed at global, regional, or national level and the findings are general, making it challenging to devise site-specific crop and management measures applicable on smallholder farms (van Bussel et al., 2015). A better approach is to estimate yield gaps and understand the causes at local level, before scaling the results to larger spatial areas (van Ittersum et al., 2013). This will result in crop and soil measures that are applicable on both small and large spatial scales.

Yield gaps can be quantified using simulated or measured potential yield as reference. Simulated potential yield provides a better estimate of maize yield gaps because it accounts for genotype, environment, and management interactions, unlike estimates derived from experimental stations and farmers' fields (van Ittersum et al., 2013). However, unavailability of the data needed to effectively calibrate simulation models for smallholder farming conditions limits their use. Yield gaps can also be estimated by comparing yield on the 90th percentile of farms, representing the genotype-environment interactions prevailing in smallholder production, with that on other farms within the same area, to capture local variability (Lobell et al., 2009). This is a more accurate approach taking consideration of smallholder farming conditions than basing estimates on optimal yield data from experimental stations (van Ittersum et al., 2013).

Linear regression and correlation methods have been widely used in yield gap studies to show specific factors influencing crop yields (Krupnik et al., 2015; Mackay et al., 2011; Neumann et al., 2010; Sawasawa, 2003). However, the heterogeneity in smallholder farms is likely to result in high spatial variability in yield gaps and their causes. To obtain a spatial view of the causes of yield gaps on smallholder farms, multivariate statistics such as Classification and Regression Tree (CART) are needed (Roel et al., 2007). CART models have been used to explain variables and interactions influencing crop yields in Eastern India (Banerjee et al., 2014). Other methods such as Factor Analysis (FA) can cluster variables into common and easily interpretable factors (Yong and Pearce, 2013). This can help show consistent factors causing yield gaps over a larger spatial scale and guide policy interventions to enhance yields. The method has been used in clinical studies to obtain general conclusions on clinical conditions (Oh et al., 2016; Ohshiro and Ueda, 2018), but its use in agricultural studies is still low. Combining different methods to examine factors influencing maize yield gaps can provide complementary findings that are relevant at different spatial scales in smallholder farming systems, improving yield gap studies.

The aim of the study was to improve the understanding of consistent and site-specific factors limiting yields on smallholder farms and the causes of yield gaps in two agro-ecologically contrasting regions, by applying different multivariate methods. Specific objectives were to (i) assess consistent soil and crop management-related factors across agroecology affecting maize yield gaps; (ii) assess specific-agroecology crop and management-related factors affecting maize yield gaps; and (iii) recommend approaches based on the findings for reducing maize yield gaps.

It was hypothesized that studying yield gaps at two contrasting agro-ecologies by applying different multivariate methods will result in both consistent and specific agroecology factors influencing maize yield gaps and improve the applicability of findings on smallholder farms in enhancing yields. The study will also fill the knowledge gaps on the variability of soil properties including the possible effect of rooting depth (depth to compact layer) on maize yield gaps as suggested by (van Bussel et al., 2015).

3.2 Materials and method

3.2.1 Description of the study sites

The study was conducted in Mukuyu village (0^{o}38’N, 35^{o}41’E), Kakamega County and Shikomoli village (0^{o}4’19N, 34^{o}43’E), Vihiga County in Kenya (Figure 3.1). Both villages are included in the Intensification of food crops agriculture (Afrint) project (Djurfeldt et al., 2011) and were selected based on intensification potential in production of staple crops such as maize regarding agroecology, population density, and market access (Karugia, 2003).

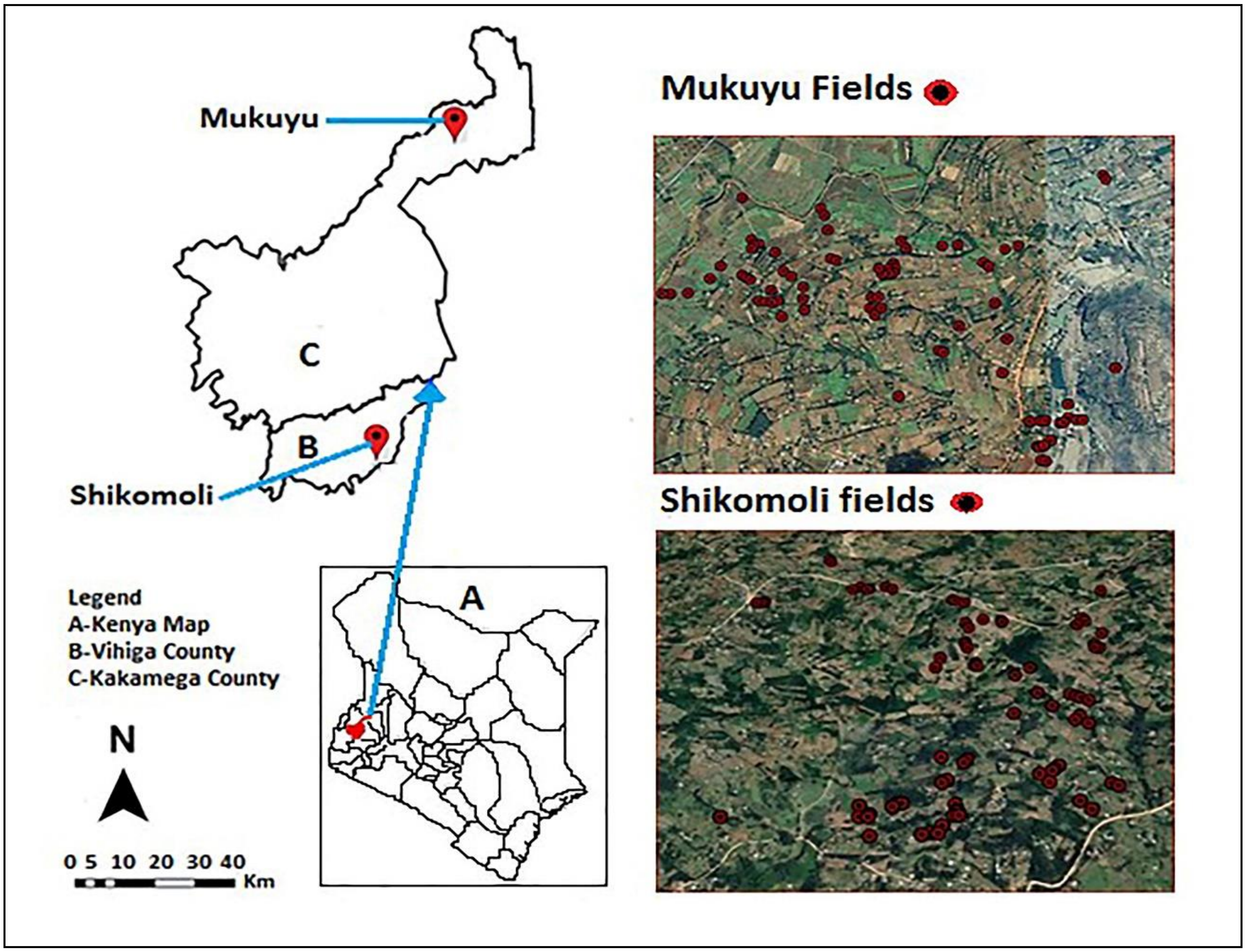


Figure 3. 1: Location and distribution of maize fields in Mukuyu and Shikomoli Villages of Kakamega and Vihiga Counties, Kenya.

Mukuyu village is located in Kakamega County (0^0, 38’N, 35^0, 41’E) at an altitude of 1600 m above sea level and in the agro-ecological zone Upper Midland 3 (UM3). The annual rainfall ranges between 1000 and 1600 mm with a mean of 1450 mm. The rain is bimodal with long- and short-rains occurring between March-August and October-November, respectively, while the rest of the months are partially dry. The daily temperature varies between 14 and 26^0C with a mean of 20^0C. The dominant soil is Ferrasols, which is well drained, with Acrisols found in some places (Jaetzold et al., 2010). In the long-rain season maize and beans are generally intercropped, but some farmers prefer to grow maize as a pure stand to facilitate easy weeding. The maize varieties with a growing period of 6-8 months are preferred due to their high-yield potential (One Acre Fund, 2016). Harvesting of maize takes place between September-October after which crop residues are removed and used as animal feed. Land is then generally cultivated for production of beans, potatoes and vegetables, and sometimes left fallow and animals graze in-situ. Mukuyu village covers approximately 3.56 km^2 with an estimated population of 1,664 people (KNBS, 2010). The average farm size is 1.5 hactares (Djurfeldt and Wambugu, 2011).

Shikomoli village is located in Vihiga County (0^0 4’ 19N, 34^0 42’ 43E) at an altitude of 1400 m above sea level. The area is predominantly in the agro-ecological zone Upper Midland 1 (UM1). It experiences equatorial type of climate with annual rainfall of 1600-2000 mm (mean 1700 mm). The rains are received in the long- and short-rains in the months of February-July and August-December, respectively. The daily temperature ranges between 14^oC and 32^oC with a mean temperature of 23^oC. Largely, the soils are Cambisols which are sandy, stony and moderately deep. Other soil types found in the village include Acrisols and Nitisols (Jaetzold et al., 2010). Short-season certified maize varieties that last between 4-5 months are preferred during the long rain season. Farmers grow indigenous maize varieties during the short rain season as these are presumed to be drought tolerant and more suited to this season because of less rainfall. The village covers an area of 1.37 km^2 with an estimated population of 2,923 people (KNBS, 2010). The average farm size is 0.5 hactares with few large scale farms of approximately 1.6 hactares (Djurfeldt and Wambugu, 2011).

Inorganic fertilizer having 18% N and 20% P used in the study sites is on average 135 and 71.6 Kg ha^{-1} for Mukuyu and Shikomoli correspondingly. This amount is below the recommended 250 kg/ha requirement for maize growth despite the Kenyan government initiative to provide subsidized fertilizer (Oseko & Dienya, 2015). High costs and inadequate knowledge on amount, frequency and timing of fertilizer application are the impeding factors to inorganic fertilizer use (Mavuthu, 2017; Sheahan et al., 2012). Organic fertilizer utilization is low and is hampered by low availability, especially in Mukuyu where land holdings are large, and low quality resulting from poor preparation and storage methods in Shikomoli. Both family and hired labor is used for agricultural production with women taking a large share. Youth participation in agriculture is low as most of them have ventured into other income generating activities (KNBS, 2010). Land under maize cultivation is decreasing both in Mukuyu and Shikomoli because of the shift to enterprises considered more productive for income generation such as sugarcane farming and planting of trees for timber production (MEMR, 2013).

3.2.2 Identifying and geo-referencing of maize plots

The units of sampling were plots having maize in the current season. These were delineated based on present management practices, distance from the homestead and size. The maize plots were sampled from 70 randomly selected households. The first 60 households (30; Mukuyu, 30: Shikomoli) had participated in the Intensification of food crops agriculture in Sub Saharan Africa (Afrint) project which had been carrying out research with these households since 2002 (Djurfeldt et al., 2011). The additional 10 households, 5 per each village were selected randomly and added to the initial sample size using the Afrint sampling design (Djurfeldt et al., 2011). The Afrint project used a purposive sampling based on the intensification potential with regard to agro-ecology and market access to select the two villages. This was then followed by a random selection 30 out of 150 households in every village (Karugia, 2003).

To avoid over-segmentation, only maize plots with an area above 0.04 and 0.004 hactares were sampled in Mukuyu and Shikomoli, respectively, since plot sizes were much smaller in Shikomoli than in Mukuyu. For each household and maize plot identified, coordinates and circumference were recorded using a hand-held Garmin Global Positioning System (GPS) (GPSMAP® 62), and the area estimated from the coordinates. The total number of identified maize plots were 170 (89 Mukuyu; 81 Shikomoli). Subsequently, a 4m × 4m area hereafter referred to as the study plot was marked at the center of each identified maize plot, and georeferenced.

3.2.3 Measuring crop performance and weed pressure

Data on crop performance indicators and weed pressure were collected to determine management-related factors influencing maize yield gaps. The crop performance indicators measured were maize density, maize development stage, height, chlorophyll level (Soil Plant Analysis Development (SPA) readings), vigor, and yield. The weed pressure indicators were weed cover and weed height. The measurements were conducted in the study plots at ear initiation and at silking and tasseling, corresponding to maize development stages 1 and 3, respectively, according to O'Keeffe (2009). Maize density was determined by taking a count of all maize plants, maize height was measured on 10 randomly chosen plants, and maize development stage was determined by counting the number of leaves from the base of the maize plant to the youngest fully developed leaf having a visible leaf collar (O'Keeffe, 2009). This was done early in the day and care was taken not to include leaves within whorl, not fully expanded and with no visible leaf collar. The majority leaf value within the study plot was then used to describe the maize development stage.

Maize height was measured on 10 randomly chosen plants by a method described by Keeffe, (2009). The Chlorophyll levels were determined using a SPAD 502 chlorophyll meter (Minolta Camera Co., Osaka, Japan) by taking readings of the youngest fully developed leaf from 15 randomly selected plants per study plot, at approximately 25% from the leaf tip and leaf base, respectively. Crop vigor was determined as presence of disease and pests through observations on 10 randomly selected plants and using a 1-5 Likert scale Sherpherd, (2010) where: 1 = almost completely infested with pest or diseases (75-100%), 2 = heavily infested (50-75%), 3 = moderately infested (10-50%), 4 = low infestation (less than 10%), and 5 = no diseases or pests. Weed coverage was assessed using an improvised mottle chart with 12 percentage levels (1%, 3%, 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 75%, and 90%), where 1% represents low weed infestation and 90% represents severe weed infestation (Sherpherd, 2010). Weed height was determined on 10 randomly selected plants in the 4m by 4m plot.

Maize yield was determined at the end of the growing period on a dry matter basis using the method described by Tobergte and Curtis (2013). In brief, all plants in the study plots were harvested and the grain was shelled, cleaned, weighed, and recorded in kg. A subsample of approximately 200 g was oven-dried at 75℃ for 24 h and weighed to determine moisture content and to calculate yield as kg dry matter for the 4m x 4m study plot. The values obtained were converted to tonnes per ha. The grain yield was determined at 13% moisture content.

3.2.4 Soil measurements, sampling, and analysis

Slope, soil erosion status, and depth to compact soil layer were recorded in the study plot, and soil samples were taken and analyzed for texture, pH, and soil nutrient status. Plot slope was determined at the start of the maize growing season, using a Likert scale; 1-Flat, 2-Gentle, 3-Steep (FAO, 2006), and percentage slope was determined using a modified L-Square. Soil erosion status was determined during maize stages 1 and 3 using a Likert scale developed by FAO (2006). Depth to soil compaction layers with resistance of 200, 300, and 500 pounds per square inch (psi) was determined when the soil was at field capacity, using a Humboldt H-4210A Portable Static Cone Penetrometer with 10 section points. In all study plots, the static cone penetrometer was pressed into the soil until the gauge read 200 psi (and then 300 and 500 psi). For each psi gauge value, a recording was made for the penetrometer sections that remained aboveground. The exact penetrometer value was computed by subtracting the values for the penetrometer sections aboveground from the values for the 10 section points. This was repeated 10 times at randomly selected points. The penetrometer values were then converted to centimeters.

In January 2016, at the start of the maize growing season, soil samples were taken to a depth of 0-20 cm at 10 randomly selected points in each plot, using a soil corer (Ø 25 mm), and bulked to one composite sample per study plot. The soil samples were air-dried and passed through a 2 mm sieve at Crops and Nutrition Laboratory Services in Nairobi. Soil texture, pH, total soil carbon (C) and nitrogen (N), and extractable soil nutrients were determined using methods described by Pansu and Gautheyrou (2006) (Table 1). The extractable soil nutrients measured were: boron (B), calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), phosphorus (P), sulfur (S), and zinc (Zn). Cation exchange capacity (CEC) was calculated from the amounts of Mehlich-3-extraction nutrient elements (Table 3.1) and exchangeable acidity. In evaluating soil fertility, the soil nutrient concentrations were compared with critical values established for maize production (FAO, 2007).

Table 3.1: Soil analysis methods applied in the study

Soil measurement	Method
Soil pH and EC	Potentiometric method using reference and measurement electrodes with soil:water of 1:2
B, P, Ca, Cu, Fe, Mg, Mn, K, S, Zn.	Extraction with Mehlich 3 solution containing diluted ammonium fluoride and ammonium nitrate followed by Atomic Emission spectrometry (ICP)
Total N	Kjeldahl digestion followed by colorimetric determination
Total C	Walkley and Black method through wet oxidation by acidified dichromate in the presence of sulphuric acid.
Clay, Sand, Silt	Hydrometer method using 10% sodium hexametaphosphate as the dispersing agent
Exchangeable Al	Colorimetric method using KCl (1N) extraction
Exchangeable Acidity	Titration after extraction with KCl and titration with NaOH

3.2.5 Quantifying maize yield gaps

Maize yield gaps were determined at farm levels using yields determined in section 3.2.3. The yield gaps were computed by comparing yields on the 90th percentile of farms to that on other farms within the same site (Lobell, 2009). The 90th percentile yield was computed for each site based on yield as:

$$K^{th} = L[\frac{(P-cfb)}{f}]U - L \qquad \text{Equation 1}$$

where Kth is the 90th percentile; L is the lower limit of the critical value within which the 90th percentile occurs; P is the critical interval where the 90th percentile occurs, calculated as (K/100) multiplied by the number of values in the distribution; cfb is the cumulative frequency of all intervals below the critical value, but not including the critical value; f is the frequency in the critical interval; and U is the upper limit of the critical value that is not included in the critical interval.

Maps showing the frequency of plots with large and small maize yield gaps were then drawn using the Geo-statistical Analyst tool in Arc Map 10.1 (Hengl, 2007).

3.2.6 Data analysis

Descriptive statistics and t-test analysis in R statistics were used to assess crop performance, weed pressure, and soil properties at the two sites. The data were subjected to Generalized Linear Mixed Models (GLMM) and CART analysis. In GLMM, the Penalized Quasi-Likelihood (PQL) technique implemented in R statistics was used to identify significant factors influencing maize yield gaps (Hui et al., 2016). The analysis involved setting random and fixed effects, where the random effects were the study plots and the fixed effects were the soil and crop variables that were identified. CART analysis employed the binary recursive partitioning technique, where variables were divided into exclusive homogeneous variables in three steps (Bickel et al., 2010). First, the tree split the parent node (average maize yield gaps in tonnes/ha) into two homogeneous child nodes, which were placed to the right and left, depicting low and high yield gaps, respectively. The two child nodes were further split and the process continued, resulting in an overgrown tree that was pruned by setting the cost complexity (cp) value at 0.01. The CART analysis indicated the level of variable occurrence that resulted in large or small maize yield gaps. In each split, the left side, with “yes” as a Boolean choice, showed factors that contributed to reducing yield gaps, while the right side, with “no” as a Boolean choice, indicated factors that led to large maize yield gaps. The analysis was implemented using the recursive partitioning (rpart) package in R statistics (Therneau and Atkinson, 2015). CART and GLMM were chosen owing to their ability to handle highly skewed data (Gordon, 2013). Factors influencing maize yield gaps identified by CART and GLMM were subjected to FA in R statistics (Beaujean, 2014), using varimax rotation to regroup variables into small easily interpretable sets based on shared variance (Yong and Pearce, 2013).

3.3 Results

3.3.1 Crop performance and weed pressure at key maize development stages

There were significant differences in crop performance and weed pressure between key maize development stages (ear initiation (stage 1), silking and tasseling (stage 3) and also sites (Table 3.2). Chlorophyll content decreased as maize progressed through stages 1 to 3 at both sites. Higher plant densities were recorded during ear initiation than during silking and tasseling (Table 3.2). Weed coverage was high across sites both during the early and later stages of maize development. Maize height, maize vigour and weed height was significantly different between Mukuyu and Shikomoli during early maize stages (Table 3.2). At later maize stages, maize height, maize vigour, weed coverage and weed height was higher in Mukuyu than Shikomoli (Table 3.2).

Table 3.2: The mean, minimum, and maximum values for crop performance and weed pressure at maize development stages 1 and 3 in Mukuyu and Shikomoli.

	Stage 1		Stage 3		Stage 1 vs 3
Mukuyu	Mean	Min and Max	Mean	Min and Max	
Maize density, plants/hectare	$44e^{+3}$ a	$37e^{3}$-$56e^{3}$	$35e^{3}$a	$28e^{3}$ - $48e^{3}$	**
Maize height (cm)	41 a	18-47	245 a	213-278	
Maize vigor	3.9 a	2-5	4.1 a	3-5	**
SPAD values	38 a	33-43	36 a	16-65	**
Weed coverage (%)	29 a	15-60	46 a	20-75	**
Weed height (cm)	10 a	6-12	31 a	25-36	**
Shikomoli					
Maize density, plants/hectare	52 e^{+3}b	$37e^{+3}$- $71e^{+3}$	$32e^{+3}$a	$26e^{+3}$ - $43e^{+3}$	**
Maize height (cm)	58 b	28-66	172 b	172	
Maize vigor	3.8 a	1-5	4.2 b	4.2	**
SPAD values	37 a	27-40	34 a	34	**
Weed coverage (%)	31 a	15-50	34 b	34	**
Weed height (cm)	13 b	8-17	23 b	23	**

Legend: The ** indicate ($p \leq 0.001$) significant at 0.95 t test statistics, showing crop performance and weed pressure variables differ at key maize development stages-stage 1 and 3. The different letters (a&b) and (the same letter a&a) along the rows are showing statistical and no statistical differences respectively between sites-Mukuyu and Shikomoli. SPAD - Soil Plant Analysis Development. Max and min is the highest and lowest value recorded for a given variable, the mean is the average value of the observations. Maize height was not computed across stage because height increases height, and it was bound to show huge variation.

3.3.2 Characterization of soil physical and chemical properties

Soil properties differed between sites, except extractable B, total Cu, Fe, S, acid saturation, clay and electrical conductivity (Table 3.3). In both sites, total C, total N, exchangeable B, total K, Mg, P and S, and C.E.C were below the critical values required to support important physiological processes in maize growth. Soil organic matter (calculated from total C) was on average 2.4% and 1.7% and the C: N was 14 and 10 for Mukuyu and Shikomoli respectively (Table 3.3). The soils in Mukuyu and Shikomoli exhibited shallow compacted soil layers. Significant differences were noted for erosion status and slope with Shikomoli exhibiting high erosion status and steep slopes. There was, however, variability of soil properties within the villages as indicated by the minimum and maximum values (Table 3.3).

Table 3.3: The mean, Minimum (Min) and Maximum (Max) values for soil chemical and physical properties in Mukuyu and Shikomoli

	Mukuyu		Shikomoli			
Soil variables	Mean	Min and Max	Mean	Min and Max	Critical values	
Carbon (C) (%)	1.4*	0.8-3.4	1.01*	0.5-2	>2.7[a]	**
Nitrogen (N) (%)	0.1*	0.08-0.3	0.1*	0.06-0.2	>0.2[a]	**
Potassium (K) (ppm)	174	52-865	100	32-785	>94[a]	**
Calcium (Ca) (ppm)	1032	287-3440	687	212-1840	>400[a]	**
Magnesium (Mg) (ppm)	160	57-582	106*	36-251	>120[a]	**
Phosphorus (P) (ppm)	20*	1.3-112	44	4.7-334	>30[a]	**
Sulphur (S) (ppm)	9*	1.7-24	8*	2.7-21	>20[a]	
Boron (B) (ppm)	0.3*	0.04-2.5	0.4*	0.02-1.6	>0.8[a]	
Copper (Cu) (ppm)	2.4	1.02-7	2	1-5	>1[a]	
Iron (Fe) (ppm)	160	60-462	148	70.4-242	>10[a]	
Manganese (Mn) (ppm)	98	11-291	197	61-355	>20[a]	**
Zinc (Zn) (ppm)	4	0.6-31	11	0.8-46	>5[a]	**
pH	5.6	4.7-7.6	5.8	4.9-6.9	>5.5[a]	
Exchange Aluminum (meq/100g)	0.2	0.01-1.04	0.1	0.01-0.78	<0.5[a]	**
Acid Saturation (%)	6	0.22-32	5.8	0.5-34	<10[a]	
Cation Exchange Capacity (CEC; meq/100g)	10*	5-34	6*	3-13	>15[a]	**
Electrical Conductivity (mS/m)	44*	9-140	38*	15-116	>80[a]	
Sand (Sa) (%)	54	30-79	66	49-84		**
Silt (Si) (%)	9.8	4-32	8	4-14		**
Clay (Cl) (%)	36	14-54	24	12-44		
Erosion Status	1	1-2	2	1-3		**
Slope (%)	3	1-7	6	1-12	0-2[b]	**
Depth to compaction (cm)	20	9-25	21	8-25	>50[b]	**

*Value below the critical level for maize growth. **Significant difference (p=<0.0001) between sites. Critical values (NAAIAP, 2014); [b](FAO, 2007) represent extractable nutrient concentration in soil above which an economic yield response to added nutrient is unlikely. Max and min is the highest and lowest value recorded for a given soil variable, mean is the average of all observations.

3.3.3 Maize yields and yield gaps in Mukuyu and Shikomoli

The 90th percentile yields were 5.1 and 4.8 t ha^{-1} (Figure 3.2) in Mukuyu and Shikomoli respectively. The average measured maize yields were 3.3 t ha^{-1} and 2.2 t ha^{-1} for Mukuyu and Shikomoli, respectively.

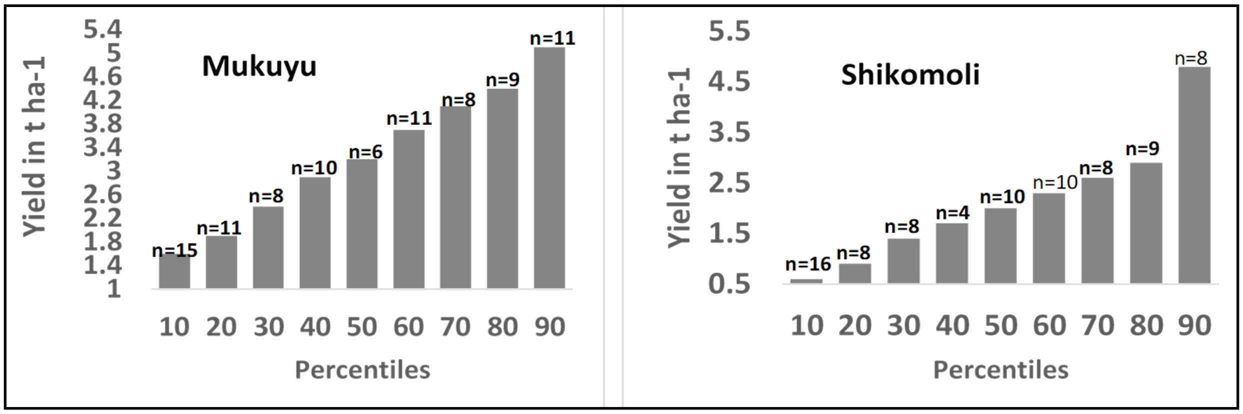


Figure 3.2: Distribution of maize yields in Mukuyu and Shikomoli

The y-axis represents the average yield for each of the percentiles bar, n is the number of plots

The yield gaps in Mukuyu and Shikomoli were significantly different ($p= 0.0001$) and averaged 1.8 t ha^{-1} and 2.6 t ha^{-1} respectively, representing 35% and 54% of unachieved yields at the farmer level when compared to the highest 90th percentile yields. Maize yield gaps were high in Mukuyu compared to Shikomoli (Figure 3.3 and 3.4)

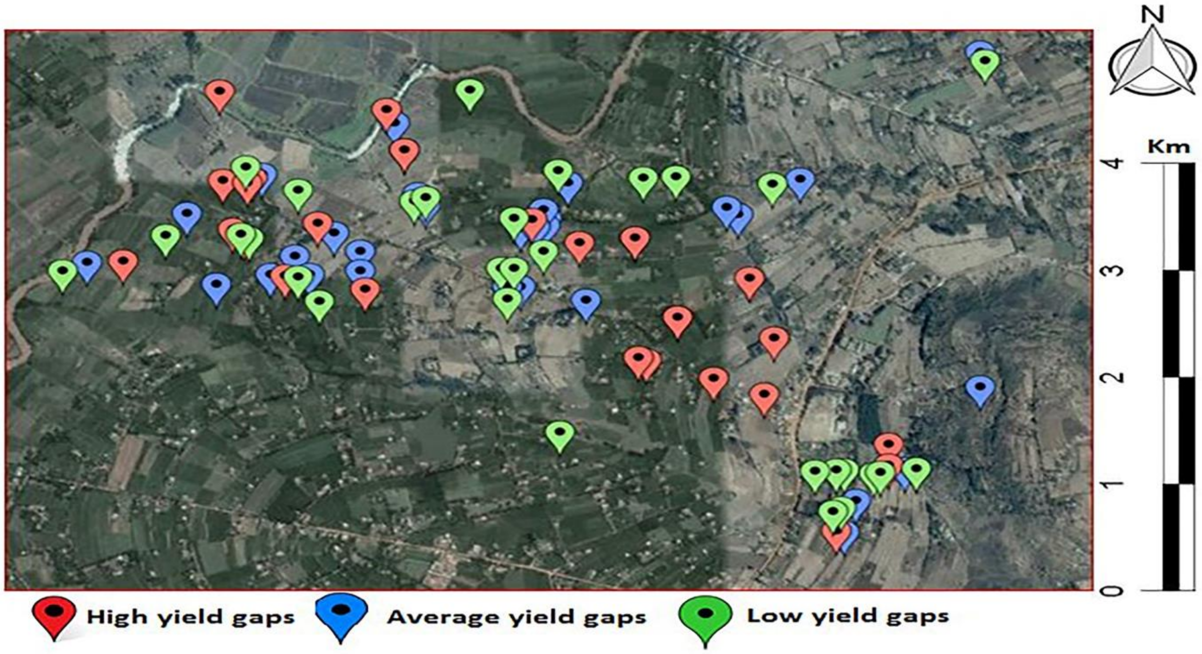


Figure 3. 3 Maize yield yaps in Mukuyu

Legend: The red points show high yields gaps (2.00 to 4.55 t ha-1), the blue points are average yield gaps (1.0 to 1.99 t ha^{-1}), green points show low yield gaps (-2.3 to 0.97 t ha^{-1}).

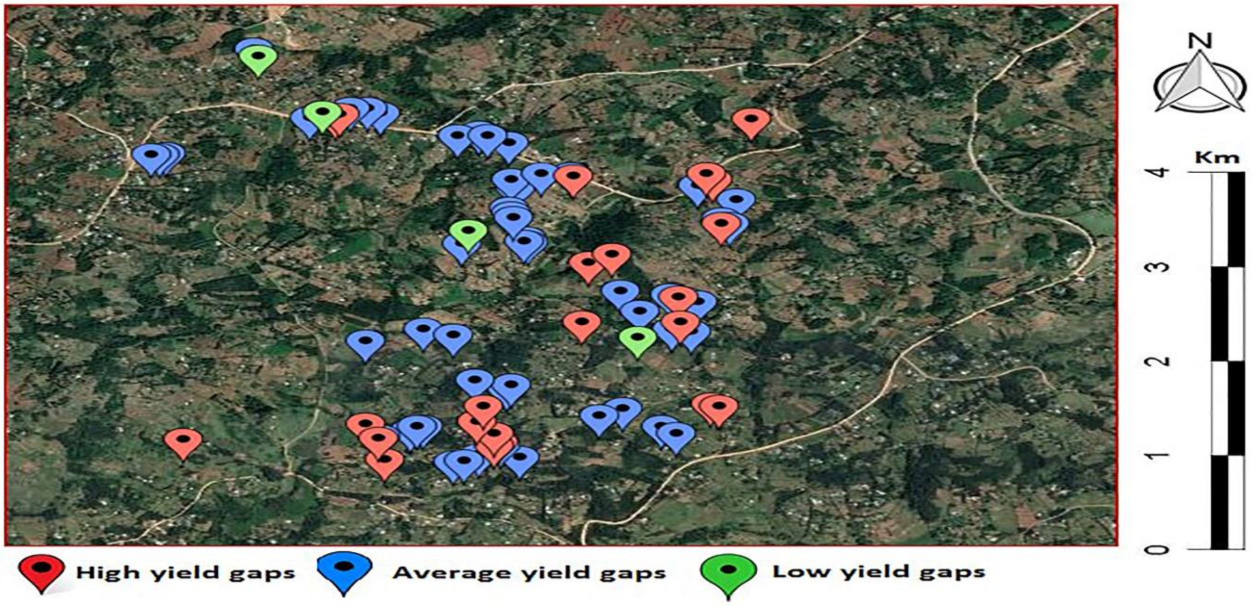


Figure 3.4: Maize yield gaps in Shikomoli

Legend: The red points show high yield gaps (2.00 to 4.63 t ha^{-1}), the blue points indicate average yield gaps (1.0 to 1.99 t ha^{-1}), green points show low yield gaps (-0.01 to 0.55 t ha^{-1})

3.3.4 Soil and Management-related Factors contributing to yield gaps in Mukuyu

In Mukuyu, the GLMM analysis showed that maize yield gaps were significantly affected by weed coverage and weed height in the early stages of maize development, SPAD readings at stage 3, extractable Zn, P and percentage silt (Table 3.4). High weed height and weed coverage at stage 1 contributed to large yield gaps as shown by the positive coefficient and R-values, while high SPAD readings (at stage 3), Zn and P concentration and percentage of silt resulted in low yield gaps as shown by the negative coefficient and R-values.

Table 3. 4: The Coefficient*, R and P value for factors influencing maize yield gaps in Mukuyu

Soil and management-related factors	Coefficient Value	R-Value	P-value
Intercept	2.311	0.999	0.0006**
Weed coverage in stage 1	0.033	0.529	0.0000**
Extractable Zn	-0.144	-0.173	0.0001**
Weed height in stage 1	0.058	0.333	0.0016**
SPAD readings in stage 3	-0.061	-0.897	0.0015**
Available P	-0.023	-0.200	0.010**
Silt (%)	-0.0029	-0.386	0.051**

*Level of increase or decrease in maize yield gap with a one unit increase or decrease in the factor. The ** indicate p values significant at 0.95 test statistics.

The CART analysis for Mukuyu showed that weed coverage at development stage 1 (WC1) was the main factor causing yield gaps (Figure 3.5). In the first split, the 53% of plots with weed coverage <28% (Node 1) had an average yield gap of 0.86 t ha^{-1}, whereas the 47% of plots with higher weed coverage had an average yield gap of 2.9 t ha^{-1}. Plots where depth to compact layer (CmpD) was great (≥10 cm) (Node 2) showed smaller yield gaps, as did plots with maize density at development stage 3 (MDD3) ≥ 32,000 ha-1 (Node 4). Other important variables that resulted in reduced yield gaps were relatively high soil Mn, tall maize plants at stage 3, and low weed height at stage 1. The 10% of plots that had weed coverage below 28%, an easily penetrable soil to at least 10 cm depth, maize density above 32,000 plants ha^{-1}, and extractable Mn above 83 mg kg-1 showed an average yield gap of -0.96 t ha^{-1} (Node 15).

Factors that increased yield gaps were weed coverage at stage 1, tall weeds (>9.6 cm) at stage 1 (WH1) (Node 3), low P availability (<17 ppm) (Node 5), and low maize density (Node 7). The 10% of plots that had weed coverage above 28%, weed height more than 9.6 cm in stage 1 (WH1), and maize density below 37,000 plants ha^{-1} at stage 3 (MDD3) showed an average yield gap of 4.6 t ha-1.

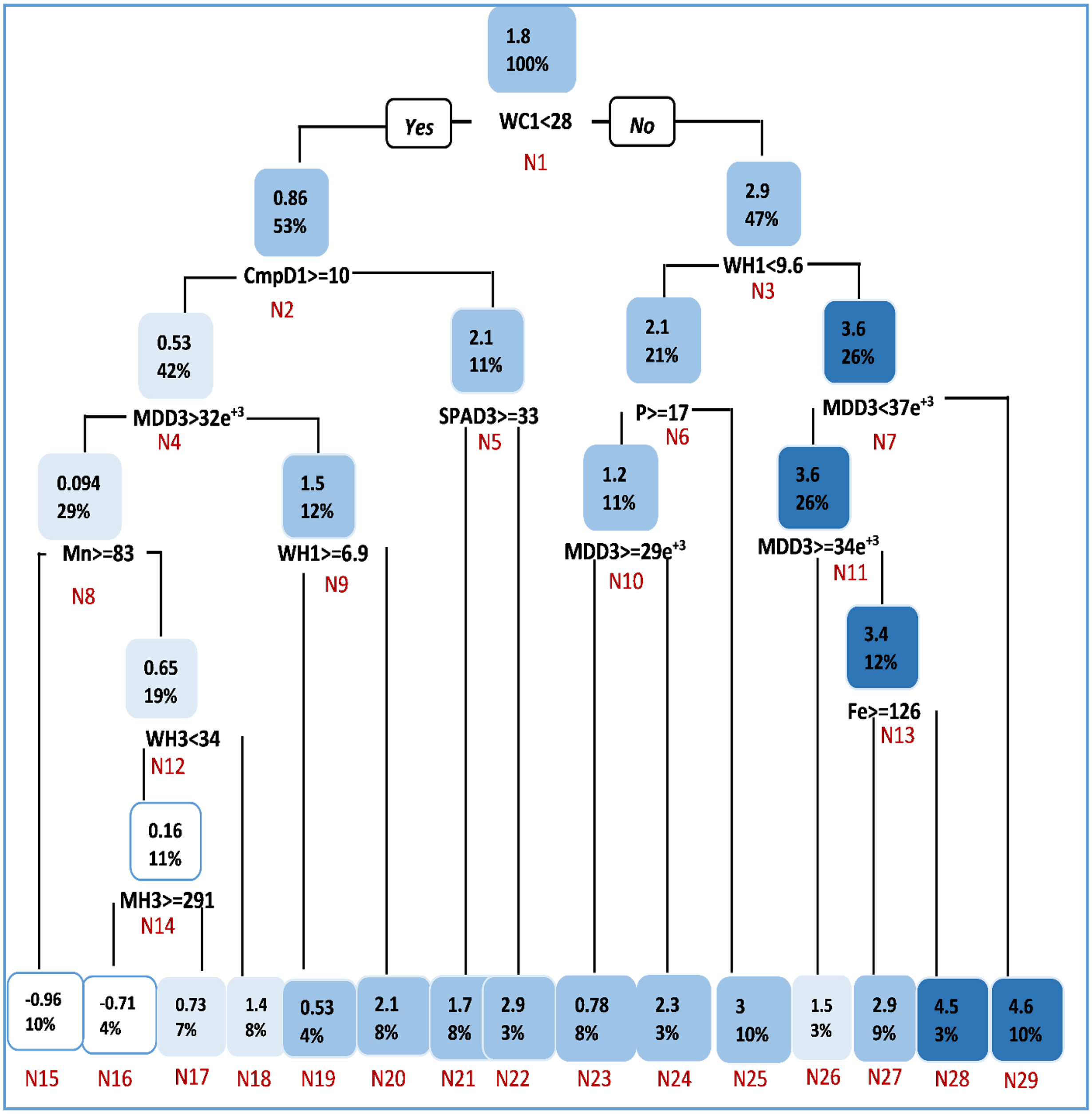


Figure 3. 5 Classification and regression tree showing factors resulting in small or large maize yield gaps in Mukuyu

Legend: WC1-Weed coverage in stage 1, SPAD3-SPAD readings in stage 3, MH3-Maize height in stage 3, WH1-Weed height in stage 1, CmpD1-Depth of compaction at 500 pressure units, Mn-manganese, WH3-Weed height in stage 1, Fe-iron, P-phosphorus. Boxes show average maize yield in t ha-1 (e.g.,1.8, 0.86, 2.8….4.6) and percentage of farms (e.g 100%, 64%, 36%…10%). Intensity of box coloration increases with increase in yield gaps, white to light blue boxes show low yield gaps and dark blue boxes show large yield gaps. N1, N2, N3……N29 are nodes and each node represents a split point for a certain variable.

In FA, the clustering of variables influencing maize yield gaps in Mukuyu showed that factors 1, 2, and 4, with a total proportion of variance of 0.42, were predominantly soil variables, while factors 3 and 5, with a total proportion of variance of 0.19, were management-related variables (Table 3.5).

Table 3. 5: Factor regrouping of soil and management-related variables influencing maize yield gaps in Mukuyu

Variable	**Factor 1 (S)**	**Factor 2 (S)**	**Factor 3 (M)**	**Factor 4 (S)**	**Factor 5 (M)**
Weed height	0.53*				
Depth to Compaction layer	0.79*				
Iron (Fe)	0.75*				
Zinc (Zn)		0.96*			
Phosphorus (P)		0.66*			
Weed coverage			0.94*		
Silt	0.58*			0.81*	
Manganese (Mn)	0.43			0.57*	
SPAD values					0.82*
Maize height					0.42
	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**
Sum of Squared loadings	2.04	1.44	1.06	1.05	1.02
Proportion variance	0.19	0.13	0.10	0.10	0.09
Cumulative variance	0.19	0.32	0.41	0.51	0.60**
Eigen values	2.46	2.03	1.37	1.24	1.03

Test of hypothesis that 5 factors are sufficient. The chi square statistics is 10.11 on 10 degrees of freedom. The * and **represent factors with higher and cumulative variance. S and M are soil and management related factors respectively. Weed height, weed coverage, maize height and SPAD values are indirectly affected by field management practices farmers carry out hence they are being referred as management-related

3.3.5 Factors contributing to maize yield gaps in Shikomoli

The GLMM analysis indicated that maize yield gaps in Shikomoli were significantly affected by; maize density and maize height at late maize stages, CEC, depth to compact layer, Mg concentration, and silt content (Table 3.6). High plant density and maize height at stage 3 and high Mg, CEC, silt percentage, and depth to compact layer reduced maize yield gaps, as shown by the negative coefficient and R-values (Table 3.6).

Table 3.6: The Coefficient*, R and P value for soil and management-related factors influencing maize yield gaps in Shikomoli

Soil and management-related factors	Coefficient Value	R-Value	p-value
Intercept	8.35	0.999	0.0000**
Maize density at harvest	-0.007	-0.63	0.0000**
Maize height at stage 3	-0.008	0.450	0.0061**
Cation Exchange Capacity	-0.2	-0.335	0.0076**
Depth to500 psi penetration resistance	-0.06	-0.732	0.0069**
Magnesium concentration (Mg)	-0.010	-0.440	0.0078**
Silt (%)	-0.117	-0.397	0.0073**

*Level of increase or reduction in maize yield gap with a one unit increase or decrease in the factor. The * indicate p values significant at 0.95 test statistics.

The CART analysis identified maize density as the most important factor contributing to yield gaps in Shikomoli (Figure 3.6). The approximately 64% of plots with maize density at harvest (MDD3) ≥32,000 ha^{-1} (Node 1) had a yield gap of 2.1 t ha^{-1}, whereas the 36% of plots with lower maize density had an average yield gap of 3.5 t ha^{-1} (Node 1). Lower yield gaps were also recorded for plots with greater depth to compact layer (CmpD3 ≥24 cm) (Node 2), sand content <53% (Node 4), EC ≥ 43 meq 100g^{-1} (Node 7), Na content ≥ 16 ppm (Node 11), and Zn content ≥7.3 ppm (Node 13). The 4% of plots with maize density >32,000 ha^{-1}, CmpD3 >24 cm, and sand content <53% had a yield gap of -0.1 t ha^{-1}.

Factors that increased the yield gap (right side of Figure 3.6) were low maize density in stage 3 (MDD3), low maize height in stage 3 (MH3) (Node 3), and low chlorophyll content in stage 1 (SPAD1 <38) (Node 6). The 10% of plots that had MDD3 <32,000 ha^{-1}, maize height <219 cm, SPAD1 <38, and maize density in stage 1 (MDD1) <48,000 ha^{-1} had an average yield gap of 4.3 t ha^{-1} (Node 29).

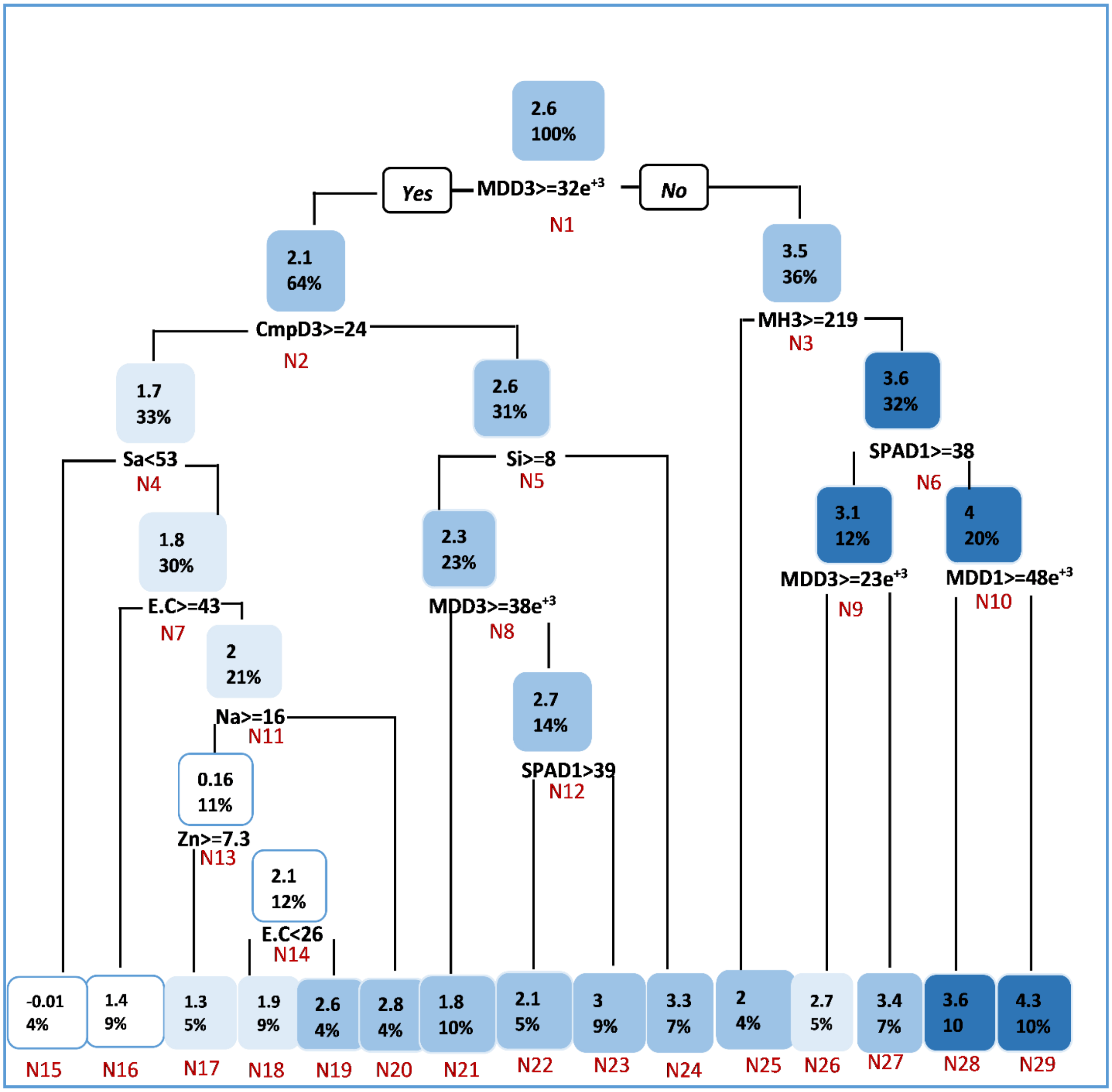


Figure 3. 6 CART showing factors resulting in low or high maize yield gaps in Shikomoli.

Legend: MDD3-Maize density at harvest, CmpD3-Depth of compaction at 500 pressure units, MH3-Maize height in stage 3, SPAD1-SPAD readings in stage1, Na-Sodium, WH3-Weed height in stage 3, MDD1-Maize density at stage 1, Si-Silt content, , Sa-Sand content, Zn-Zinc content, EC-Electrical Conductivity. The rounded rectangular box contain average maize yield in t ha-1 (e.g 2.6, 2.1, 3.6…4.3) and percentage of plots (e.g 100%, 64%, 36%…10%). The coloration of plots increases with increasing yield gaps white to light blue boxes showing low yield gaps and dark blue boxes show large yield gaps. N1, N2, N3……N59 are nodes each node represents a split point for a certain variable.

In Shikomoli, the FA showed that soil variables had a total proportion of variance of 0.32 and loaded on factors 1 and 3. Management factors had a total proportion of variance of 0.24 and loaded on factors 2 and 5 (Table 3.7). Factor 4 had either soil or management factors, with a proportion of variance of 0.06.

Table 3.7. Factor regrouping of soil (S) and management-related (M) variables influencing maize yield gaps in Shikomoli

Variables	**Factor 1 (S)**	**Factor 2 (M)**	**Factor 3 (S)**	**Factor 4 (S/M)**	**Factor 5 (M)**
Zinc (Zn)	0.73*				
Cation Exchange capacity (CEC)	0.61*				
Magnesium (Mg)	0.80*		0.38		
Maize density at stage 3		0.99*			
Maize density at stage 1		0.68*			
Silt percentage			0.59*		
Sand percentage			0.94*		
SPAD values					0.75*
Compaction depth				0.54*	
Maize height				0.31	
	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**
SS loadings	1.77	1.56	1.54	1.11	0.82
Proportion variance	0.17	0.15	0.15	0.06	0.09
Cumulative variance	0.17	0.32	0.47	0.53	0.62**
Eigen values	2.9	1.7	1.6	1.10	1.02

Test of hypothesis that five factors are sufficient (Chi square statistic = 10.11 on 10 degrees of freedom, p-value = 0.844). The p-value is the probability that the source data perfectly fit the number of factors specified, five in this case, so larger values are better. *Factors with higher variance (>0.5). **Cumulative variance.

3.3.6 Consistent factors influencing maize yield gaps at both sites

Factor analysis showed that soil was the overarching factor influencing maize yield gap, rather than management-related factors (Tables 3.5 and 3.7). CART analysis showed that consistent factors influencing maize yield gap at both sites were: maize density, SPAD value, maize height, and depth to compact layer (Figures 3.5 and 3.6). GLMM analysis identified silt content as a constant factor affecting maize yield gaps at both sites (Tables 3.4 and 3.6).

3.4 Discussion

3.4.1 Consistent factors influencing maize yield gaps regardless of agroecology

The high maize yield gaps observed show potential to increase yield by 35-54% at smallholding level in Mukuyu and Shikomoli, with high and low agroecological potential respectively. Similarly, Gathala et al. (2015) and Liu et al. (2012) report exploitable maize yield gaps of >40% and recommend adjustments in soil and crop management measures to increase yield. Use of integrated analysis (CART, GLMM, FA) showed that maize yield gaps were influenced by factors that were consistent across agroecological zones and by site-specific factors. This extends findings by van Loon et al. (2019), who used an integrated approach and identified only site-specific factors influencing maize yield gaps on smallholder farms.

The high proportion of variance attributable to soil properties at both Mukuyu and Shikomoli, as demonstrated by FA (Tables 3.5 and 3.7), suggests that soil factors were more important in influencing maize yield gaps than management-related variables. Both sites showed some nutrient concentrations below the critical value for maize growth (Table 3.3), suggesting that nutrient supply was inadequate to support maize development (NAAIAP, 2014). Factors leading to low soil nutrition status were a high percentage of sand, high concentrations of extractable Fe and Al oxides, and considerable erosion, especially in Shikomoli (Table 3.3). Low soil nutrition status is also an indication of other underlying factors occurring within smallholder farming systems, such as insufficient use of inorganic and organic fertilizers and crop residues (Achieng et al., 2010; Oseko & Dienya, 2015). Since maize is a staple crop in Kenya and in most parts across the globe, policy measures aimed at improving general soil fertility, such as leaving crop residues *in situ*, applying organic and inorganic fertilizers, and growing cover crops, are important. Low-cost technologies to chop crop residues for easier incorporation into the soil could also improve soil fertility. Making soil testing services available to smallholder farmers and having a supply chain for suitable fertilizers are also important measures.

The CART and GLMM analysis showed that maize yield gaps were influenced by both soil and within-season management-related factors that were consistent across sites. These were: maize density, SPAD values, maize height, depth to compact layer, and silt content (Figures 3.5 and 3.6; Tables 3.4 and 3.6). Previous studies have found that low plant density exacerbates the maize yield gap on smallholder farms (Tittonell et al., 2008; Keating et al., 2010; Delmotte et al., 2011). Maize density decreased between stages 1 and 3, indicating reduced yield potential, and decreased more in Shikomoli than in Mukuyu, as shown by CART analysis (Figure 3.6). This was due to lodging of maize resulting from strong winds in June-July, exacerbated by the steep terrain in Shikomoli (Table 3.3). Stem lodging in maize plants could also have been caused by morphological traits such as tall plants, short internode length, low basal strength, and low soil nutrition (Mi et al., 2011; Shah et al., 2017). Low maize density at harvest means that a smaller amount of crop residues is available to improve soil organic matter and fertility, contributing to a vicious low soil fertility cycle. The strong influence of maize density on maize yield gaps at both sites indicates a need for farmers and government authorities to introduce measures aimed at achieving and maintaining high plant density throughout the production period. At farm level, measures such as timely planting to escape adverse wind effects and ensuring adequate soil nutrition status would be helpful. At government level, measures could include breeding for maize varieties with high lodging resistance and carrying out on-farm research to establish the optimal plant population for different agroecological zones.

Maize yield gaps were also influenced by SPAD values and maize height, confirming findings by Ghimire and Timsina (2015) and Boomsma et al. (2010). The SPAD values observed in maize development stages 1 and 3 (27-43) were below the value reported to prevent yield loss (52) (Lindquist et al., 2010). The SPAD values decreased as maize developed, indicating decreasing N concentration in the leaves, a sign of reduced assimilation and remobilization of N to yield components at the silking and tasseling stage (Yan et al., 2017; Han et al., 2015). Insufficient and untimely fertilizer use at both study sites most likely contributed to the low SPAD values and maize height, as previously described (Oseko & Dienya, 2015). This reflects the limited ability of smallholder farmers to access adequate fertilizer and their limited awareness of the importance of supplying adequate nutrition to maize during the critical yield determination period. Hence, increasing the accessibility of fertilizers and educating smallholder farmers on the need to time fertilizer applications to critical crop nutrient requirement stages is important. The lower than average precipitation experienced at the silking and tasseling stages (Uhe et al., 2018) could also have contributed to plant stress, leading to low nutrient use efficiency, low SPAD values, and shorter maize in Mukuyu. To mitigate such challenges, managing soil moisture by growing cover crops and legume intercrops for enhanced water use efficiency will become increasingly important under high climate variability. National and county governments could invest in irrigation facilities.

Dense soil at shallow depth (short distance to compact layer) (Table 3.5) indicated restricted maize rooting depth, limiting uptake and assimilation of nutrients and moisture (FAO, 2007). The effect of root resistance on maize yield gaps has been documented previously (Chen & Weil, 2011; Głąb, 2011). Soil compaction at shallow depth could have been caused by ploughing when the soil was wet (Elaoud and Chehaibi, 2011). This is more likely to have occurred in Mukuyu, where farm size is larger. In Shikomoli, shallow soil could be due to the rockiness and stoniness of the terrain (Jaetzold et al., 2010). Farmers at both study sites graze animals in the maize fields, due to inadequate pasturage. Trampling by animals could have resulted in hard layers in the soil. Given the rocky and stony terrain that characterizes most smallholder farms, untimely use of tractor/animal-drawn ploughs, and use of crop residues *in situ* as animal feed (FAO, 2012), the negative effect of restricted rooting depth on maize yields could be aggravated. Hence there is a need for government measures to increase water and nutrient use efficiency, such as breeding for varieties that grow well on soils with high penetration resistance and have high N and P acquisition efficiency. There is also a need to inform smallholder farmers about the importance of avoiding ploughing wet soil in order to minimize compaction.

3.4.2 Agroecology-specific factors influencing maize yield gaps

The GLMM and CART analysis identified a number of agroecology-specific factors influencing maize yield gaps. The findings are consistent with previous recommendations for site-specific extension services on soil and crop management strategies to reduce yield gaps (Banerjee et al., 2014; Krupnik et al., 2015; Tamene et al., 2016; Yengoh, 2012).

Weed cover during early maize stages was the most yield-limiting factor in Mukuyu (Figure 4). High weed cover in stages 1 and 3 increased competition for soil nutrients and moisture, resulting in lower soil N availability for maize growth, as shown by low SPAD values (Table 3,2). High weed cover in stage 1 has been previously shown to reduce dry matter accumulation in earlier maize stages, which is essential for grain formation (Page et al., 2012). High weed cover in stage 3 has been shown to lengthen anthesis and silking stages, resulting in lower grain number (Reid et al., 2014b). High weed cover in both stages 1 and 3 is therefore a predictor of low maize yield. Imoloame and Omolaiye (2017) also report negative effects of weed cover on maize performance between the 3rd and 6th weeks of development, resulting in low yield. High weed cover may be the result of unavailability of labor for timely weed control, because of financial constraint (Sims et al., 2018). Low returns from agriculture have also been shown to decrease investment in hired labor for weeding (Usman, 2017). Interviews with farmers in Mukuyu confirmed that low returns from maize sales had prevented them from hiring labor for weeding. High weed cover during early stages indicates an effect of other factors related to field management, such as delayed land preparation and past farmer weed management measures, which need to be investigated. Ongoing migration to cities is reducing the labor force in rural areas, with impacts on weed control (Sims et al., 2018). The high engagement of young people in other income-generating activities at the study sites seemingly has a similar effect. Given the strong influence of weeds on maize yield, farmers need to invest in early weed management measures such as labor-saving technologies (low-cost tillage equipment), and extension services need to create awareness among farmers of the significance of early land preparation in controlling weeds.

Previous work in Western Kenya has demonstrated the negative effects of low soil nutrient concentrations on crop yield (Kihara et al., 2016). Low nutrient availability in soils contributed to yield gaps at both sites in the present study, with the most important factors being low Zn and P in Mukuyu, and low Mg and CEC in Shikomoli (Tables 3.3 and 3.4). Masood et al. (2011) and Tariq et al. (2014) have previously reported effects of P and Zn deficiency on maize production. Low P values result in reduced root development and can lead to decreased uptake of moisture and nutrients (Fageria, 2009). Low Zn impairs protein metabolism and has been shown to affect yield (Cakmak, 2000). Low Mg is an indication of reduced biomass formation and increased susceptibility of maize crops to environmental stress (Senbayram et al., 2015). Low CEC resulted from the dominant soil types (Acrisols, Ferrasols, Nitisols) at the study sites and indicates low ability of the soils to hold important nutrients in a plant-available pool. This contributed to low crop performance, as shown by low SPAD values (Table 3.2) and high maize yield gaps. Low P, Zn, and Mg also reflect lack of access by smallholders to fertilizers containing Zn, Mg, and potentially other nutrients, or unaffordability of sufficient doses. Measures that raise the availability of P, Zn, and Mg in soils on smallholder farms are therefore needed. Such measures at national and county government level might include increasing the accessibility and affordability of Zn, S, and P fertilizers to smallholder farmers. Measures at farm level might include improving soil organic matter content by applying organic manure to increase nutrient availability and CEC.

3.4.3 Methodological applicability and relevance in yield gap studies

This study examined causes of maize yield gaps using an integrated approach and identified relevant consistent and agroecology-specific factors. CART, GLMM, and FA all revealed some factors that influenced maize yield gaps at both sites, and some that were specific for each site. Factor analysis showed that, when evaluated together, soil factors exerted more influence on maize yield gaps than management-related factors. CART analysis revealed more consistent factors influencing maize yield gaps at the two sites with contrasting agroecological potential than GLMM analysis (Section 3.3.6), while GLMM analysis revealed more agroecology-specific factors. In addition to identifying the specific most limiting factors for crop yields at each site, CART analysis also showed the weight of soil and management-related factors on yield gaps (Figures 3.5 and 3.6). Thus despite the complexity of the smallholder farming systems, it proved possible to identify consistent factors and agroecology-specific soil and management-related factors limiting crop yield. Knowledge of consistent factors across agroecological zones can assist regional and national authorities in policy development, while knowledge of agroecology-specific factors can assist county and local authorities in prescribing soil and crop management measures to improve yields. In devising measures, it is important to consider the relative occurrence of the factors limiting yield, in order to enhance resource utilization efficiency.

Smallholder farms require a suite of management options they can select and adapt to improve yields, since they operate under resource constraints (Ronner et al., 2018). The CART method showed variability in occurrence of maize yield gaps and identified a combination of interacting factors that led to small (Figure 4; Node 15) and large (Figure 4; Node 29) yield gaps. The method thus revealed interacting factors not identified by GLMM and factor analysis. This can aid in devising a suite of soil and crop management measures for use on smallholder farms, based on extension work, on-farm research, and agronomic trials.

The results demonstrate the significance of an integrated approach in providing complementary findings which have relevance at different levels of authority (regional, national, local) and usability on smallholder farms. This indicates that simultaneous and concerted efforts at different levels are needed to close maize yield gaps on smallholder farms. Future work could employ on-farm trial research and remote sensing technologies as complementary methods to further unravel causes of low yields on smallholder farms.

3.5 Conclusion and Recommendation

This study makes a novel contribution to the existing literature on yield gaps by demonstrating the usefulness of combining different multivariate methods (CART, GLMM, FA) in revealing consistent and site-specific factors limiting yields in different agroecological regions. Maize yield gaps were found to be consistently influenced by maize density, chlorophyll values (SPAD), maize height, depth to compact layer, and soil texture. In an area with high agroecological potential (Mukuyu), maize yield gaps were also increased by high weed pressure. Low soil fertility contributed to yield gaps at both sites, but the deficient nutrients differed between the sites. Low phosphorus and zinc were the most limiting soil factors in Mukuyu and Shikomoli respectively. The study also provides new knowledge on the variability of soil properties, including depth to compact layer (rooting depth), and the effect on maize yield gaps. The results indicate great potential to increase maize yields on smallholder farms through simultaneous measures introduced by national, regional, and local authorities that address multiple constraints affecting yields such as; improving soil fertility, sustaining an optimal plant population, and managing weeds.

CHAPTER FOUR

INTEGRATING FARMER DERIVED MANAGEMENT ON ON-FARM TRIAL RESEARCH TO ASSESS YIELD VARIABILITY AND POTENTIAL YIELDS ON SMALLHOLDER FARMS IN SUB-HUMID AREA

Abstract

Variations in maize yield in sub-humid areas with potential for agricultural intensification continue to widen yield gaps on smallholder farms. This study integrated best farmer management practices identified in past surveys into on-farm omission trials, in order to identify causes of yield variation, estimate potential yield, and optimize management practices to bridge yield gaps on smallholder farms in sub-humid zones. On-farm trial plots with best farmer management and plots with best practices omitted one at a time in three other treatments were laid out in a randomized complete block design on 33 farmers' fields in Mukuyu and Shikomoli villages, Western Kenya. The best farmer management (positive control) treatment applied practices used to obtain the 90th percentile yields in past surveys within each site. These practices included improved nutrient application, timely weed control, and optimal plant density. The treatments in the omission treatment plots represented reduced management intensity, and involved low nutrient supply, delayed weed control, and low plant density. Crop performance, weed pressure, weather data at critical yield determination stages of maize development, and yield were determined and analyzed by Linear Mixed Effects Model (LMER).

The highest yields were recorded in the best management treatments, with an average of 7.8 and 6.6 t ha^{-1} in Mukuyu and Shikomoli, respectively. These yields represented a 45-47% and 27-35% increase, respectively, compared to the 90th percentile yields in past surveys, mainly due to higher precipitation in the current season. Factors contributing to high best management yields were sufficient nutrient supply, weed control at critical yield-determining stages in maize, and high maize count at harvest. By integrating best management into on-farm omission trials, it was possible to assess the impact size of dominating management levels resulting in reduced yields in smallholder maize production. The best management yields can act as reference in the design of measures for improving yields and reducing yield gaps on smallholder farms.

Key words; Integrated approach, Past survey, On-farm trials, Best farmer management

4.1 Introduction

The plateauing yields in staple crops such as rice, wheat, and maize in China, France, Italy, India and German is putting pressure on other regions such as Sub Saharan Africa to accelerate yield growth (Van Wart et al., 2013). This is because yields of crops such as maize in Sub Saharan Africa have not attained production potential. As a result, yield gaps >60% have been recorded (Manyong et al., 2007; Ray et al., 2013). Increasing yields in such areas present an opportunity to achieve food security for the growing human population which is expected to double in the coming decades (van Bussel et al., 2015). Understanding spatial and temporal causes of yield variation and identifying potential yields that can be achieved within certain agro-ecology is needed to guide policy intervention and adjust crop and soil management measures for enhanced yields (Ittersum et al., 2013).

On-farm trials research coupled with management practices from past survey findings has been recommended to understand spatial and temporal constraints to crop yields (Anderson et al., 2016). This is because survey methods which have mostly been used to asses causes of yield variation are unable to account for all spatial and temporal variability of certain constraints that occur within the crop development period (Anderson et al., 2016). However, existing studies on on-farm trial research are based on management practices recommended from highly controlled field experiments which assume optimum environmental, socio-economic and management conditions (Karki et al., 2014; Mugwe et al., 2009; Sileshi et al., 2010). These conditions might not represent ideal smallholder farmer conditions in explaining temporal and spatial causes of yield variability. Management practices among high yielding farms derived from survey findings have the advantage of ensuring genotype and environment interaction which is representative of the smallholder diverse conditions (Ittersum et al., 2013). Management practices from best producing farms compared to average farmer conditions practices can provide robust information on causes of yield variation when controlled and non-controllable factors have been measured on on-farm trial research. This is because crops on-farm trials are subjected to significant soil and topographic diversity compared to well managed on-stations experiments (Florin et al., 2009; Kravchenko et al., 2005). Hence can better explain spatial causes of yield variability on smallholder farms without bias. Used as diagnostic tools, on-farm trials can be able to identify within seasons crop constraints and overcome temporal data limitations common with surveys (Anderson et al., 2016). To date, studies have either used surveys (Dzanku et al., 2015; Hall et al., 2013) or field experiments (Kravchenko et al., 2017) to understand causes of yield variations. A combined approach is expected to add value in understanding the causes of yield variability.

Estimating yield gaps based on maximum farmers yields from survey findings has been recommended to quantify maize yield gaps applicable to farmer conditions (Lobell et al., 2009). More often, obstacles related to weather events, market access of farm inputs and timely agronomic management prevent farmers from obtaining maximum yields possible resulting in underestimated yield gaps (van Ittersum et al., 2013). By subjecting management practices based on maximum farmer yields on on-farm trial experiments in another season of production, some of the effects related to weather limitations on yield can be minimized. This can result in better yield potential and improve estimation of yield gaps based on maximum farmer yields.

The potential yield on smallholder farms is a result of interaction between the genotype, the environment and the local farming practice (Tittonell and Giller, 2013). To effectively obtain potential yield that can be used to estimate maize yield gaps, there is the need to maximize the effect of each management practice factor and take advantage of the synergistic interaction of multiple management factors so that the total effect on yield is large (Below et al., 2011). This is because improvement and response of one management practice is additive and is dependent on the addition of one or more other practices (Anderson et al., 2011). This can be done using the omission trial method which has more often been used to evaluate the deficiency of different soils and recommend fertilizer requirements (Nziguheba et al., 2009).

The overall objective of the study was to evaluate the significance of integrating farmer derived management practices from past survey findings and on-farm trial research in understanding spatial and temporal causes of yield variation and estimating potential yields on smallholder farms. The objectives were; To assess causes of spatial yield variation by comparing best and average derived farmer management practices, 2. To assess the causes of temporal yield variation by comparing management practices at different time periods 3. Identify potential smallholder farmer yields based on best farmer management practices

4.2 Materials and methods

4.2.1 Description of experimental sites

The study was conducted in two sites; Mukuyu and Shikomoli (Figure 4.1) villages drawn from the Intensification of food crops agriculture in Sub Saharan Africa Project (Afrint) (Djurfeldt et al., 2011). Mukuyu has fairly developed soils but poor market access, while Shikomoli has poorly developed soils with fairly good market access (Karugia, 2003).

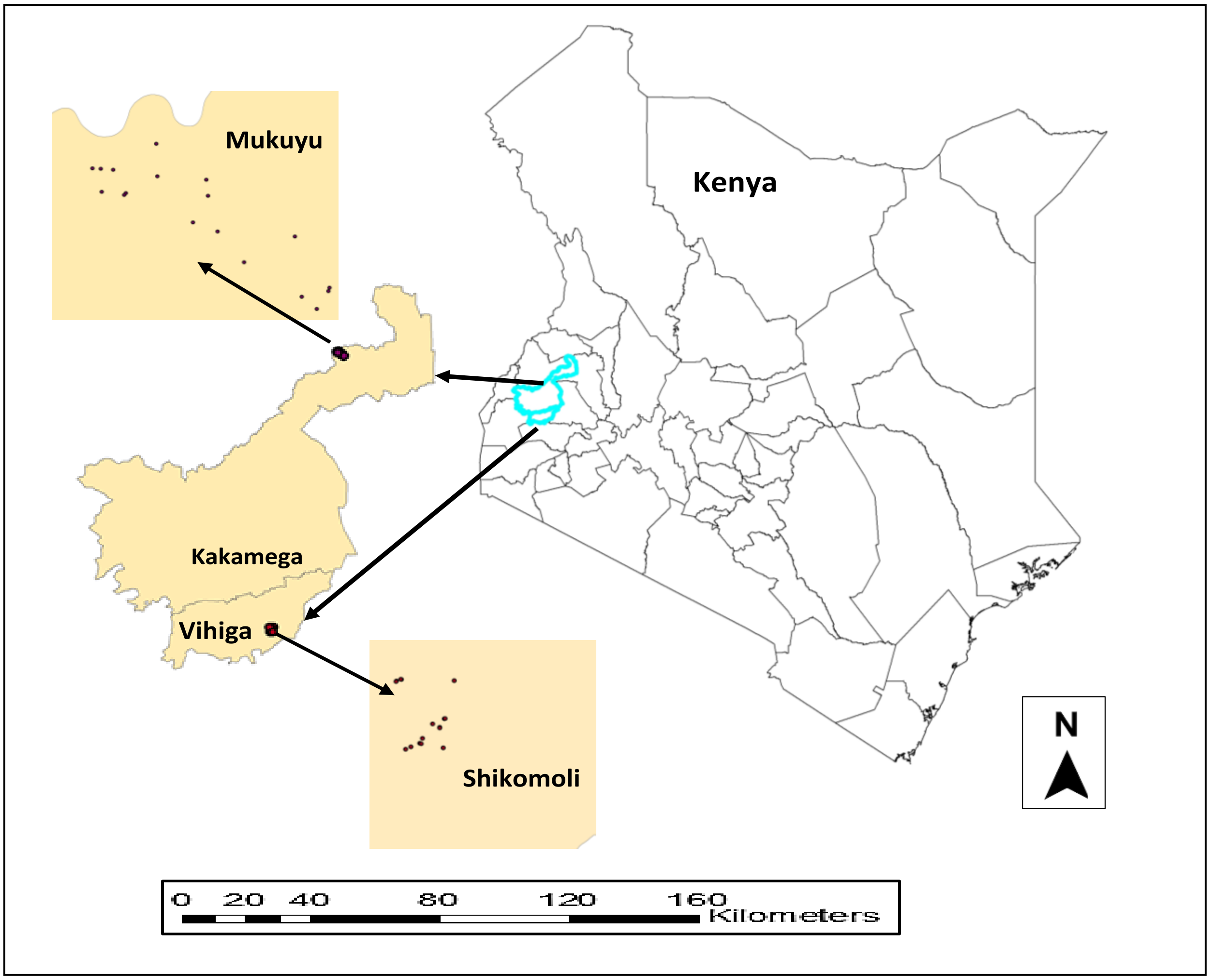


Figure 4.1: Location of the on farm trial plots in Mukuyu and Shikomoli of Kakamega and Vihiga Counties

Mukuyu village is located in Kakamega County (0°, 38’N, 35°, 41’E) at an altitude of 1600 m above sea level and in the agro-ecological zone Upper Midland 4 (UM4) with well suited climatic and soil conditions for production of maize (FAO, 2007). The annual rainfall ranges between 1000 and 1600 mm with a mean of 1450 mm. The rain is bimodal with long and short rains occurring between March-August and September-November, respectively while the rest of the months are partially dry. The daily temperature varies between 14 and 26℃ with a mean of 20℃. The dominant soils are Ferrasols, which are well drained, with Acrisols found in some places (Jaetzold et al., 2010).

Shikomoli village is located in Vihiga County (0˚ 4’ 19N, 34˚ 42’ 43E) at an altitude of 1400 m above sea level. The area is predominantly in the agro-ecological zone Upper Midland 1 (UM1) (Jaetzold et al., 2010). It experiences modified equatorial climate with high reliable annual rainfall of 1600-2000 mm (mean 1700 mm). The rains are well distributed and bimodal, showing two distinct seasons; long and short rains occurring in the months of February-July and August-December. The daily temperature ranges between 14 and 32^{o}c with mean temperature of 23^{o}C. The main soil types are Acrisols and Nitisols that are well drained, and Cambisols which are sandy, stony and moderately deep are also found in some places (Jaetzold et al., 2010). The rainfall amounts and distribution and temperature for Mukuyu and Shikomoli for the year 2016 and 2017 are shown (Figure 4.2).

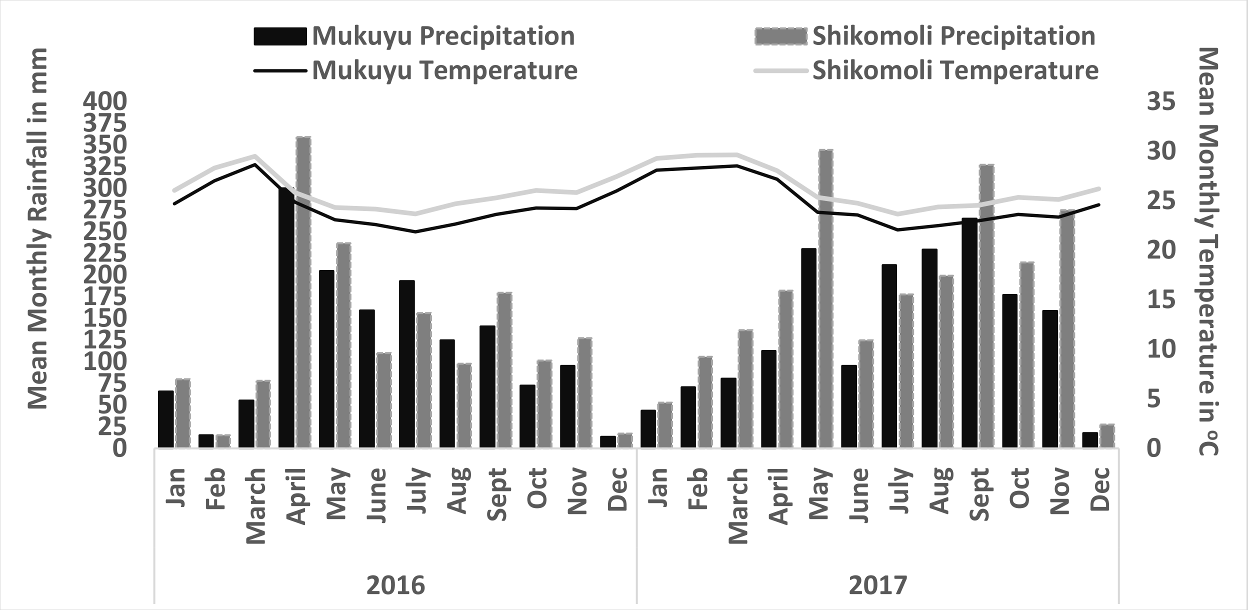


Figure 4. 2: Monthly precipitation and temperature for Mukuyu and Shikomoli
Data source: Kenya Meteorological Department 2016 and 2017 (KMD, 2018)

Soil fertility improvement measures practiced in the sites vary between farms and include application of inorganic and organic fertilizers, planting of cover crops, legumes, crop residue utilization, use of terraces and grass strips. Utilization of highly nitrogenous fertilizers (diammonium phosphate, urea and calcium ammonium nitrate) for maize production has been increasing gradually due to the government subsidy programme which started in 2007 (Mavuthu, 2017). On average total fertilizer use is estimated at150kg/ha and 120kg/ha in Mukuyu and Shikomoli with large variation between individual farms. However, the rate of fertilizer use is still below the recommended 250 kg/ha requirement for maize growth (Oseko and Dienya, 2015). Some farmers use only planting fertilizer, while others in addition, apply top dressing fertilizer after first weeding and just before the silking and tasseling stages. Organic manure utilization is low and is hampered by low availability, especially in Mukuyu where land holdings are big, and low quality resulting from poor preparation and storage methods. Crop residue is used as fodder or fuel, and in a few cases farmers leave the crop residue in the soil to enhance soil fertility. The gentle and nearly steep terrains that characterize farms in Shikomoli motivate occasional use of trenches and raised beds to reduce the effect of heavy runoff on soils during the rain period. Other erosion control measures include planting of grass strips. The variability in soil fertility measures has contributed to differences in levels of soil nutrients such as nitrogen, phosphorus, potassium, sulphur and boron, which occur below the critical thresholds required for maize production (Munialo et al., 2019). Tillage operations such as use of tractors when soils are extremely wet contribute to creating hardpans which reduce the rooting depth and the ability of plants in the uptake of water and soil nutrients. These factors have contributed to cause yield variation and yield gaps. The plant density is also low and contributes to increased maize yield gaps.

4.2.2 Description of treatments and layout

The experiment was established at the onset of rainfall in the first and second week of March 2017. On-farm omission trials with 4 treatments were laid out using the randomized complete block design replicated on 33 farms (18 in Mukuyu and 15 Shikomoli) spatially distributed within the sites (Figure 4.1). The farms represented the blocks (Figure 4.A.1 and 4.A.2-see Appendices). The treatments included; best farmer management, low nutrient (i.e. no top dressing), delayed weeding and low plant density. The management practices tested were determined from a previous survey which identified most contributing factors to maize yield gaps which included crop nutrition, plant density and weed control (CHAPTER 3). The best management (treatment 1) which acted as the positive control treatment, represented practices identified from the 10% (90th percentile) high yielding farms in each study village (Table 4. A.1). Treatment 1 had high nutrient levels; supplied through fertilizer application at 3 splits (Table 4.1), timely weed control done 3rd and 6th weeks after germination and high plant density achieved using spacing of 75 cm by 20 cm. Treatments 2, 3 and 4 received management practices on nutrient supply, weed control and plant density at lower intensity compared to treatment 1, to represent farmer average conditions. Treatment 2 was supplied with less nutrients where fertilizer was only applied at planting (Table 4.1). Treatment 3 had 1st and 2nd weeding delayed to the 5th and 7th weeks after germination. Treatment 4 had lower plant density (plant spacing of 75 cm by 25 cm). Maize varieties H628 and H6215 suited for Mukuyu and Shikomoli, respectively, were planted. Plot size varied depending on field size but was on average 50m^2 and 28m^2 in Mukuyu and Shikomoli respectively.

Table 4.1: Nutrient levels applied at planting and top dressing per hectare for the different treatments

Site	Time of nutrient supply	Best management (Treatment 1)	Low nutrient (treatment 2)	Delayed weeding (treatment 3)	Low plant density (treatment 4)
Mukuyu	Planting	34kg N 87 kg P	34 Kg N 87 Kg P	34 Kg N 87 Kg P	34 kg N 87 Kg P
	3rd week Ear initiation	87 kg N		87 Kg N	87 Kg N
	8th week Two weeks before Tasseling and silking periods	49.4Kg N		49.4 Kg N	49.4 Kg N
Shikomoli	Planting	28.3 Kg N 73.6 Kg P	28.3 Kg N 73.6 Kg P	28.3 Kg N 73.6 Kg P	28.3 kg N 73.6 Kg P
	Ear initiation (3rd week)	73.6 Kg N		73.6 Kg N	87 Kg N
	6th week Two weeks before Tasseling and silking periods	41.6Kg N		41.6Kg N	41.6 Kg N

4.2.3 Data collection

Data was collected on chlorophyll content (SPAD readings), maize vigour, maize density, maize height, weed coverage and weed height at three key maize development stages namely; at the ear initiation (stage 1), ear determination (stage 2) and at the silking and tasseling (stage 3). These measurements were done at 28, 50, 78 and 28, 43, 60 days representing the three maize development stages for Mukuyu and Shikomoli respectively because of the differences in altitude. Maize density was determined by counting all the maize plants in each plot. Maize height was measured on 10 randomly chosen plants by a method described by O'Keeffe (2009). Chlorophyll levels were determined using a SPAD 502 chlorophyll meter (Minolta Camera Co., Osaka, Japan) by taking readings of the youngest fully developed leaf from 15 randomly selected plants per study plot, at approximately 25% from the leaf tip and leaf base. Crop vigor indicated disease incidences was determined through observations on 10 randomly selected plants and with the aid of a Likert scale FAO, (2010), 1 to 5; 1-Almost completely infested with pest or diseases (75-100%), 2-Heavily infested with pests or diseases (50-75%), 3-Moderately infested with pest or diseases (10-50 %), 4-Few plants infested with pest or diseases(less than 10%); 5-No disease or pest. Weed height was measured on 10 randomly selected weeds using a meter rule. Flowering status was determined by counting the number of maize crops that had tassled among 10 randomly selected plants at the start of tasseling period. Maize yield was determined on a dry matter basis using a method described by Tobergte and Curtis, (2013). Maize was first harvested from each treatment plot. All the grain was shelled, cleaned, weighed and recorded in kg. A sub-sample approximately 200g was put in an envelope and labelled and transported to a laboratory where it was oven dried at 75^0C for 24 h and weighed. This sub sample was used to determine moisture content and to calculate the yield as kg dry matter for the harvested area. The determined yield in each treatment plot was then extrapolated in tonnes per hectare.

4.2.4 Statistical analysis

Data analysis was done using the Linear Mixed Effects Model (LMER) Bates et al. (2015) to determine the effect of treatment, site and maize development stage and the interactions on the measured variables. Treatment, site and development stage were the fixed effects and the location (farm) was set as random effect. The chi-square test was then performed to test the significant effect of treatment, stage and farm on the measured variables using the Anova function. The emmeans function was then implemented to estimate the means of the measured variables at different treatments, sites and maize development stages. Tukey's honest significant difference (HSD) test was used for treatment mean separations with the threshold probability level set at $p \leq 0.05$. The analysis was done in R software. For each variable the following model equation was used.

Y =Treatments + Stage + Site + (Stage × Treatment) + (Site × Treatment) + (Site × Stage) + (Site × Treatment × Stage) + (1|Farm); Model Equation 1

Where y was the measured variable such as chlorophyll (SPAD values) or maize vigour or height or yield.

Treatments; best management, low nutrient, delayed weeding and low plant density

Stages; Stage 1- ear initiation stage, Stage 2-ear length determination, Stage 3- tasseling and silking.

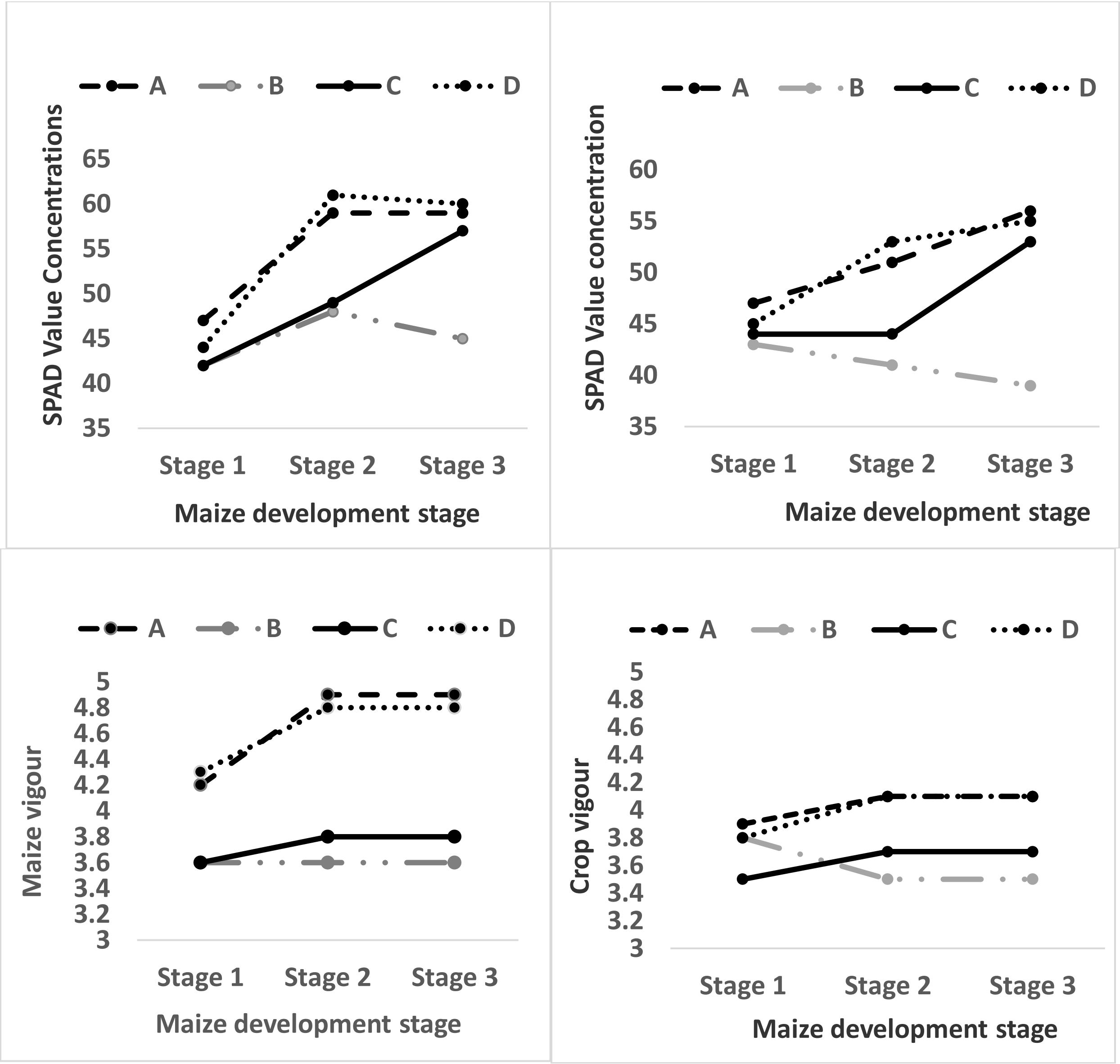
Sites; Site 3-Mukuyu and Site 4- Shikomoli.

Farm was where the treatments were laid and which was treated as the random variable.

4.3 Results

4.3.1 Crop performance and weed pressure at key maize development stages and at different sites

The chlorophyll content (SPAD values) and maize vigour were significantly affected by treatment, site and maize development stage (Figure 4.3) and (Table A.4.3- see Appendices). Treatment by stage and site by stage interactions also affected SPAD values, while maize vigour was affected by site by stage interaction (Figure 4.3) and (Table A.4.3- see Appendices). The SPAD values and maize vigour for the best management, low nutrient and delayed weeding treatments were high at stage 1. In stage 2, the SPAD values for the low nutrient and delayed weeding treatments were significantly lower than the best management and low density treatments. In stage 3, the best management, low density and delayed weeding treatments had high SPAD values than the low nutrient plots (Figure 4.3) and (Table 4.A.2- see Appendices). Maize vigour for the best management and low plant density plots was high at stage 2 and 3 compared to the delayed weeding and low nutrient treatments. There was an increase in SPAD values and maize vigour for the best management, delayed weeding and low plant density from stages 1 to 3. While the no top dressing treatment the SPAD values increased from stages 1 to 2 and decreased in stage 3 for Mukuyu, and in Shikomoli, the values decreased across the stages. Maize vigour remain constant in Mukuyu across the 3 stages, while in Shikomoli, it decreased in stage 2 and remained constant in stage 3.The plots in Mukuyu had higher SPAD values and maize vigour than Shikomoli (Figure 4.3) and (Table 4.A.2-see Appendices).



Legend: A-best management, B-Low nutrient C-delayed weeding, D-low plant density. Stages include; stages 1, 2, 3 and represent the maize development stages in Mukuyu (left) and Shikomoli (right)**.**

Figure 4. 3: The mean values of SPAD concentration and maize vigour at different treatments

Maize density was significantly affected by treatment, stage, site, treatment by stage, treatment by site by stage effects (Table 4.A.3-see Appendices). There was decline in maize density as maize advanced from stages 1 to 3 (Figure 4.4) and (Table 4.A.2-see Appendices). The decline was highest for the low nutrient and delayed weeding treatment in stage 2 and 3. Maize density at stage

2 and 3 was lower in Shikomoli than in Mukuyu. Maize height was affected by treatment and site effects (Table 4.A.3-see Appendices). The best management and low density treatment had taller maize plants compared to low nutrient and delayed weeding treatments. Mukuyu had taller maize plants compared to Shikomoli (Figure 4.4).

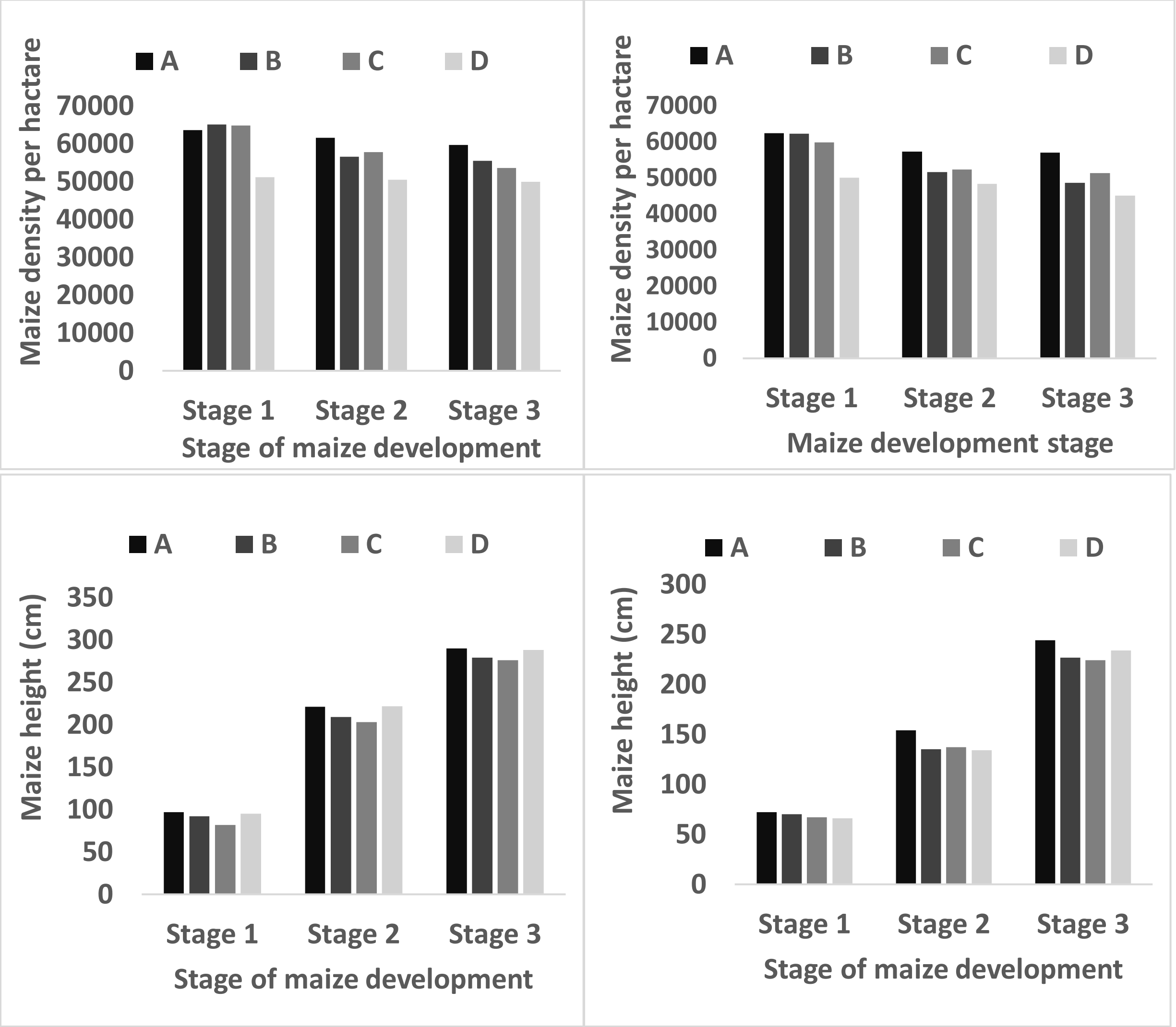


Figure 4.4: The mean values for maize density and maize height at different treatments
Legend: A-best management, B-Low nutrient C-delayed weeding, D-low plant density and maize development stages in Mukuyu (left) and Shikomoli (right)

Weed cover was affected by treatment and treatment by maize development stage while weed height was affected by treatment, stage and treatment by stage effects (Table 4.A.3-see

Appendices). Delayed weeding treatment showed much higher weed height and cover at stage 1, but decreased over time. At stage 2 and 3, the low plant density treatments showed higher weed cover in Mukuyu and weed height in Shikomoli compared to other treatments (Figure 4.5).

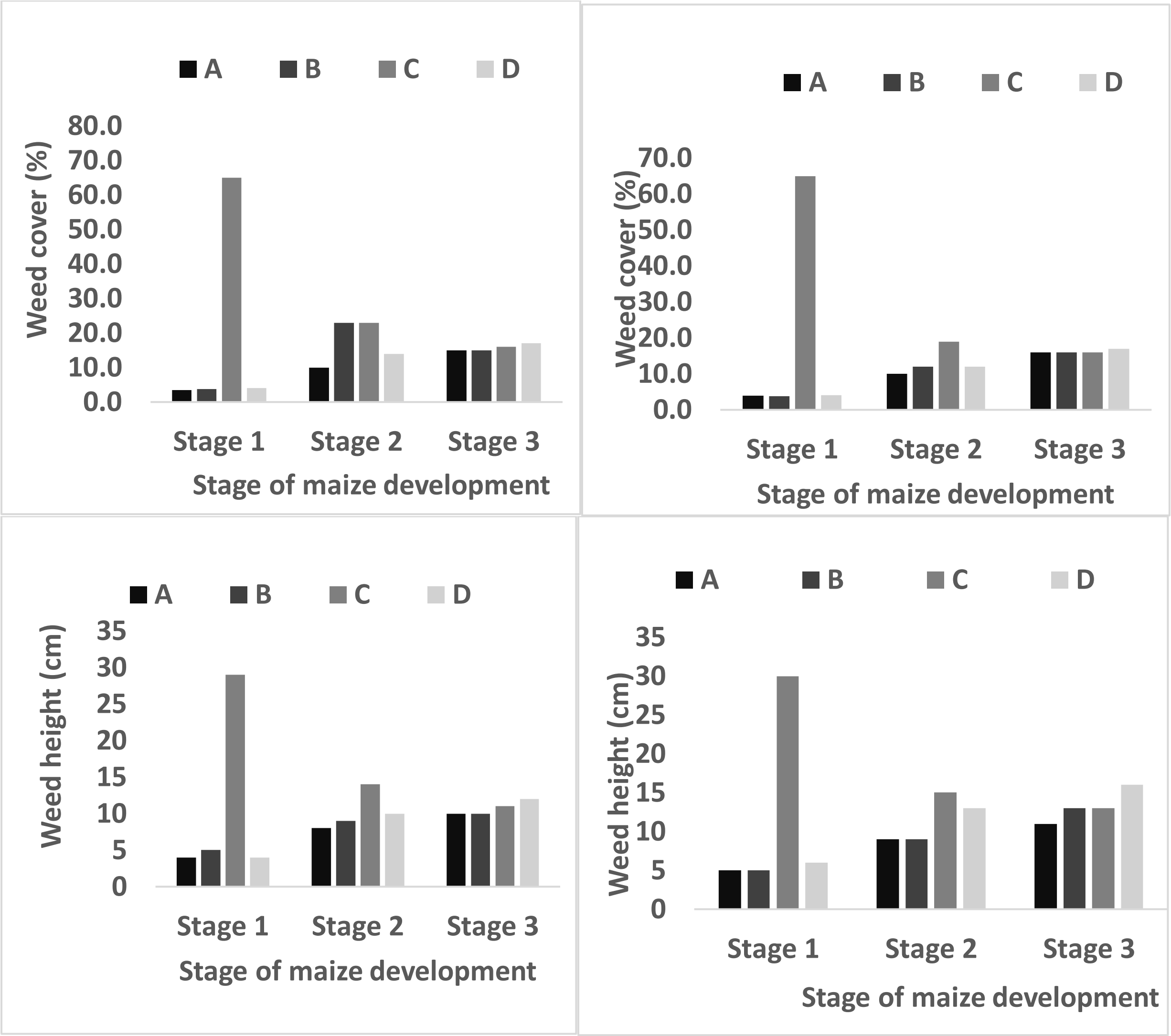


Figure 4. 5: The mean values for weed cover and weed height at different treatments
Legend: A-best management, B-Low nutrient C-delayed weeding, D-low plant density and maize development stages in Mukuyu (left) and Shikomoli (right)

Flowering was significantly affected by treatment (Table 4.A.3-see Appendices). At the silking stage, best management and low plant density had high percentage of flowering maize plants at averages of 76% and 80% for Mukuyu and 78%, and 80% respectively for Shikomoli. While the no low nutrient and delayed weeding plots had low flowering percentages (Figure 4.6).

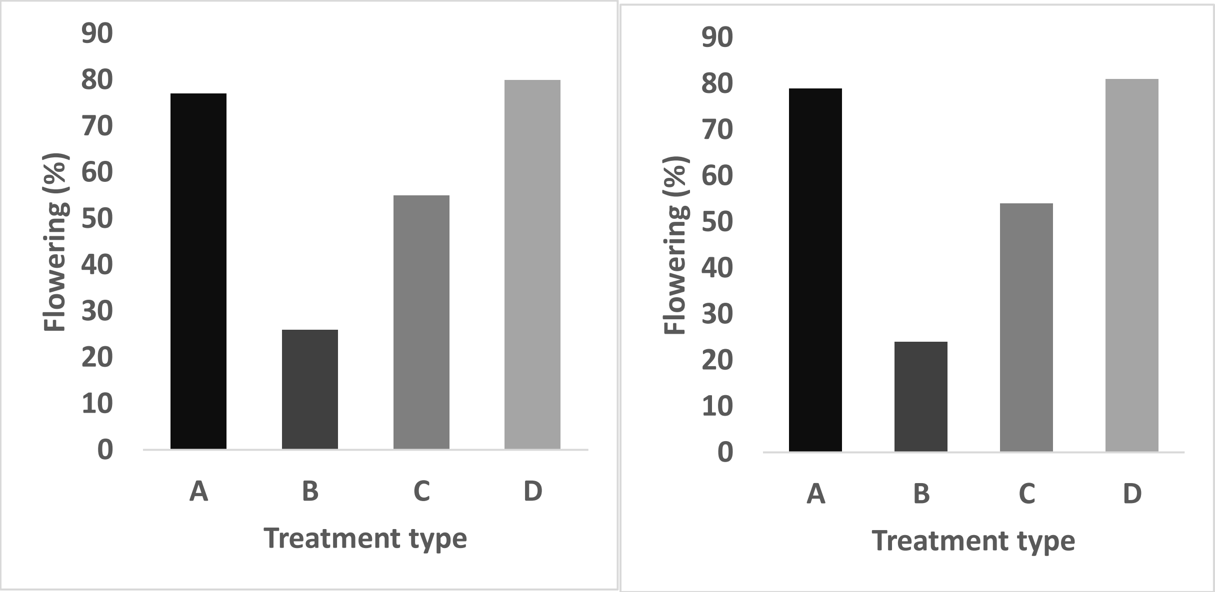


Figure 4. 6: The mean values for flowering status at different treatments
Legend: A-best management, B-Low nutrient C-delayed weeding, D-low plant density and maize development stages in Mukuyu (left) and Shikomoli (right)

4.3.2 Maize yields at different treatments and sites

Maize yields significantly differed between treatments and site (Table 4.A.4- see Appendices). Highest maize yields averaging 7.8 and 6.6 t ha^{-1} were recorded for the best management treatment in Mukuyu and Shikomoli respectively. The lowest yields of 4.3 and 3.5 t ha^{-1}were recorded on plots which received no top dressing. This represented 45 and 47% reduction in yields compared to the best management treatment for Mukuyu and Shikomoli respectively. Significantly lower yields were also recorded on treatments with delayed weeding and low plant density compared to the best management treatment. Yields in Shikomoli were lower than in Mukuyu (Figure 4.7). The best management treatments resulted in yield increments of 35% and 27% for Mukuyu and

Shikomoli respectively compared to the 10% top yielding farms from the past survey findings (Figure 4.A.3-see Appendices).

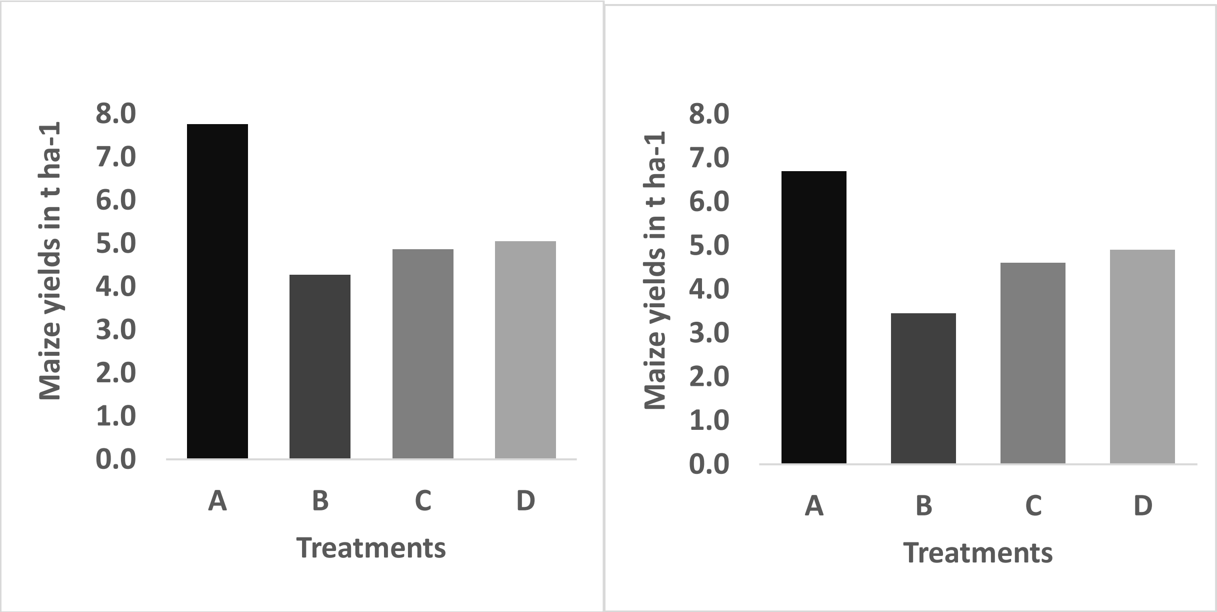


Figure 4. 7: The mean yield of maize in t ha^{-1} for the best management, no top dressing, delayed weeding and low plant density

Legend: There was a significant effect of treatment, site and treatment × site effect (p=0.0001) on yield values for Mukuyu (left) and Shikomoli (right) are 0.22 and 0.24 respectively.

4.4 Discussion

4.4.1 Management-derived variations in crop performance and yield

There were differences in crop performance and yield between the best management treatment and the average management in treatments with lower management intensity in terms of nutrient inputs, weed management, and plant density. The findings coincide with Vogel and Below, (2018) who has shown high yield through a combination of different management practices such as plant spacing and fertilizer use on maize yield. The findings also agree with (Getnet et al., 2016), who found variation in yields on comparing best- and average-performing farmers based on nutrient use efficiency. Declining SPAD values (Figure 4.3) in the low nutrient treatment indicated declining nitrogen availability as the maize matured, which increased the risk of delayed flowering (Figure 4.6). Environmental factors such as low nitrogen affect and delay silking (Borrás and Vitantonio-mazzini, 2018). This may have caused unsynchronized emergence of silks and anthers, resulting in barrenness in some plants contributing to low yields (Li, 2013). Plant density decreased in the low nutrient treatment because of lodging at later maize stages (Figure 4.4). Bian et al. (2016) has also reported the lodging in maize plants caused by wind at late stages of development. This could have been caused by low soil nutrient levels resulting in weak maize plants that were susceptible to strong winds, which are common, especially in Shikomoli, in May-June. Maize in the low nutrient treatment also had low crop vigor (Figure 4.3) and showed signs of Spodoptera frugiperda (fall armyworm) attack, which is common in the region (Sisay et al., 2019).

The treatment with delayed weeding beyond early maize stages resulted in high weed incidence (Figure 4.5), which smothered maize plants still in delicate early stages. Delayed weeding also resulted in weed overgrowth, especially couchgrass in Mukuyu. This made weeding challenging and more maize plants being uprooted during weeding, which could have contributed to reducing plant density in the delayed weeding treatment. Amiri et al. (2014) also showed the negative effect of high weed intensity on plant density. The high weed intensity also competed for nutrients, which resulted in low soil nutrition, manifested by low SPAD values at stage 3, in the delayed weeding treatment. Similarly, (Hakim et al., 2013) found low chlorophyll values with increased weed competition. Wilting of maize plants and increased incidence of pests and diseases also occurred in the delayed weeding treatment, illustrating the multiple and interconnected effects of high weed incidence at different stages of maize development. Effect of early weed infestation on yield have been reported previously (Reid et al., 2014). High weed incidence at an early stage of maize growth is a sign of inadequate land preparation (Munialo et al., 2019).

The low maize density treatment had reduced maize count per unit area, an indication of low cob yield and also less residue production, which in the longer term will contribute to low soil fertility. The low plant density treatment also experienced high weed prevalence at later maize stages (Figure 4.4). This was an indication of conditions favorable to weeds, such as increased light interception resulting from wider maize spacing (Abouziena, 2008).

The higher yields in best management plots derived from a combination of different management practices, i.e., increased nutrient supply through topdressing, high plant density, and timely weed control (Figure 4.A.3). Fertilizer was applied in split doses, at planting, ear initiation, and tasseling-silking, which are critical yield-determining stages in maize. Others have also shown good crop performance and high maize yields with application of nitrogen fertilizer at planting, jointing, pre-filling, and post-filling stages (Yan et al., 2017). Weeding before the first and second topdressing in best management plots reduced weed infestation, which resulted in less competition and made soil nutrients available for assimilation into photosynthetic products and yield components. High plant density helped increase the ability of maize to compete with weeds and eased the task of weed management. It also resulted in a high number of ears per unit area. The combination of different management practices in BFMP therefore gave an interactive effect that led to high yield (Vogel and Below, 2018).

4.4.2 Yields under best management

Heterogeneity in agro-ecological and economic conditions in smallholder farming systems, coupled with difficulties in deciding which potential yield to use as a reference yield, make it challenging to estimate yield gaps (Affholder et al., 2013). Accurate estimation of potential yields can help design site-specific crop management strategies that enhance yields (Banerjee et al., 2014; Ittersum et al., 2013). Past studies have estimated potential yield as the 90th percentile in data collected from farmers' fields (Munialo et al., 2019; Silva et al., 2017). Obstacles relating to weather patterns and access to inputs may, however, prevent farmers from achieving high yields, leading to underestimation of potential yield (van Ittersum et al., 2013). This study improved on past studies estimating potential yield at farmer level by integrating survey data into on-farm trials replicated over 33 farms. The yields obtained in the best management treatment were on different soils and topography representing smallholder farming conditions. Applying management practices from the 90th percentile yields (top-yielding farms from previous season) on smallholder fields in the next growing season, characterized by higher rainfall (Figure 4.2), resulted in higher yields (Figure 4.6). Maize production under BFMP involved differences in soil and topography, interactive management effects, and various weather conditions, and the obtained yields were consistent with potential water-limited yields reported for Kenya (GYGA, 2018). The approach used in this study could be used for estimating yield gaps in areas with differing agro-ecological conditions, and for designing soil and crop management interventions to improve yields.

4.4.3 Innovative strategies to enhance yields on smallholder farms

Past surveys have identified maize density, soil nutrition, and weed pressure as causes of yield variation on smallholder farms, without considering the timing of these factors relative to different stages of maize development (Banerjee et al., 2014; Tittonell et al., 2008). Survey data have spatial and temporal limitations by failing to account for certain constraints to yield (Anderson et al., 2016). This study improved on past studies by integrating survey findings into on-farm omission trials to determine spatial variations in critical factors at different stages of maize development. On-farm trials enabled collection of data on crop development status such as chlorophyll content (SPAD values) and maize plant height, vigor, density, and flowering status. This helped assess within-season causes of yield variation by comparing best management to lower intensity management conditions. On-farm trials thus helped overcome temporal data limitations common with survey methods, resulting in more robust findings.

The high yields obtained in the best management treatment show the potential for yield increments on smallholder farms if limitations related to plant nutrition, crop density and weed control are tackled timely and in combination. This will require awareness among farmers of the need to ensure that management practices such as fertilizer application and weed control are timed to coincide with key physiological maize stages. Access to extension services will be important in raising farmers´ knowledge level in these matters, and access also to inputs and tools for e.g. facilitated weed management necessary for farmer implementation. Investing in technologies such as mobile phone applications that illustrate different macro- and micro-nutrient deficiencies could help smallholder farmers identify and correct crop nutrient deficiencies. Sufficient and timely application of fertilizer at early maize stages is also needed to achieve strong, healthy maize plants that are more resistant to invasive pests and diseases.

Smallholder farms mostly operate under rainfed conditions, and yield variability is likely to result from seasonal factors (Anderson et al., 2016). The higher yields in BFMP plots in Mukuyu and Shikomoli than on the 90th percentile farms in previous surveys, despite the same management practices, reflected such inter-annual variability, probably resulting from the higher precipitation in 2017 than 2016 (Figure 4.2). This suggests that having early information on the likelihood of sufficient seasonal precipitation before the growing season begins can help increase investment in maize production to achieve high yields and avoid wasting fertilizer in dry seasons. Investing in weather forecasts and early warnings of weather related shocks at local level is also important, as it would enable farmers to make informed decisions on the timing of agronomic practices such as fertilizer application. Innovative approaches, such as having weather applications installed on farmers' mobile phones, can be helpful.

4.5 Conclusion

The study examined variations in maize performance and yield and determined potential yield by integrating past survey findings on best farmer management practices (BFMP) into on-farm omission trials. The results revealed high between-farm yield variations resulting from crop nutrition status, weed management, and plant density. The potential to increase maize yields on smallholder farms by enhancing measures aimed at improving soil nutrition, controlling weeds, and ensuring optimal plant density was demonstrated as well as the importance of timely management actions. These measures included increased availability of fertilizer, early weed management, maintenance of optimal plant density. Yields in the best management treatment represent a proxy for potential yield from farmers' fields in different contexts and with varying weather conditions. They can therefore be used as a reference for estimating yield gaps on smallholder farms and serve as a basis for designing measures striving to reach the potential.

CHAPTER FIVE

THE EFFECT OF THE INTERRELATIONSHIP BETWEEN SOCIO-ECONOMIC, MANAGEMENT AND BIOPHYSICAL FACTORS ON MAIZE YIELD GAPS IN WESTERN KENYA

Abstract

Yield gaps in staple crops such as maize continue to persist on smallholder farms. Past research has shown that factors such as biophysical, management and socio-economic, influencing maize yield gaps have been studied singly. As a result recommendations provided to enhance maize yields are based on a single factor, that is, either biophysical or management or socio-economic. However maize yields are affected by a combination of biophysical, socio-economic and management factors. The study used a multi-disciplinary approach where socio-economic, management and biophysical factors influencing maize yield gaps on smallholder fields were studied together. The aim was to investigate important factors and the interactions influencing yield gaps in order to provide an integrated approach in enhancing maize yields. The study was conducted in two contrasting sites; Mukuyu and Shikomoli of Western Kenya with regard to agro-ecology, market access and population density. Household surveys, soil sampling and analysis, as well as field measurement were used to collect socio-economic, management and biophysical factors on 170 maize fields identified from 70 households randomly selected from the two sites. Regression methods; Generalized Linear Mixed Models (GLMM) well as Factor Analysis (FA) were used for data analysis. Results of FA showed socio-economic as the overarching factors influencing maize yield gaps over management and biophysical factors in both the study sites. The GLMM also identified consistent factors across the two agro-ecologies that influenced maize yield gaps and they included; education, age, membership to groups, access to markets, family labour, gender, credit facility, maize variety, crop residue utilization insitu, quantity of organic and inorganic fertilizer use. The GLMM analysis also showed a two level significant interaction effect of the factors which was agro-ecology specific. In Mukuyu the number of inorganic fertilizer use and gender of the operator as female significantly interacted to increase yield gaps. In Shikomoli, membership to groups and timeliness in execution of agronomic activities such as land preparation, planting and weeding significantly interacted to reduce maize yield gaps. Conjunctively studying socio-economic, management and biophysical results in overarching and agroecology-specific interactions influencing maize yield gaps, hence the need for an integrated soil and crop management system to enhance yields.

Key words: Integrated approach, Yield gaps, Agroecology-specific factors, Overarching factors

5.1 Introduction

Factors influencing yield gaps in staple crops such as maize ranging from socio-economic, biophysical, and management have been studied singly (Affholder et al., 2013; Poeydebat et al., 2013; Tittonell et al., 2006; Yengoh, 2012). As a result, recommendations provided to enhance maize yields are based on a single factor. However crop yields are affected by a combination of biophysical, socio-economic and management factors (Sumberg, 2012). An integrated approach based on socio-economic, biophysical and management practices is needed to reduce yield gaps in staple crops such as maize and achieve food security sustainably (Meng et al., 2013)

Yield gaps in staple crops such as maize are highly dependent on the interaction between biophysical, agronomic and socio-economic factors which operate both at micro and macro levels (Tittonell et al., 2008). Having information on soil conditions prior to farming can increase knowledge on fertilizer use and result in optimal yields (Chen et al., 2018). Takele et al. (2015) found pricing of inorganic fertilizer to influence soil fertility. In addition, educational background of the farmers may influence the manner in which the limited resources are allocated to farm management activities (Oduro-ofori et al., 2015). Access to market and capital by the smallholder maize producers directly affect farmers' ability to acquire and use inorganic fertilizer and certified seeds (Salami et al., 2010). Farmer characteristics such as availability of labour, determine the timing and frequency of agronomic operations such as weeding (Banerjee et al., 2014). At a macro level inadequate information, poor market accessibility, lack of credit facilities, land tenure insecurity and weak access to research and education have been shown to affect smallholder application of field management practices thus impacting crop productivity (Oluoch-kosura, 2010). The inclusive analysis of these factors and the interactions requires the application of multivariate regression where linear and non-linear interrelationships can be unraveled (Tittonell et al., 2008).

Multivariate models such as the Generalized Linear Mixed Model are able to robustly handle highly skewed and unbalanced data over classical linear models without subjecting the data to linear transformation which might result in interaction effects being lost (Manning, 2007). They also have the advantage of including random effects as a predictor and they describe an outcome as the linear combination of fixed effects and conditional random effects associated with subjects and items (Hui et al., 2016). Other methods such as factor analysis with the ability to regroup and summarize measured variables can describe a general overview of the most important factors influencing maize yields gaps (Yong and Pearce, 2013). Heterogeneity on smallholder farms with regard to agro-ecology, farming systems and weather conditions requires a combined analysis to divulge into causes of yield gaps (Loon van et al., 2019). More often classical linear regression methods have been used in analysis of the causes of maize yield gaps (Krupnik et al., 2015; Mackay et al., 2011; Neumann et al., 2010; Sawasawa, 2003). Linear regression models might fail to account for certain factors influencing yield gaps. Combined, GLMM and FA methods could provide robust findings on socio-economic, management and biophysical factors and the interaction influencing maize yield gaps on smallholder farms over classical linear models.

The study focus was to improve the understanding of causes of maize yield gaps by analyzing the interrelationship between socio-economic, management and biophysical factors using different multivariate regression methods. The study sought to answer two questions; How do management, biophysical and socio-economic factors interact to influence maize yield gaps? Which are the most important factors; socio-economic, biophysical, management factors influencing maize yield gaps?

The main objectives was to provide an understanding of the socio-economic, biophysical and field management factors and interactions as a scope for improving maize yields on smallholder farms.

The specific objectives were; 1. to characterize socio-economic, biophysical and field management factors influencing maize yield gaps on smallholder farms 2. to investigate the interactive effect of socio-economic, management and biophysical factors on maize yield gaps

5.2 Materials and methods

5.2.1 Description of the study sites

The study was conducted in Mukuyu and Shikomoli villages of Kakamega and Vihiga Counties in Kenya shown CHAPTER 3. The two study areas were chosen due to the agro-ecological potential with regard to production of maize which is dominating food crop in Kakamega and Vihiga as well as neighboring Counties in Western Kenya (Ali-Olubandwa et al., 2011). Mukuyu has good agro-ecological potential with regards to soil characteristics which are favorable for maize production and low population density compared to Shikomoli. While Shikomoli has fairly good market access, poorly developed soils and high population density (Karugia, 2003).

Mukuyu village is located in larger Kakamega County (0^0, 38'N, 35^0, 41'E) at an altitude of 1600 m above sea level and in the agro-ecological zone Upper Midland 3 (UM3). The annual rainfall ranges between 1000 and 1600 mm with a mean of 1450 mm. The rain is bimodal with long- and short-rains occurring between February-August and September-November, respectively, while the rest of the months are partially dry. In the long-rain season mainly maize and beans are grown. The maize varieties with a long maize growing period ranging from 6-8 months are preferred due to high yielding characteristics (One Acre Fund, 2016). The daily temperature varies between 14 and 26^0C with a mean of 20^0C. The dominant soil are Ferrasols, which are well drained, with Acrisols found in some places (Jaetzold et al.,2010).

Mukuyu village covers approximately 3.56 km^2 with an estimated population of 1,664 people. Women and youth constitute the larger portion of the population. The population of youth below 18 years is 54%, adult men 21% and adult women 24% (KNBS, 2010). About 90% of the district's population lives in the rural areas mainly participating in farming activities (KNBS, 2010). The average farm size is 2.5 hactares (Karugia, 2003). The main cash crops are maize; which acts as a cash and food crop, coffee, sugar cane and sunflower. Other food crops include beans, sweet potatoes, cassava, sorghum, millet, vegetables and fruits. Other farming activities include poultry keeping, dairy, apiculture and fish farming (Wandere and Egesah, 2015).

Shikomoli village is located in Vihiga County (0^0 4’ 19N, 34^0 42’ 43E) at an altitude of 1400 m above sea level. The area is predominantly in the agro-ecological zone Upper Midland 1 (UM1). It experiences modified equatorial type of climate with high reliable annual rainfall of 1600-2000 mm (mean 1700 mm). The rains are well distributed and bimodal, showing two distinct seasons; long- and short-rains in the months of February-July and August-December. Maize and beans are grown in both seasons. The daily temperature ranges between 14 and 32^oC with a mean temperature of 23^oC. Largely, the soils are Cambisols which are sandy, stony and moderately deep. Other soil types include Acrisols and Nitisols (Jaetzold et al., 2010).

Shikomoli village has a higher population density compared to Mukuyu. The village covers an area of 1.37 km^2 with an estimated population of 2,923 people. Proportion of population by gender is as follows; children and youth below 18 years 57%; adult women 23% adult men 19% (KNBS, 2010). The average farm size is 0.4 hectares with few large scale farms of approximately 1.6 t hactares (Karugia, 2003). The main food crops produced are maize, beans, sweet potatoes, sorghum, finger millet and groundnuts. Short season certified maize varieties are preferred that approximately last between 4-5 months during the long rain season. Farmers also grow indigenous maize varieties during the short rain season as these are presumed to be drought tolerant as less rainfall is received during this season in comparison to the long rain season. The cash crops include tea, coffee and horticultural crops. Other agricultural activities are dairy cattle, dairy goat, goats, sheep and poultry (MEMR, 2013). Market accessibility in Shikomoli is averagely good compared to Mukuyu which has poor road connectivity with an average distance of 6 and 20 km to the nearest all weather road respectively (Karugia, 2003).

Fertilizer use in the study sites is on average low because of the financial constraint farmers face. Other impeding factors to fertilizer use include; inaccessibility to markets due to poor roads and inadequate knowledge on fertilizer use; amount, frequency and timing (Mavuthu, 2017; Sheahan et al., 2012). Organic fertilizer use is also still low (Ndwiga et al., 2013). Both family and hired labour is used for agricultural production with women being more involved and in some cases the youth (KNBS, 2010). The sites have low cultivated land size, as land under maize cultivation is decreasing because of a shift to enterprises that are considered more productive for income generation than maize. Farmers in Shikomoli and Mukuyu are increasingly growing trees and sugarcane respectively on farms that originally were used for maize production (MEMR, 2013).

5.2.2 Conceptual framework guiding the study

The conceptual framework guiding the study is illustrated in figure 5.1. Maize productivity which is the measure of outputs per unit of inputs used in production, is affected by a combination of socio-economic, biophysical and management factors. The utilization of these factors can result in high or low productivity, the difference being maize yield gaps which could either be small or large in a given location. Therefore, maize yield gaps are caused by the interaction of socio-economic, biophysical and management practices. The extent to which these factors cause maize yield gaps varies.

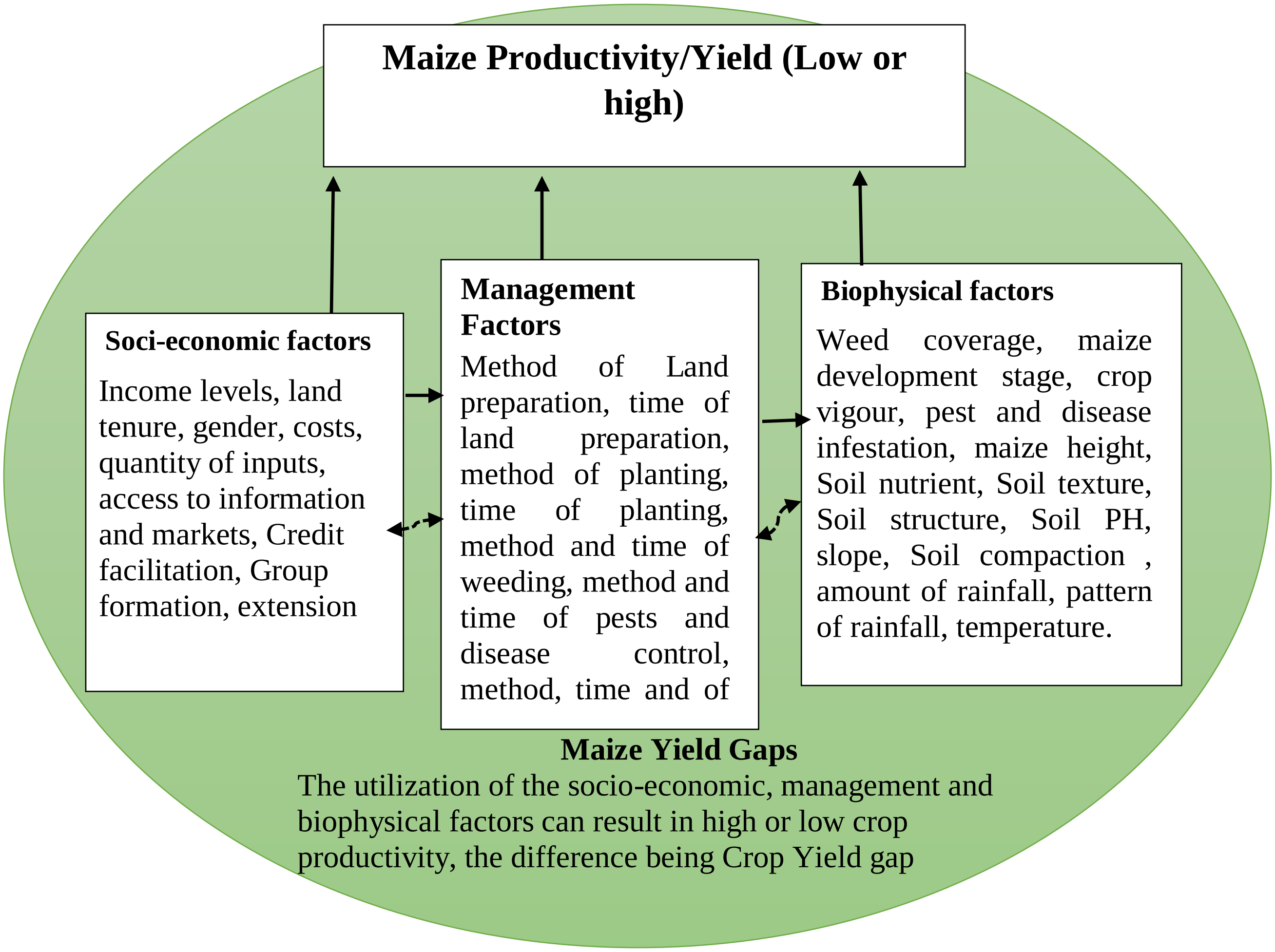


Figure 5. 1: Conceptual framework

Source: Authors own development

5.2.3 Collection of biophysical, field management and socio-economic factors

Biophysical, field management and socio-economic factors as well as maize yields (Table 5.1) were collected using various methods namely; soil sampling and analysis, field measurements and household surveys. This was done on 70 randomly selected households; 35 households in Mukuyu and 35 in Shikomoli. The selection and sampling of households and maize fields is explained in CHAPTER 3.

Table 5.1: Socio-economic, biophysical and management variables collected

Variable	Description
Education level of operator	Formal education received by the farm operator; categorized as – Illiterate (0-3 years of study); primary (4-8 years); secondary (9-12 years) and tertiary (above 12 years).
Household size	Number of members in a family who share food from a single source.
Land size	Size of the cultivable land in hectares (whether inherited, leased or purchased) owned by the farmer.
Total labor	Total family and hired labor used for all operations related to maize cultivation (man hour per hectare); categorized as 1-Family, 2-Hired, 3-Family+Hired.
Distance to market	Physical distance (km) from the household to farm output market.
Age of operator	Length of time in years the person responsible for the daily farm activities has lived.
Gender of farm operator	The state of the farm operator being male=1; or female=2.
Decision making	The person in charge of farm operation and management decision making. Categorized as 1-Plot operator, 2-Household head; 3-Spouse; 4-Adult male; 5-Adult female child; 6-Others.
Family involvement in farm activities	Proportion of family members taking part in actual farm operations such as cultivation, planting, weeding etc.
Membership to groups	Belonging to a group; farming group, women group, men group, welfare group, credit and savings group
Hired labour	Proportion of hired labour taking part in actual farm operations such as cultivation, planting, weeding etc.
Credit facility	Whether the farmer has access to formal institutional credit; Yes=1; No=0.
Input use	Quantity of inputs used such as inorganic, organic and seed
Timing of farm operation	The time when the farm activities such as land preparation, planting, weeding, fertilizer application, harvesting is done.
Soil and land conservation measures	Erosion control planting of trees, using grass strips, trenches, gabions, cover crops crop residue utilization measures such as leaving crop residue in situ, grazing in situ, using as mulch, using as animal feed
Soil properties	Soil nutrients; Boron (B), Calcium (Ca), Carbon (C), Copper (Cu), Iron (Fe), Nitrogen (N), Molybdenum (Mo), Magnesium (Mg), Phosphorus (P), Potassium (K), Sulphur (S) and Zinc (Zn)., cation exchange capacity, Exchangeable acidity, soil PH, Compaction status, slope, Erosion status and etc. Determination of these properties described in CHAPTER 3.
Biophysical factors	Maize density, maize height, weed pressure, chlorophyll values, maize yield. Determination of these variables described in CHAPTER 3.

5.2.4 Quantifying maize yield gaps

Maize yield gaps were quantified as described in CHAPTER 3.

5.2.5 Data analysis

Descriptive statistics were done to generate frequency distribution tables showing differences in maize yields based on the determined variables. The Leaps package (Regression Subset Selection) found in R was then utilized to identify variables that were likely to predict maize yield gaps using the exhaustive subset technique (Lumley, 2017). Leaps performed an exhaustive search using an efficient branch-and-bound algorithm to identify a set of variables for predicting maize yield gaps. Several sets having different variables were identified respectively. The best selected set was the one that had the highest Bayesian Information Criterion (BIC) (Figure 5.A.1, 5.A.2, 5.A.3, 5.A.4, 5.A.5, 5.A.6) (see Appendices). The GLMM using the Penalized Quasi Likelihood (PQL) technique was used to identify significant factors and the interactions causing maize yield gaps (Hui et al., 2016). The GLMMs are generated from the well-known generalized linear model (GLM) by adding random effects to the linear predictor (Xia et al., 2018). The PQL was used because the technique is able to handle non-normal data, unbalanced design and crossed random effects. The PQL is used to estimate the regression effects and the variance component of the random effects (Xia et al., 2018). The analysis involved both random and fixed effects. The random effects were the plot Identification numbers (ID) while the fixed effects were a set of variables that had lowest BIC selected by leaps package as described above. Factors influencing maize yield gaps identified by GLMM model were then subjected to FA using varimax rotation to regroup variables into small easily interpretable sets based on variance (Yong and Pearce, 2013). The implementation of factor analysis was done with R statistics (Beaujean, 2014). Factor Analysis was used to summarize socio-economic, management and biophysical variables to identify most important factors influencing maize yield gaps, and help understand relationships and patterns.

5.3 Results

5.3.1 Household characteristics of the study sites

The average household size was 5 and 6 persons per household in Mukuyu and Shikomoli respectively. The proportion of males and females above 16 years was similar in Mukuyu and Shikomoli (Table 5.2). The population of children was high compared to adults in both the two sites with Shikomoli having a higher proportion compared to Mukuyu. Age of farm operator was proportionally higher in age class 55-69 years in both Mukuyu and Shikomoli. Illiteracy level of farm operator was markedly higher in Shikomoli compared to Mukuyu. Education among the farm operators was very low in Shikomoli compared to Mukuyu. In Shikomoli, the percentage of female farm operators was higher than in Mukuyu. Distance from households to the nearest markets was long in Mukuyu compared to Shikomoli. Households in Mukuyu had larger land size and incomes levels compared with the ones in Shikomoli.

Table 5.2: Household characteristics of the study sites

		Mukuyu		Shikomoli	
	Class	Frequency (%)	Maize yield (t/ha)	Frequency (%)	Maize yield (t/ha)
Household size	Males above 16 yrs	32.50	3.23*	31.20	2.73*
	Females above 16 yrs	31.90	3.45*	29.00	2.43*
	Children (<16 yrs)	35.60	1.98	39.80	1.50
Age of farm operator	25-39	13.92	5.20*	7.68	2.76*
	40-54	33.01	3.51	33.25	2.15
	55-69	47.11	2.99	43.50	2.39
	70-84	5.96	2.96	17.57	1.86
Education level of operator	Illiterate (0-3)	10.67	3.18	46.60	2.04
	Primary (4-8)	34.28	2.84	29.21	2.63
	Secondary (9-12)	26.46	3.45	22.41	2.12
	Tertiary (above 12)	28.59	4.26*	1.77	3.19*
Gender of operator	Male	43.82	3.44	21.07	2.24
	Female	56.18	4.48	78.93	2.21
Distance to market (Km)	0-5	20.04	3.27	47.70	2.28*
	above 5	79.98	3.72	53.30	1.03
Income levels in $	0-100	41.57	3.0	54.00	2.28
	101-200	38.20	3.3	38.00	2.20
	201-300	8.98	3.2	5.00	1.82
	301-400	7.86	3.1	1.00	0
	401-500	n/a	n/a	2.00	1.92
	901-1000	3.30	5.1	n/a	n/a
Total land size in acres	0-2.5	40	2.90	92	2.2
	2.6-5.5	30	3.77	8	2.4
	5.6-7.5	7	2.13	n/a	n/a
	7.6-10.0	21	3.51	n/a	n/a
	10.6-15	2	5.33	n/a	n/a

* Correlation significant at 5% probability, n/a implies there were no response in the category

Source: Own computation from Yield gaps survey data 2016/2017

5.3.2 Variability of maize yields and yield gaps in Mukuyu and Shikomoli

Maize yield varied more in Shikomoli indicating higher variability compared to Mukuyu (Figure. 5.2 and 5.3). Productivity of maize ranged between 0.1 t ha^{-1} and 7.13 t ha^{-1} in Mukuyu and 0.01 t ha^{-1} and 5.14 t ha^{-1} in Shikomoli. The average yields were 3.3 t ha^{-1} and 2.2 t ha^{-1}, while maize yield gaps averaged 1.8 t ha^{-1} and 2.6 t ha^{-1} for Mukuyu and Shikomoli respectively.

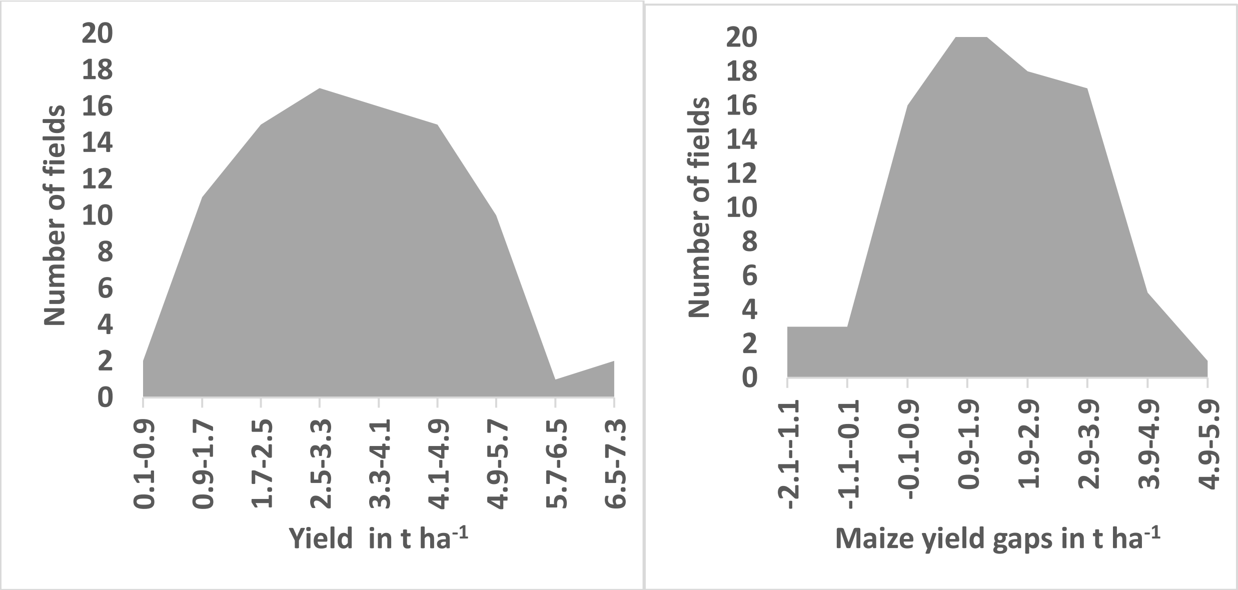


Figure 5. 2: Distribution of maize yield and yield gaps in Mukuyu

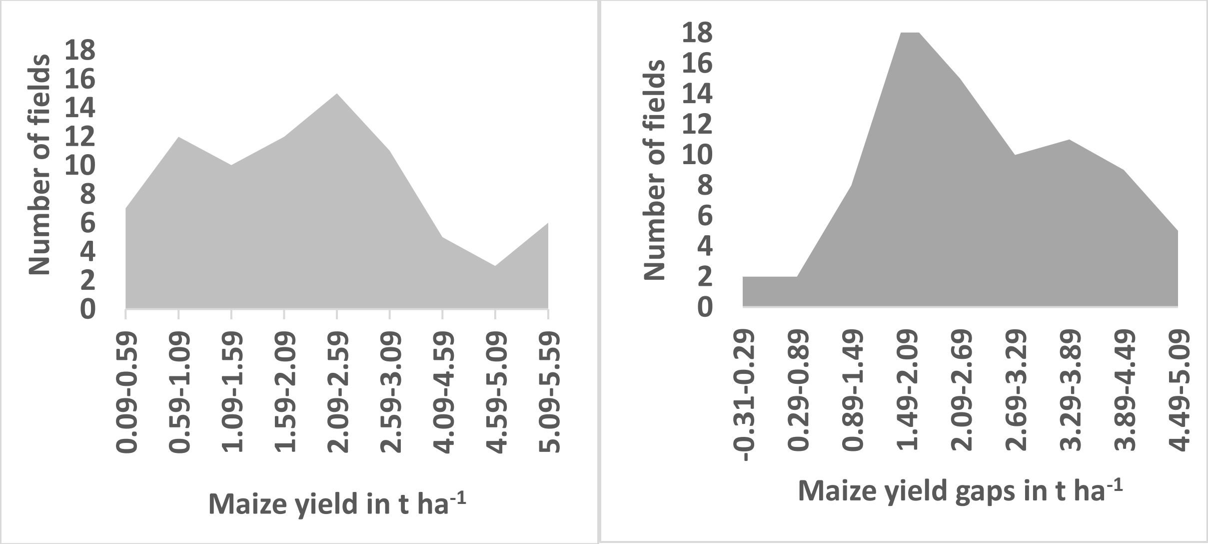


Figure 5. 3: Distribution of maize yield and yield gaps in Shikomoli

5.3.3 Factors influencing maize yield gaps in Mukuyu

Both socio-economic, management and biophysical factors significantly influenced maize yield gaps (Table 5.3). The GLMM analysis showed that in Mukuyu, maize yield gaps increased with age of operator, operator as female head and number of females involved in farm operations as shown by the positive coefficient and R values (Table 5.3). Maize yield gaps reduced when the operator was well educated, used credit facility in farming, had large total land size, when cost of transport was low and when the farm operator belonged to a social group as shown by the negative coefficient and R values. Maize yield gaps increased with the following management factors; use of grass strips as erosion control measures and crop residue utilization as animal feed. Maize yield gaps reduced with increased use of inorganic and organic fertilizer, early land preparation at least 1 month to onset of rainfall and use of hybrid seed variety. Biophysical factors causing high yield gaps were low Zn and P, high sand content, high weed height and weed coverage at stage 1 and low SPAD readings (chlorophyll content) at stage 3.

The interaction of socio-economic, management and biophysical factors also significantly influenced maize yield gaps. Maize yield gaps reduced with interaction of low weed cover at stage 1 and phosphorus, early land preparation and maize density at stage 3, organic fertilizer use and cation exchange capacity, depth to compact layer and crop residue utilization in situ. However, the interaction between the number of inorganic fertilizer use and female head as farm operator together with weed coverage and crop residue utilization as animal feed increased maize yield gaps.

Table 5.3: The GLMM analysis showing important socio-economic, management, biophysical factors and the interactions influencing maize yield gaps in Mukuyu.

	Coefficient value	R-value	P-value
Socio-economic factors			
Age of farm operator	0.04	0.22	0.005*
Education level of farm operator	-0.16	-0.28	0.004*
Gender of farm operator as female	0.87	0.24	0.040*
Credit facility	-1.09	-0.18	0.037*
Family labour	-0.47	-0.15	0.046*
Number of females involved in farm operations	0.41	0.24	0.061*
Total land size owned by the farmer	-0.08	-0.13	0.001*
Cost of transport from household to the market	-0.003	-0.27	0.010*
Membership to farmer groups	-0.12	-0.11	0.002*
Management factors			
Total quantity of inorganic fertilizer	-0.07	-0.28	0.002*
Quantity of farmyard manure	-0.08	-0.10	0.032*
Time of land preparation 1 month to onset of rain	-1.29	-0.37	0.003*
Use of hybrid variety (certified seeds)	-2.24	-0.43	0.004*
Erosion control using grass strips	1.28	0.60	0.004*
Crop residue utilization as animal feed	0.66	0.10	0.006*
Biophysical factors			
Weed Coverage in stage 1	0.033	0.529	0.0000*
Extractable Zinc (Zn)	-0.144	-0.173	0.0001*
Weed height in stage 1	0.058	0.333	0.0016*
SPAD readings in stage 2	-0.061	-0.897	0.001*
Phosphorus (P)	-0.023	0.200	0.0101*
Sand content	0.0029	0.386	0.0507*
Depth of compaction at 500 psi	0.11	-0.46	0.02*
Interactions			
Low weed coverage at stage 1*Phosphorus	-0.001	-0.15	0.05*
Early land preparation *Maize density at stage 3	-0.001	-0.33	0.009*
Number of organic fertilizer* Cation exchange capacity	-0.065	-0.57	0.03*
Number of inorganic fertilizer*Role of operator as female head	0.46	0.15	0.04*
Depth of compaction at 500 psi*crop residue use insitu	-0.18	-0.45	0.001*
Weed coverage at stage 1*crop residue utilization as animal feed	0.033	0.11	0.004*
Intercept	5.82	0.99	0.0000

Legend: GLMM is Generalized Linear Mixed Model. The * indicate p values significant at 0.95 test statistics. The interactions were either between socio-economic and management, or socio-economic and biophysical or management and biophysical factors.

Factor analysis showed that socio-economic factors loaded on factors 3, 4, 5 and 7 and had a high cumulative variance of 0.28 compared to biophysical factors and management factors that had a total variance of 0.15 and 0.05 respectively in Mukuyu (Table 5.4). Biophysical factors loaded on factors 1 and 2 while management factors loaded on factors 10. Both socio-economic and management with a shared variance of 0.12 loaded on factors 6 and 8, while biophysical and management loaded on factor 9 and had a shared variance of 0.05.

Table 5.4: Factor loading of biophysical, socio-economic and management factors based on shared variance in Mukuyu

Variables	Factor 1 (B)	Factor 2 (B)	Factor 3 (S)	Factor 4 (S)	Factor 5 (S)	Factor 6 (S-M)	Factor 7 (S)	Factor 8 (S-M)	Factor 9 (B-M)	Factor 10 (M)
Biophysical										
Available P	0.80									
Available Zn	0.91									
Sand (%)									0.60	
Weed cover in stage 1		0.95								
Weed height in stage 1		0.60								
Socio-economic										
Age			-0.96							
Education			0.38	0.35	0.47			0.38		
Role of operator			0.36		-0.36					
Credit facility								-0.50		
Distance to Market				0.90						
Number of female involved in farm operations						0.90				
Female involvement in organic fertilizer use							0.98			
Management										
Quantity of inorganic fertilizer					0.73					
Maize variety								0.70		-0.60
Time of land preparation										0.43
Erosion control										0.37
Crop residue utilization						-0.36			0.42	
SS Loading	1.64	1.40	1.34	1.24	1.19	1.13	1.13	1.10	0.95	0.93
Proportion variance	0.08	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.05	0.05
Cumulative variance	0.08	0.15	0.22	0.28	0.34	0.40	0.45	0.51	0.56	0.60

Legend: S- B-Biophysical, Socio-economic and M-Management. Test of the hypothesis that 10 factors are sufficient. The chi-square statistics is 28.68 on 35 degrees of freedom. The p-value is 0.766

In Shikomoli, maize yield gaps were also influenced by socio-economic, management and biophysical factors as shown by the p values. Maize yield gaps increased when the farm operator was aged, decision making on farm operations was done by male head and when family members were involved in organic manure application, when maize varieties with a short length of growing season were planted, with high sand content and erosion status on maize fields as shown by positive coefficient and R values (Table 5.5). Yield gaps reduced when the farm operator was educated, the farm operator was a female head, more family members were involved in farm activities, credit was acquired to facilitate farm activities, farm operator belonged to a social group, distance from the household to the market was less, high utilization of organic manure, inorganic fertilizer, planting of medium duration maize varieties utilization, timely planting and weeding of maize, high weeding frequency and when crop residues were left in the maize fields to decompose, as shown by negative coefficient and R values. Maize yield gaps were also reduced with high maize density during harvest, maize height, cation exchange capacity, extractable boron, magnesium content and depth to compact layer.

The interaction of biophysical, socio-economic and management factors also influenced maize yield gaps. Membership to groups for the farm operator interacted with timely planting, weed control, and maize variety to reduce maize yield gaps. Distance to market interacted with the number of inorganic fertilizer use to reduce maize yield gaps. Maize yield gaps increased with the interaction of farm operator as female head and the number of weed control.

Table 5.5: The GLMM analysis showing important socio-economic, management, biophysical factors and the interactions influencing maize yield gaps in Shikomoli.

	Coefficient value	R value	P-Value
Socio-economic factors			
Age of operator	0.028	0.22	0.001*
Gender of operator as female head	-0.40	-0.24	0.047*
Education level of operator	-0.043	-0.45	0.050*
Family man-hours spent in farm operations	-0.007	-0.33	0.043*
Decision of farm operations made by male head	0.107	0.10	0.022*
Family involvement in organic manure application	0.084	0.10	0.047*
Credit facility	-0.517	-0.12	0.035*
Membership to farmer groups	-0.805	-0.11	0.001*
Distance from the household to the market	-0.078	-0.12	0.013*
Management			
Quantity of farmyard manure	-0.309	-0.10	0.037*
Quantity of inorganic fertilizer	-0.107	-0.23	0.024*
High frequency of weeding	-0.058	-0.67	0.027*
Timely planting	-0.1	-0.41	0.000*
Crop residue utilization insitu	-0.066	-0.51	0.000*
Medium maize variety (4-5 months)	-0.031	-0.73	0.003*
Short maize variety(3 months)	0.37	0.76	0.001*
Timely weeding	-1.08	-0.28	0.001*
Biophysical			
Maize density at harvest	-0.007	-0.63	0.0000*
Maize height at stage 3 (cm)	-0.006	0.450	0.006*
Cation Exchange Capacity	-0.943	-0.335	0.008*
Extractable Boron	-1.82	0.22	0.009*
Depth of compaction at 500 psi	-0.052	-0.732	0.007*
Magnesium content	-0.010	-0.440	0.008*
Sand content	0.118	0.397	0.007*
High erosion status	2.64	0.24	0.007*
Socio-economic*Management*Biophysical factors			
Membership to groups*Maize variety	-0.72	-0.40	0.019*
Membership to groups*Time of weeding	-0.016	-0.11	0.001*
Membership to groups*Time of planting	-0.12	-0.33	0.007*
Number of weed control*Membership to groups	-0.38	0.41	0.000*
Distance to market*Number of inorganic fertilizer use	-0.02	-0.20	0.04*
Operator as female head*Number of weed control	0.42	0.86	0.01*
Intercept	3.42	0.99	0.0000

Legend: GLMM is Generalized Linear Mixed Model. The * indicate p values significant at 0.95 test statistics. The interactions were either between socio-economic and management, or socio-economic and biophysical or management and biophysical factors.

Socio-economic factors loaded on factors 2, 4, 5, 6 and 7 and had a cumulative variance of 0.24, biophysical factors loaded on factors 1 and 10 and had a variance of 0.14 while management factors loaded on factors 9 and had a variance of 0.05 and. Both socio-economic and management loaded on factors 3 and had a shared variance of 0.06, while biophysical and socio-economic factors with a shared variance of 0.05 loaded on factor 8. Cumulatively, socio-economic, management and biophysical factors had a variance of 0.60 (Table 5.6).

Table 5.6: Factor regrouping of significant factors influencing maize yield gaps in Shikomoli

Variables	Factor 1 (B)	Factor 2 S	Factor 3 (S-M)	Factor 4 (S)	Factor 5 (S)	Factor 6 (S)	Factor 7 (S)	Factor 8 (B-S)	Factor 9 (M)	Factor 10 (B)
Biophysical factors										
Cation exchange capacity	0.92									
Magnesium	0.95									
Boron	0.41									
Sand content	-0.48									
Depth to compact layer										0.78
Maize density								0.51		
Socio-economic factor										
Age						0.72				
Membership to groups			0.35		0.73					
Education		-0.88				-0.35				
Role of operator		0.69		0.37		-0.40				
Decision of operator			0.56							
Credit facility				0.30	0.79					
Distance to Market			0.60							
Number of female involved in farm operations				0.79						
Man hours female							0.97			
Management factors										
Quantity of inorganic fertilizer use			0.53							
Quantity of organic fertilizer						0.40				
Number of weed control			0.35	0.59						
Maize variety								-0.61		
Time of land preparation									0.97	
SS Loading	2.44	1.56	1.50	1.46	1.43	1.34	1.26	1.25	1.22	0.98
Proportion variance	0.10	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.04
Cumulative variance	0.10	0.17	0.23	0.29	0.35	0.41	0.46	0.51	0.56	0.60

Test hypothesis that 10 factors are sufficient. The Chi square statistics is 44.73 on 42 degrees of freedom. The p-value is 0.358. S- B-Biophysical, Socio-economic and M-Management.

5.4 Discussion

5.4.1 Important factors influencing maize yield gaps

The high variance and commonality of socio-economic factors shows the high contribution of these factors to influence maize yield gaps over management and biophysical factors in Mukuyu and Shikomoli. Maize yield gaps decreased when the farm operator was more educated and male illustrating the importance of education and the role of gender in increasing farmers' production efficiency. Educational background of the farmer is important in accessing and using new input technologies such as new maize varieties and the use of chemical fertilizers (Oduro-ofori et al., 2015). There was increased inorganic and organic fertilizer use, utilization of long duration maize varieties which are high yielding, more crop residue retention on maize fields and use of erosion control measures among the educated and male farm operators (Figure 5.A.7 and 5.A.8- see Appendices).

Access to and use of family labor resulted in reduced maize yield gaps in Mukuyu and Shikomoli implying that farmers with a larger stock of workers may allow more specialization and the division of labor into distinct tasks so as to enhance efficiency use of resources (Bedemo et al., 2013). For instance, some respondents reported that they work together with the hired workers while they supervise their tasks to ensure such resources as fertilizer, seeds and time are used efficiently. The findings agree with Bedemo et al. (2013) who found use of family labour to have a high impact on farm output.

Large land size reduced maize yield gaps in Mukuyu showing the significant contribution of land in agricultural productivity. This corroborated with studies that have positively correlated the high maize production with land size (FAO, 2012; Hillocks, 2014). There was increased utilization of soil conservation techniques and credit facility use where land sizes were large (Figure 5.A.9-see Appendices). This could have resulted in improved soil fertility and subsequently high productivity. Ngwira et al. (2014) has also shown high adoption in use of conservation agriculture among farmers with large land holdings. Increased access to credit facility (Figure 5.A.9-see Appendices) could have aided in purchasing farm inputs such as seeds, fertilizer and labor. Moahid and Maharjan, (2020) have also shown increased the effect of credit facility on farming.

Distance to the market significantly influenced maize yield gaps showing the importance of market access in maize production. Maize yield gaps reduced when distance to the market was short. Households located close to the market have easier access to farm inputs such as seeds and fertilizer and this can enhance timely agronomic activities. There is also increased access to new technologies which are widely available in the market because of convergence of people from different backgrounds with diversity in farming knowledge (Neumann et al., 2010). Close proximity to markets also reduces transaction costs in the form of transport and the money can be channeled in accessing farm inputs (Li et al., 2018). The findings are incongruent with the ones of Romney et al. (2003) who showed high yields with reduced distance to market centres because of increased access to farm inputs and new innovations.

Access to credit facility significantly reduced maize yield gaps showing the contribution of credit facility in ensuring access to farm inputs. Other studies have shown the contribution of credit facility in enhancing access to farm inputs such as fertilizer and seeds which helps bridge the wide yield gaps among the producers and also helps in managing shocks and stress that are bound to occur during farming (Akwaa-sekyi, 2013; Owusu, 2017). Access to credit enables farmers to obtain improved seed, fertilizers and other necessary inputs needed to expand the scale of production (Akwaa-sekyi, 2013). There are different sources of credit that farmers in the study sites use to access money such as table banking and organizations like the One-Acre Fund. Some of the interviewed farmers observed that the high penalties imposed on the loan defaulters made it challenging to access credit. Vakis et al. (2004) similarly highlighted that the marginal contribution of credit to maize productivity is likely to be high in households that have a larger binding credit constraint than in those that are less constrained.

Farmers' involvement in group membership correlated to low maize yield gaps. Farmers who belonged to groups had access to credit services through table banking and this could have enabled them to acquire and use inorganic fertilizers and improved maize seeds. Group loans are perceived to be more secure and were much easier to acquire than bank loans. There was also a higher frequency of farms with timely land preparation and planting of maize among farmers who belonged to groups (Figure 5.A.10) see appendices. This could have resulted from formation of social associations within the groups which consisted of teams working together to carry out agronomic activities; land preparation and planting as indicated by some of the farmers that were interviewed. This enhanced the speed and volume of work and ensured timely operations thus contributing to higher maize yields among the participants and subsequently reduced the yield gaps. Mwaura (2014) similarly observed a significant increase in maize yield due to farmers' involvement in membership groups. Friis-Hansen et al. (2012) established that farmers' participation in membership groups enables them to get better access to innovation uptake, access to services and better engagement with markets. This was also observed by some of the farmers who were interviewed through key interviews.

Decisions made on farm operations by the male head increased yield gaps especially in Shikomoli showing the significant contribution of gender on agricultural productivity. Our informal discussions with the respondents revealed that some of the wives would have to consult the husbands in order to know when and which crop to grow for a given season. Some respondents revealed that the husbands have to travel from towns to approve whether to plant maize or not, and this causes delay and thus poor production. It was also established that women can only use the farmyard manure or hire labor force on permission from the household head. The study also found out that some of the men could even sell land without the knowledge of their wives or children. All these would adversely affect the maize productivity thus widening the yield gaps. Oino et al. (2014) also noted that women are generally reduced to making proposals whose decisions are ratified by men, but implemented by women. Bjornlund et al. (2019) observed that households relying on sole decision making mostly by male head have low farm income and this delays land preparation, planting, fertilizer application and subsequently results in low crop productivity.

Age of farm operator positively correlated with maize yield gaps depicting the low contribution of an aging population on maize productivity with regard to provision of labour for farm operations and utilization of soil conservation measures (Figure 5.A.9-see Appendices). Elderly farmers resist new technologies in agricultural production and tend to use old farming methods such as use of local maize varieties which contribute to low yields (Tang and Macleod, 2016). Even though an aging population might have knowledge about utilization of soil and water conservation measures, they have limited strengths to use these measures meant to improve soil fertility and increase maize production (Guo et al., 2015). The study also recorded a high proportion of aged farm operators probably mainly due to migration of a more youthful population to urban centres in search of employment (Table 5.2). The elderly farm operators and children left at the center of farm activities have to spend larger time balancing between the farm work and domestic chores. Tang and Macleod, (2016) have also found older farmers averagely being less productive than the youthful farmers and impacting negatively on crop productivity. Guo et al. (2015) also studied the impact of agricultural labor force age on maize productivity and concluded that the households with primarily youths have higher maize productivity than the households where the labor is mainly provided by elderly individuals.

5.4.2 Interactive effect of socio-economic and agronomic factors on maize yield variability

The significant contribution of socio-economic factors, management and biophysical factors to influence maize yield gaps shows the synergistic effects the factors can have in increasing maize productivity. Banerjee et al. (2014) and Loon van et al. (2019) have also shown the interacting influence of socio-economic, management and biophysical factors on maize yield gaps on smallholder farms. There was interaction between membership to groups and maize variety, time of weeding, time of planting, crop rotation and number of weed control which influence maize yield gaps. This can be attributed to increased peer shared learning. There was a high proportion of farms with timely land preparation and planting when farmers belonged to a group (Figure 5.A.10). Farmers' decisions in using certain farming techniques or farming procedures is not only based on economic considerations but also on the ability to interact with different social networks including neighboring farmers, extended families, agricultural input providers, traditional authorities and agricultural institutions among others (Hartwich and Scheidegger, 2010). Farmers discuss and accumulate knowledge and skills when they meet in groups on farming. Farmers interviewed said they learned and adopted farming practices such as use of high yield maize varieties, weeding methods, fertilizer application, manure preparation, combined use of inorganic and organic fertilizers and certain soil conservation measures including crop rotation, terracing and crop residue utilization. They used these practices to maximize the efficient use of agricultural input, such as fertilizers, as well as labor input.

Role of operator as female interacted with the number of inorganic fertilizer use and weed control to increase maize yield gaps showing the financial constraints women farm operators face in accessing farm inputs. Women farmers have difficulties accessing farm inputs such as fertilizer owing to low income status resulting from unemployment (Yengoh, 2012). They also lack access to properties such as land which could increase their chance of accessing credit facilities to enable them secure farm inputs (Yengoh, 2012). The findings relate to Engwali Fon, (2015) who has shown that women's involvement along the agricultural value chain activities such as land preparation, planting, weeding is hampered by inability to access and control farm resources and inputs. Although women are mostly involved in farming, they also play other household roles which take much of their time and hinders them from effectively concentrating in agronomic activities such as weeding (Yengoh, 2012).

Weed coverage interacted with phosphorus levels to reduce maize yield gaps showing the benefits of early weed control in ensuring available nutrients for crop use. Phosphorus levels when reduced to phosphites in the soil have been shown to suppress root growth of weeds (Achary et al., 2017; Wissuwa et al., 2017). This could have reduced competition of soil nutrients by weeds resulting in availability of the nutrients for maize growth which led to high yields. Early land preparation interacted with maize density at stage 3 showing the contribution of timely agronomic activities in ensuring high plant density at maturity. Early land preparation paves way for timely planting Erkossa et al. (2006) thus promoting early growth which allows plants to escape the adverse climatic conditions such as floods and wind. Number of organic fertilizer interacted with cation exchange capacity to reduce maize yield gaps showing the contribution of organic fertilizer in enhancing soil fertility and availability of macro and micro-nutrients in the soil (Bhatt et al., 2019). Depth of compaction interacted with crop residue use in situ to reduce maize yield gaps showing the positive contribution of crop residue in fields in promoting good soil structure (Searle and Bitnere, 2017). Weed coverage at the early maize development stage interacted with crop residue utilization as animal feed to increase maize yield gaps showing the negative effects of removing crop residue from maize fields in promoting high weed growth (Williams et al., 2016).

5.5 Conclusion

The study finds socio-economic as the overarching factors influencing maize yield gaps in both high and low agro-ecology areas over management and biophysical factors. The study also found the interaction between socio-economic, management and biophysical factors to be agro-ecology specific. In Shikomoli, membership to farmer groups positively interacted with timeliness of agronomic activities such as land preparation and weeding among others to reduce maize yield gaps. In Mukuyu, distance to market interacted with inorganic fertilizer use to influence maize yield gaps. Narrowing maize yield gaps will require general measures that address the socio-economic conditions of smallholder farmers such as improving market accessibility, relaying agricultural information, and encouraging family involvement in agronomic activities and motivating youth participation in agriculture among others, while simultaneously considering agro-ecology specific biophysical or management factors.

CHAPTER SIX

MICRO-SPATIAL ANALYSIS OF MAIZE YIELD GAPS AND PRODUCTION FACTORS ON SMALLHOLDER FARMS IN WESTERN KENYA

Abstract

Site specific land management practices taking into account variability in maize yield gaps could improve resource use efficiency and enhance yields. However, the applicability of the practice is constrained by inability to identify patterns of resource utilization to target application of resources to more responsive fields. The study focus was to map yield gaps on smallholder fields based on identified spatial arrangements differentiated by distance from the smallholder homestead, and understand field specific utilization of production factors. This was aimed at understanding field variability based on yield gap mapping patterns in order to enhance resource use efficiency on smallholder farms. The study was done in two villages; Mukuyu and Shikomoli with high and low agroecology regarding soil fertility in Western Kenya. Identification of spatial arrangements at 40m, 80m, 150m and 300m distance from the homestead on smallholder farms on 70 households was done. The spatial arrangements were then classified into near house, mid farm and far farm basing on distance from the homestead. For each spatial arrangement, landsat sensors acquired via satellite imagery were processed to generate yield gap maps. The focal statistics analysis method using the neighborhoods function was then applied to generate yield gap maps at the different spatial arrangements identified above. Socio-economic, management and biophysical factors were determined and maize yields estimated at each spatial arrangement. Results showed that heterogeneous patterns of high, average and low yield gaps were found on spatial arrangements at the 40m and 80m distance. Nearly homogenous patterns tending towards median yield gap values were found on spatial arrangements that were located at the 150m and 300m. These patterns correspondingly depicted field specific utilization of management and socio-economic factors.

Field level management practices and socio-economic factors such as application of inorganic fertilizer, high frequency of weed control, early land preparation, high proportion of hired and family labour use and allocation of large land sizes were utilized on spatial arrangements at 150 and 300m distances. High proportion of organic fertilizer and family labour use was utilized on spatial arrangements at 40 and 80m distance. The findings thus show that smallholder farmers preferentially manage the application of socio-economic and management factors on spatial arrangements further the homestead compared to fields closer to the homestead which could be exacerbating maize yield gaps. Delineating management zones based on yield gap patterns at the different spatial arrangements on smallholder farms, could contribute to site-specific land management and enhance yields. Investigating the value smallholder farmers attach for each spatial arrangement is further needed to enhance the spatial understanding of yield gap variation on smallholder farms.

Keywords: Spatial arrangements; Heterogeneous farms; Yield gap patterns; Site specific; Land management; Unequal Resource Allocation

6.1 Introduction

Smallholder farmers contribute approximately 75% of agricultural productivity and employment in many parts across the world (Salami et al., 2010). However, these farmers live on farms that are less than 2 hectares which are highly heterogeneous with regard to soil quality, productive assets and technology (FAO, 2015b). This diversity contributes to significantly higher maize yield gaps (the difference between yields in the 90th percentiles and other yields on smallholder farmers' fields) greater than 50% which continue to persist, causing food insecurity (Ray et al., 2013). Understanding yield gap variability and the causes can enhance site specific land management and improve yields (Adhikari et al., 2009). However, there is limited understanding of the causes of yield gaps at a micro-level and its causes. This is because studies on analysis of yield gaps at a local level have used methods such as surveys and field experimentation to understand factors limiting crop yields (FAO and DWFI, 2015; Licker et al., 2010). These methods have spatial data limitations where only a few randomly sampled units are used and fail to provide a comprehensive understanding of yield gaps at micro-level considering diversity which exist even within fields and plots (Lobell, 2013).

Remote sensing has the ability to overcome spatial data limitation and can complement surveys or field experimentations in understanding of yield gap variability (Lobell, 2013). Remote sensing has been successfully used to generate yield maps and enabled application of site specific management on homogenous farms (Battude et al., 2016; Prasad et al., 2016). A few studies have reported using remote sensing technology to map yield and yield gaps on smallholder farms (Burke and Lobell, 2017; Jin et al., 2017). However, diversity in topography, land sizes and management practices are still challenges hampering utilization of remote sensing on smallholder farms as far as the spatial understanding of yield gaps and the causes is concerned (Jin et al., 2017). Identifying patterns with nearly similar yield and yield gaps can help creation of management zones that could be managed uniformly thus promoting site specific land management (Kravchenko et al., 2005).

Site specific land management where inputs such as fertilizer and herbicides are applied within fields can reduce waste, maintain environmental quality and sustain crop production (Adhikari et al., 2009). Site specific land management premises on spatial dependence which assumes that near things are closely related than distant things (Zagórda and Walczykova, 2018). Smallholder farming systems are characterized by a unique arrangement where fields are located at close proximity to the homestead, at the middle and further end of the farm (Tittonell et al., 2006). These arrangements which are differentiated by distance from the homestead affect utilization of management and socio-economic factors and in occurrence of soil factors which affect yields (Tittonell et al., 2006). Mapping patterns of yield gaps at the different spatial arrangement can aid in investigating field specific management, soil as well as socio-economic factors and resource utilization patterns which can help guide site specific land management. This can be investigated using high resolution imagery and spatial analysis methods that could provide information at finer details (Chivasa et al., 2017).

High resolution multispectral imagery such as Landsat sensors acquired via satellite imagery are becoming plausible for investigating maize yield gaps on heterogeneous farming systems (Chivasa et al., 2017). Focal statistics analysis is one of the approaches that has been utilized to show fine detailed information in health studies (Kitron et al., 2006). Spatial analysis methods such as focal statistics analysis performs a neighborhood operation at different distances resulting in output raster maps where the value for each output cell is a function of the values of all the input cells that are in a specified neighborhood around that location (Zagórda and Walczykova, 2018). This function could help cluster patterns of yield gaps at the different spatial arrangements with respect to distance on smallholder farms which will provide a wide range of information and aid in field management decision making. Nonetheless, studies mapping yield and yield gaps at a local level are yet to consider the spatial arrangements found on smallholder farms.

The purpose of the study was to improve the spatial understanding of yield gaps and the causes using spatial arrangements found on heterogeneous farming systems complemented with survey data as scope for promoting site specific land management and enhancing yields. The use of spatial arrangements to map yield gaps on smallholder farms is a unique approach which contributes to the existing knowledge on use of remote sensing in mapping of yield gaps at micro-level. The study answers the following research questions; How do spatial arrangement on smallholder farms affect the distribution of maize yield gaps? Are management, socio-economic and biophysical factors inclined towards certain spatial arrangements?

6.2 Materials and methods

6.2.1 Description of the study sites

The study was conducted in two sites; Mukuyu and Shikomoli of Kakamega and Vihiga counties as shown in CHAPTER 3. The two villages were drawn from the Intensification of food crops agriculture Project in Sub Saharan Africa (Afrint). The initial selection and sampling of the sites is described by Djurfeldt et al. (2011). The sites have agricultural intensification potential yet dynamic in agro-ecology, population density and market accessibility. Mukuyu has high agro-ecological potential, however market accessibility is poor. Shikomoli has low agro-ecological potential with fairly good market access. The study sites are described in CHAPTER 3.

6.2.2 Collection of field data

Maize fields were identified and georeferenced with GPS from 70 households in Mukuyu and Shikomoli, respectively. Total number of maize fields was 170. After which a 4m by 4m area was marked at the centre of each identified maize field and acted as the study plot on which maize yields as well as biophysical, management and socio-economic factors were measured or linked.

The study identified three spatial arrangements; Near house (NH), Mid (M) and Far Farm (FF) Figure 6.1. This was done by the help of farmers. The NH pattern was a piece of land located close to the main household, M pattern was a piece of land located next to the NH but at a far distance from the main household and FF pattern was a piece of land located next to the M but at further distance from the main household. The distance from the homestead to the maize fields located at the near homestead, middle farm and far end was measured and recorded.

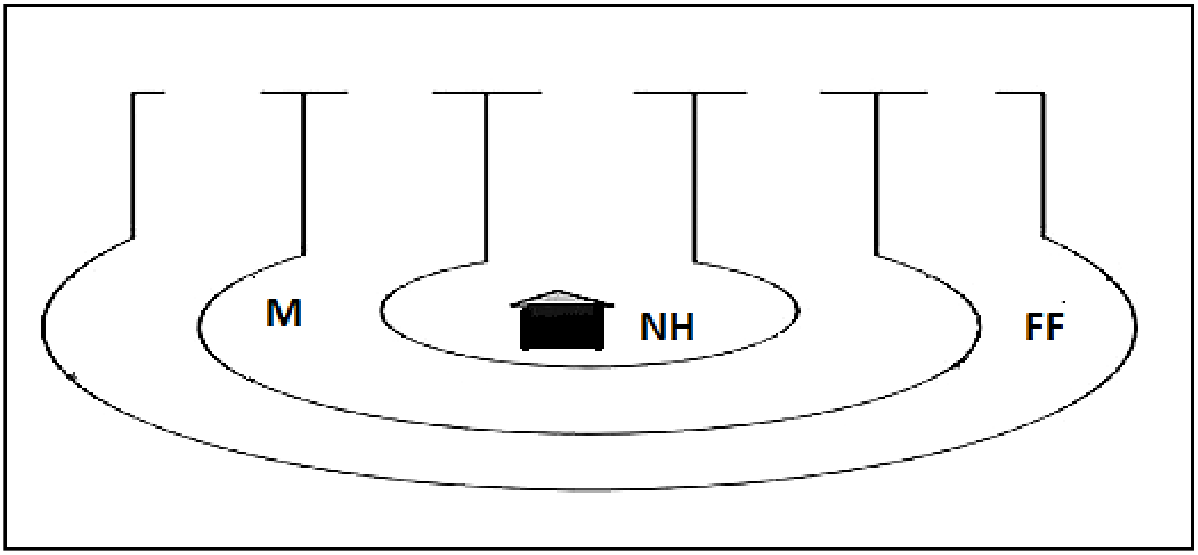


Figure 6.1: Pictorial representation of spatial arrangements found on smallholder farms
Legend: NH –Near House pattern, M- Mid Farm pattern, FF- Far Farm pattern
Source: Authors own development

Socio-economic, biophysical and management factors at each spatial arrangement that were collected are described in Table 6.1. Collection and determination of maize yield is described in CHAPTER 3.

Table 6.1: Socio-economic, Biophysical and Management factors collected

Variables	Description
Total land size (TTLs)	Size of the cultivable land in acres (whether inherited, leased or purchased) owned by the farmer.
Labor use	Family and hired labor used for all operations related to maize cultivation (man hour ha^{-1}); categorized as 1-Family, 2-Hired.
Gender of farm operator	The state of the farm operator being male (=1), or female (=2).
Credit facility	Credit acquisition for use on farm activities; Yes = 1, Otherwise = 0.
Inorganic	Quantity and frequency of inorganic fertilizer use; Yes = 1, Otherwise = 0
Organic	Quantity of organic fertilizer use; Yes = 1, Otherwise = 0
Land preparation	Time of preparing land for planting maize. 1-Before harvesting of the previous crop, 2-Immediately after harvesting, 3-2 Months before onset of rains, 4-1 month before onset of rains, 5-at the onset of rain, 6-1 week after the onset of rain, 7-2 weeks after onset of rains.
Maize variety	The duration of maize growth from planting to maturity; 1-long duration, 2-medium duration, 3-short duration
Frequency of weed control	Number of times weed control is done on the farm
Maize density	Number of maize plants per hectare. Determined through counting in the 4 m by 4 m plot quantified per hectare
Maize height	Measured on 10 randomly chosen plants in the 4 m by 4 m plot
Weed cover	Measured using a Likert scale as described in chapter 3
Weed height	Measured on 10 randomly chosen weeds in the 4 m by 4 m plot
SPAD values (chlorophyll content)	Measured using a SPAD 502 chlorophyll meter (Minolta Camera Co., Osaka, Japan) by taking readings of the youngest fully developed leaf from 15 randomly selected plants per study plot, at approximately 25% from the leaf tip and leaf base.
Soil properties	Soil nutrients; nitrogen (N), boron (B), phosphorus (P) determined by methods described in chapter 3
Slope	Measured using a Likert scale 1-3 where 1-steep, 2-gentle, 3-flat. Erosion values of 0-none, 1-slight, 2-moderate, 3-severe
Erosion status	Measured using a Likert scale 0–3 where 0—none, 1-slight, 2-moderate, 3-severe

6.2.3 Collection and processing of remote sensing data

The detailed procedure was involved and included; acquisition of satellite and Landsat 8 images, image preparation, processing of the images to yield maps and validation of yields. Two satellite images with four bands; blue-Green-Red-NIR obtained from TerroNor for Mukuyu and Shikomoli were acquired on June 19th, 2016 by GeoEye 1. Two Cloud-free Landsat 8 Collection 1 Level-2 on-demand Surface Reflection data were obtained through Earth Explorer. For Shikomoli, the image was taken on June 30th, 2016 while the image for Mukuyu was taken on June 14th, 2016. The images were projected to UTM projection (Zone 36N) using the WGS84 datum. Clouds were then removed from the Landsat 8 image using the image classification procedure in ArcGIS. The procedure identified a training sample set which was used to classify clouds and no clouds images. The cloud images was then used to mask clouds from the original fine resolution satellite image. Radiometric correction to surface reflectance was done to reduce errors using the method described by Burke and Lobell, (2017). The histogram matching process was undertaken for the 4 bands (Red-Green-Blue-NIR) in ERDAS Imagine software and this resulted in composite surface reflectance image with four bands.

6.2.4 Analysis of remote sensing data

Analysis of remote sensing data involved creation of yield and yield gap maps. Creation of yield maps involved several steps. First, the Green Chlorophyll Vegetation Index (GCVI) was calculated according to (Burke and Lobell, 2017). The Agricultural Production Systems sIMulator (APSIM) was then used to generate pseudo observations for yield (Burke and Lobell, 2017). Yields were then estimated following the SCYM methodology and yield maps drawn (Lobell et al., 2015).

The outputs were then isolated to only maize fields. This involved creating a land cover classification mask using random forests classification, following Burke and Lobell (2017). This was done in R following a tutorial by Ali Santacruz3. The random forest classifier was trained using the known locations of maize fields georeferenced earlier, as well as visual inspection of the fine resolution imagery to identify trees and urban or non-natural areas. The classified image was then used to mask out all pixels that were classified as non-maize from the estimated yield image.

Validation of the final maize yield maps was done by comparing the estimated yields to the observed yields, using adjusted R^2 to quantify the agreement between the two. The observed yields in kg/ha were calculated for each of the 4 x 4 m quadrants by dividing the yield in kg by 0.0016 ha (the size of each quadrant). The quadrants' yields were assumed to be representative of the yields for the entire plot. The estimated yields were calculated as the average yield for all of the pixels located within each plot. Outliers were removed from both the estimated and observed yields in order to ensure that both datasets met the normality assumption of linear regression analysis.

A three step process was used in mapping yield gaps within the village and involved; determining maize yield at 90th percentiles, creating constant yield map, creating yield gap maps at the different spatial patterns. Actual yields in the 90th percentile were determined using the method described by Bornmann et al. (2013) as shown in the formula;

$$K^{th} = L[\frac{(P-cfb)}{f}]U - L$$

Where:

K^{th} = the percentile to be calculated
L =the lower limit of the critical value within which the percentile will occur
P= (K/100) (n) where K is the percentile and n is the number of values in the distribution. P is the critical interval where the percentile (K) will occur.
C*f*b= the cumulative frequency of all intervals below the critical value but not including the critical value.
f=the frequency in the critical interval.
U =the upper limit of the critical value that will not be included in the critical interval.

The 90th percentiles yield values identified for each site were then used to create a constant yield map using the raster creation tool in the spatial analyst of arc gis. Yield gap map for each site was then created by comparing the yield map earlier generated versus the constant yield map using the map algebra function. The focal statistics in the neighborhood function was then used to generate yield gap maps at the different spatial arrangements (near house, mid farm and far farm); where for each, the average distance from the homestead, was used as the input value for height and width fields in the neighborhood settings function. The focal statistics method is described by Bazzoffi, (2015). For each spatial arrangement variability in yield gaps was computed using standard deviation, mean, maximum value and minimum value using the focal statistics function.

6.3 Results

6.3.1 Mapping maize yields in Mukuyu and Shikomoli

Figure 6.2 shows variability in yields within a small sub-area, highlighting several plots, as well as the component stages which went into creating the yield maps. The estimated pixel-level yield in Shikomoli was in the range of 0.08 t/ha and 4.9 t/ha, with an average of 2.2 t/ha and a median of 2.1 t/ha. In Mukuyu, the estimated pixel-level yield ranged from 1.1 t/ha to 5.5 t/ha, with an average of 2.6 t/ha and a median of 2.5 t/ha.

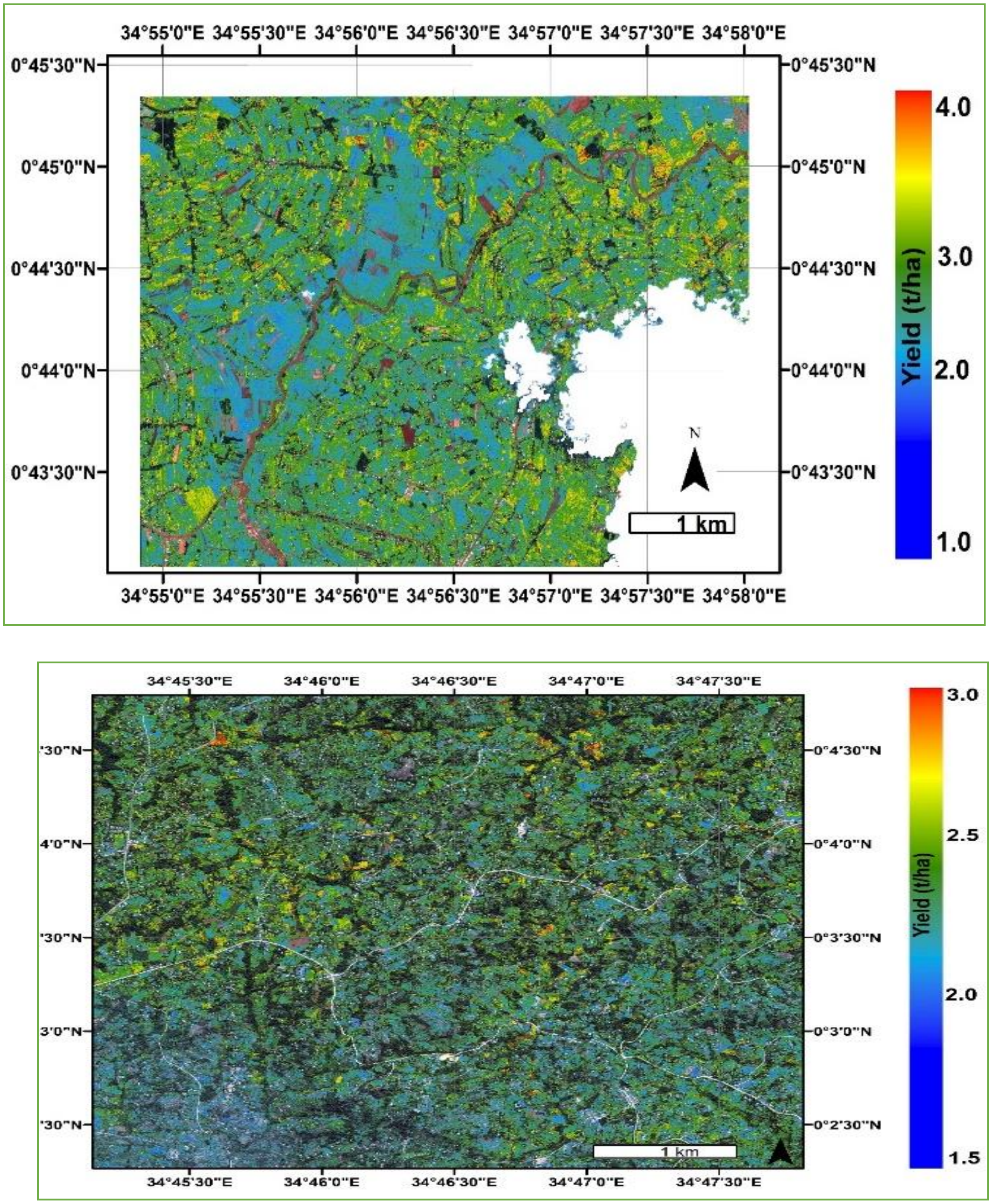


Figure 6.2: Yield map for Mukuyu (Top) and Shikomoli (Bottom)
Source (Hall et al., n.d.)

6.3.2 Spatial arrangements on smallholder fields

The average distances of the spatial arrangements on smallholder farms is shown in Table 6.2.

Table 6.2: Neighborhoods in Mukuyu and Shikomoli at near house, mid and farm plots

Mukuyu	Shikomoli	Plot location from the homestead
40m by 40m	40m by 40m	Near house
80m by 80m	80m by 80m	Mid farm
150m by 150m	150m by 150m	Far farm
300m by 300m	300m by 300m	Far farm

6.3.3 Yield gap maps in Mukuyu and Shikomoli

The 90th percentile yields which were used to create constant yield map were 5.1 and 4.8 t/ha for Mukuyu and Shikomoli. Figure 6.4 shows the yield gap mapping pattern derived from comparing the yield map (Figure 6.3) versus a constant yield map. The yield gap shows different patterns of low and large yield gaps. The min and max yield gap values were -1.0 and 3.3 t/ha for Mukuyu and

-0.9 and 3.9 for Shikomoli. The yield gaps were determined by comparing yields of the best farmers at the 90th percentiles to other yields. The negative values imply that a few farmers had yields that were more than the 90th percentile yields.

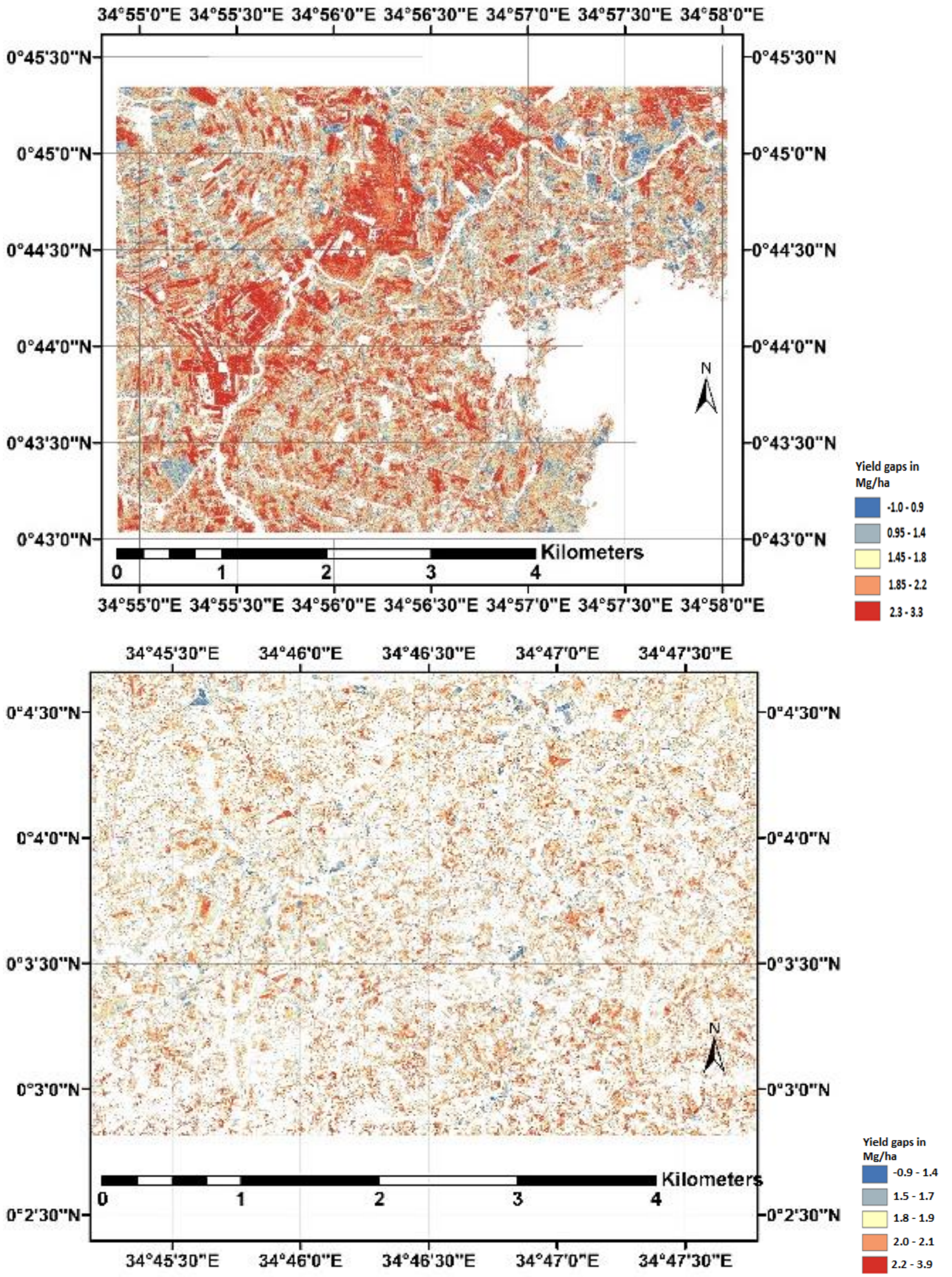
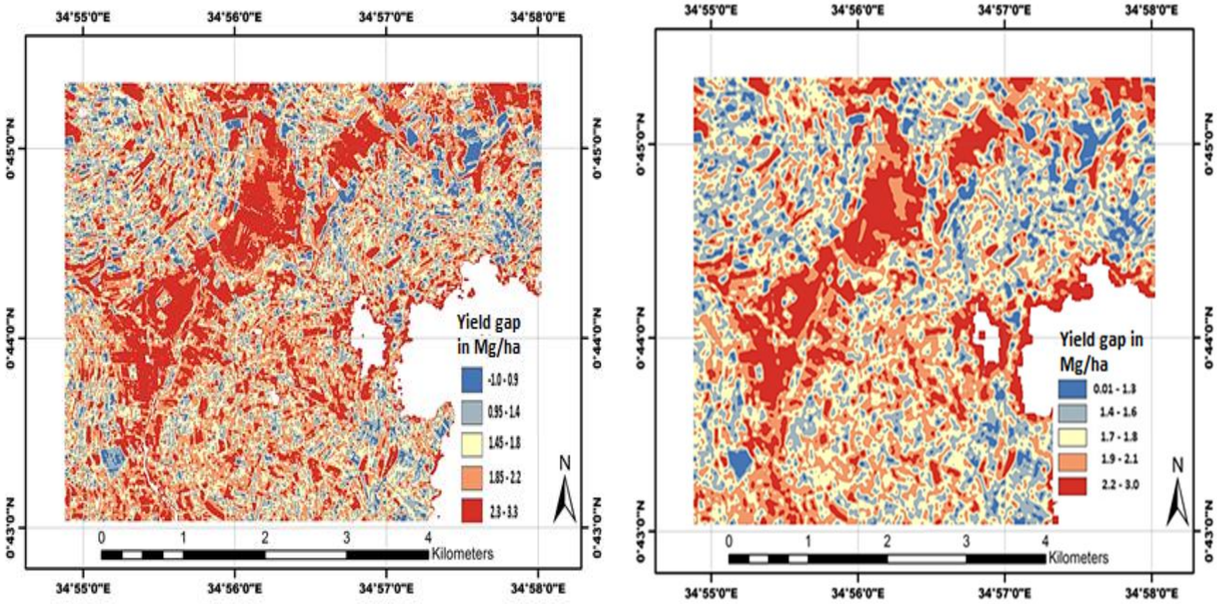


Figure 6.3: Yield gap map for Mukuyu (Top) and Shikomoli (Bottom)
The blue and red regions represent patterns of low and high yield gaps

Yield gaps generated at different spatial arrangements with respect to distance from the homestead (Figure 6.4 and 6.5). High, average and low yields gaps were identified on spatial arrangements closer to the homestead (40m by 40m). As distance increased, the high and low yield gap patterns stretched (150m by 150m) and (300m by 300m) patterns towards average values.

40m by 40m **80m by 80m**



150m by 150m **300m by 300m**

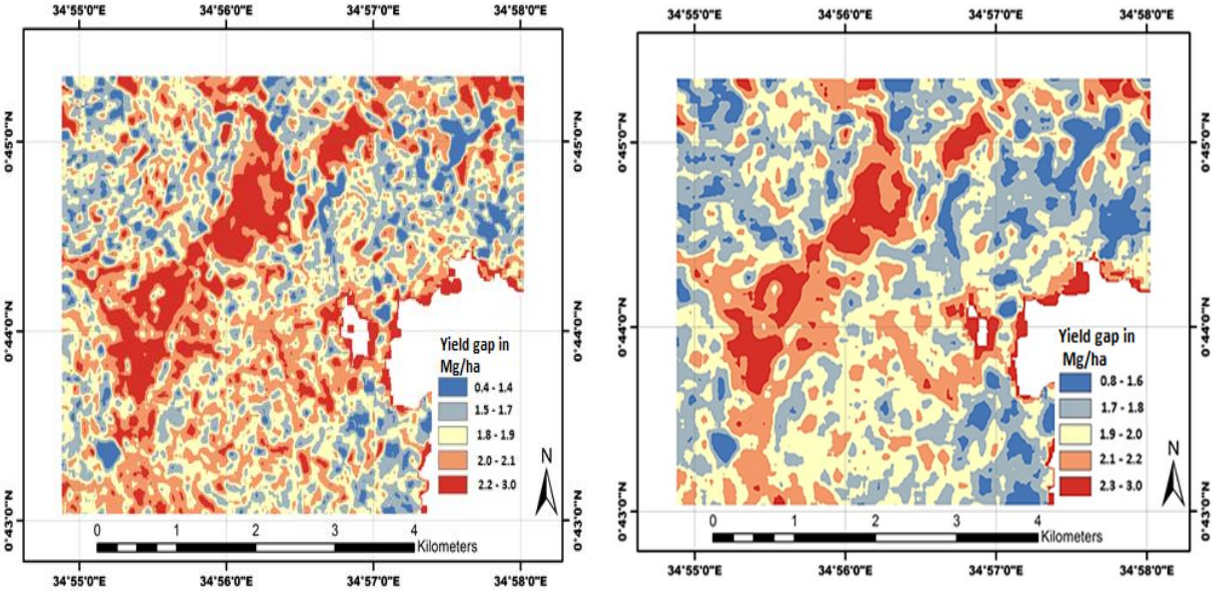
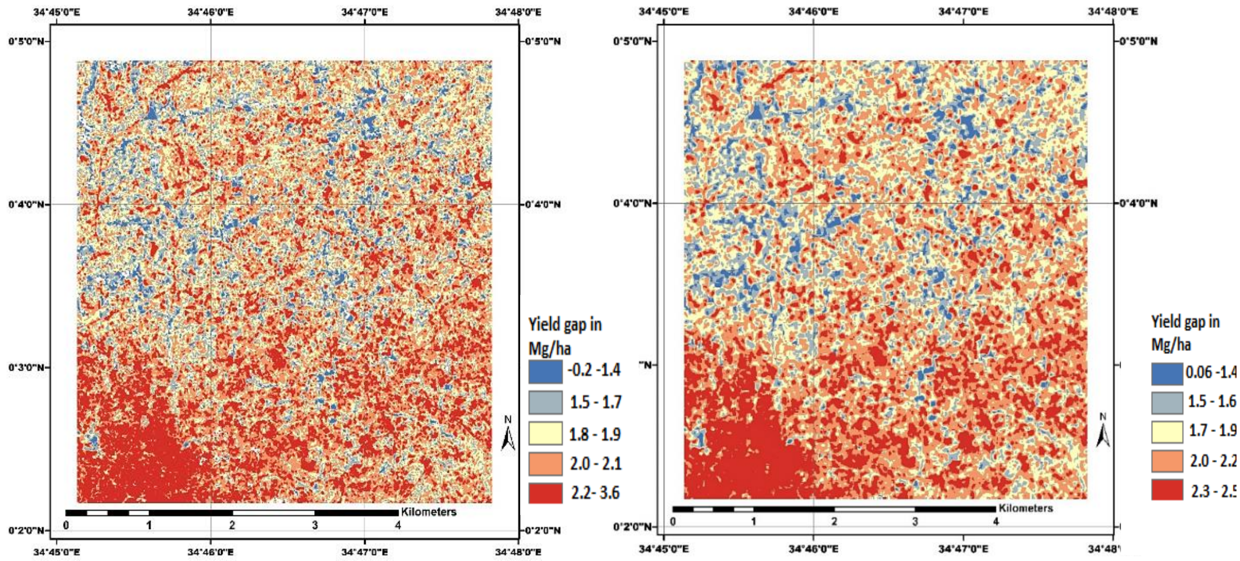


Figure 6. 4: Yield gap mapping patterns at different spatial arrangements in Mukuyu. The blue and red regions represent patterns of low and high yield gaps

40m by 40m **80m by 80m**



150m by 150m **300m by 300m**

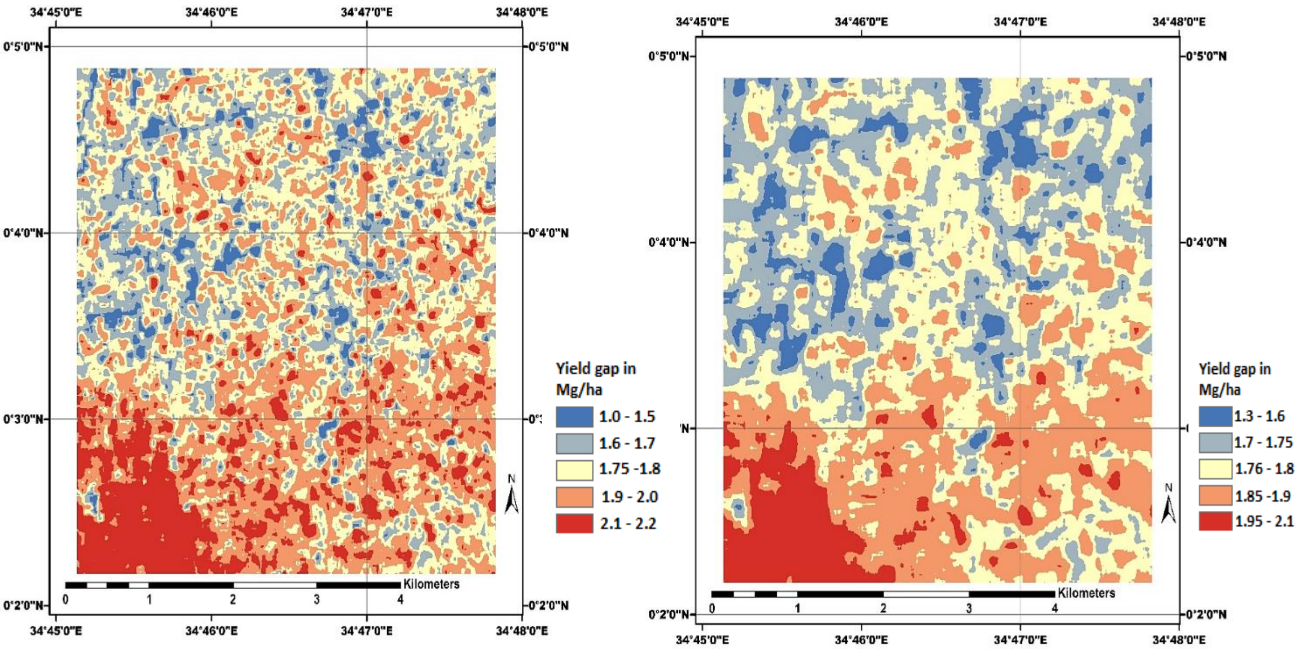


Figure 6. 5: Yield gap mapping patterns at different spatial arrangements in Shikomoli
The blue and red regions represent patterns of low and high yield gaps.

6.3.4 Variation in yield gaps as shown by the maximum, minimum, mean and variance at different spatial arrangements

The maximum mean and minimum values of yield gaps in Mukuyu and Shikomoli for the different neighborhoods are shown in Table 6.3. The minimum values of yield gaps increased while the maximum values decreased with increasing distance from the homestead. The mean values decreased as distance increased from the homestead.

Table 6. 3: The minimum (min), mean and maximum (max) values of yield gaps in Mukuyu and Shikomoli at different spatial arrangements

	Mukuyu			Shikomoli		
Neighborhoods	**Max values**	**Min values**	**Mean values**	**Max values**	**Min values**	**Mean values**
40m by 40m	3.3	-1.0	1.9	3.6	-0.2	1.85
80m by 80m	3.0	-0.1	1.89	2.4	0.06	1.84
150m by 150m	3.0	0.4	1.88	2.2	1.0	1.84
300m by 300m	3.0	0.8	1.87	2.2	1.3	1.83

Legend: The values are in t/ha. T-test statistics at 0.95 show mean, min and max values significantly different (p=0.001) between the near house and mid farm, mid farm and far farm and near house and far farm plots.

The variance of maize yield gaps for spatial arrangements that were close to the homestead was high and it decreased with increasing distance from the homestead for Mukuyu. In Shikomoli, there was a downward decrease and then an upward shift in variance after the 150m distance. The variance was high in Mukuyu compared to Shikomoli (Figure 6.6).

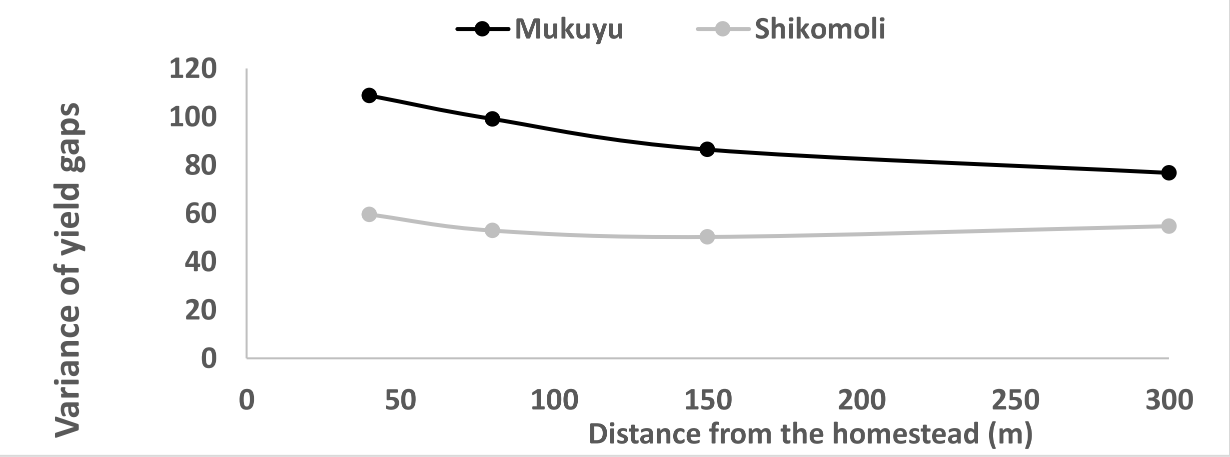


Figure 6. 6: The variance in yield gaps at different spatial arrangements

Legend: High variance indicates heterogeneous patterns of low and high yield gaps. Low variance indicates nearly homogenous patterns of yield gaps

6.3.5 Management, biophysical and socio-economic factors at spatial arrangements

There was variation in management practices, biophysical and socioeconomic factors at different spatial arrangements (Figure 6.7 and 6.8). In Mukuyu, farmers preferred to plant medium and long variety crops at the mid and far farm, while the short variety was grown at the near house plots. In Shikomoli, the short and medium maize varieties were grown at the mid and far farm spatial arrangements. High amount of inorganic fertilizer was applied on the mid farm and near house plots in Mukuyu and Shikomoli respectively. In both Mukuyu and Shikomoli, near house plots had high maize densities which decreased with increasing distance. In Shikomoli, the mid farm plots had high maize densities. In Shikomoli, the proportion of organic manure application was high for the near house plots compared to mid and far farm plots. The number of weed control increased and decreased for Mukuyu and Shikomoli respectively as distance increased from the homestead. In Mukuyu, there was delay in land preparation time for the near house plots compared to mid and far farm, while in Shikomoli, early land preparation was done on the near house plots. The erosion status for plots in Shikomoli was high especially for the far farm plots which are also steep. Phosphorus, nitrogen, SPAD value increased with increasing distance from the homestead in Mukuyu. Weed coverage reduced with increasing distance from the homestead in Mukuyu. In Shikomoli, phosphorus, boron, SPAD values decreased while weed coverage increased with increasing distance from the homestead (Figure 6.A.1 and 6.A.2). Land allocation to the near house, mid and far farm plots followed the same patterns for Mukuyu and Shikomoli (figure 6.8). There was a high allocation of land for the mid and far farm plots in Mukuyu compared to Shikomoli. In both sites farmers were likely to acquire credit facilities for the mid farm plots than for the near house and far farm plots. In Mukuyu, there was high utilization of hired labour at the mid and far farm plots compared to the near house. In Shikomoli, more hired labour was used at the near house plots compared to mid and far farms.

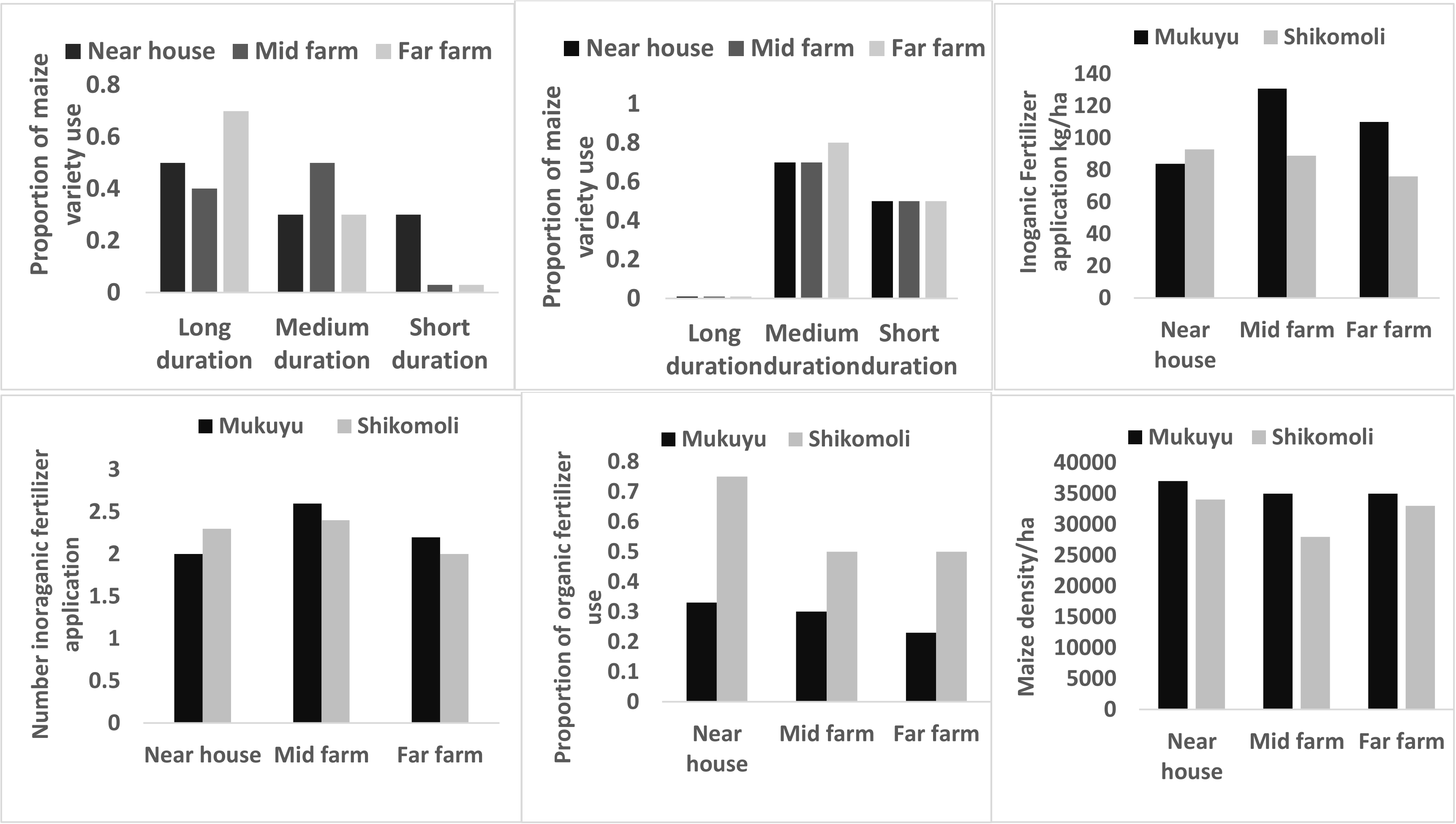


Figure 6. 7: Management and biophysical factors practices at different spatial arrangements (Near house, mid farm and far farm)

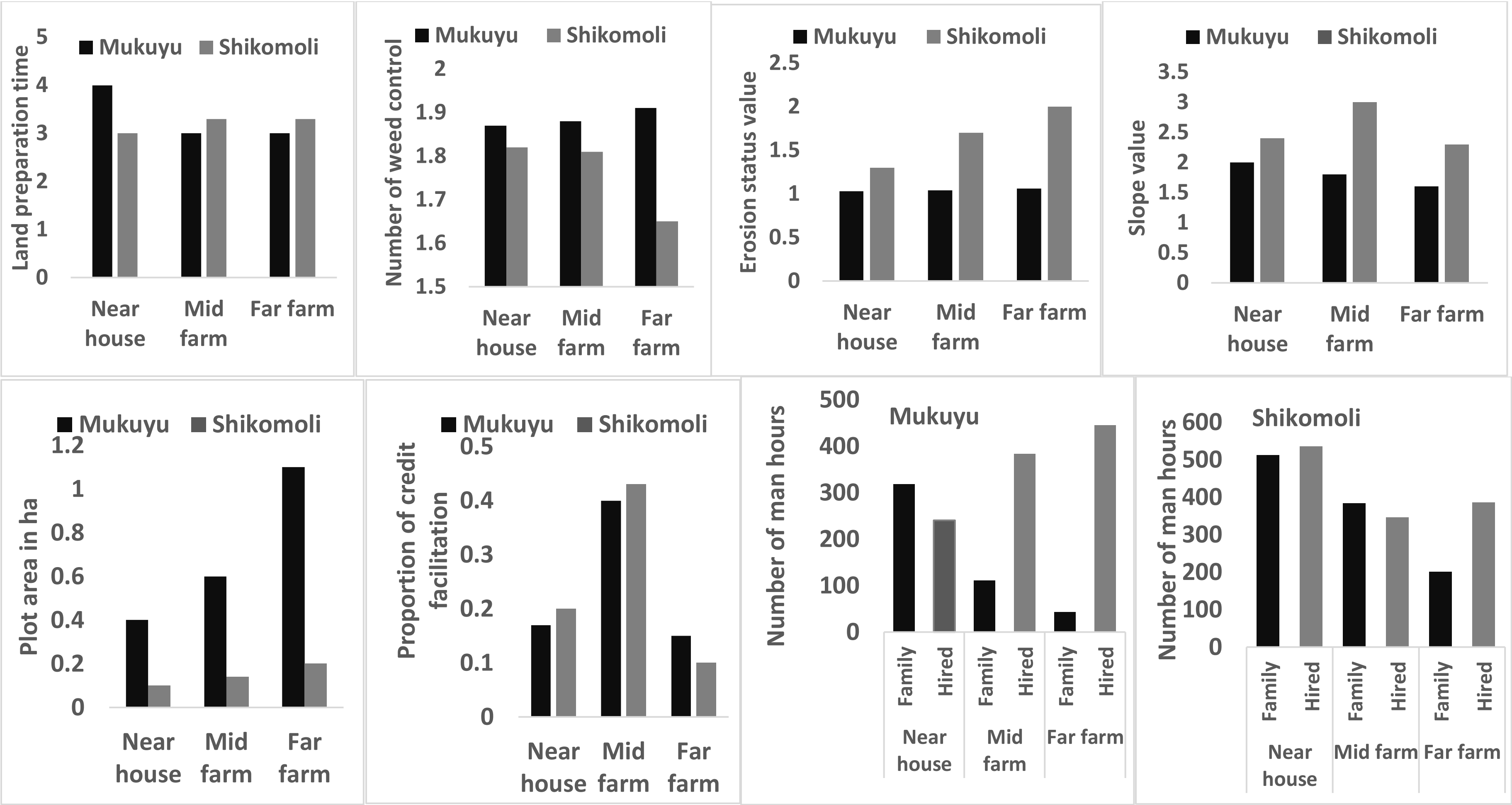


Figure 6. 8: Management, biophysical and Socio-economic factors at different spatial arrangements (Near house, mid farm and far farm in Mukuyu and Shikomoli

Legend: Land preparation (1-Before harvesting of previous crop, 2-two months before onset of rain, 3-one month before onset of rain, 4-at onset of rain), Slope of status (1-steep, 2-gentle, 3-flat), Erosion value- (0-None, 1-Slight, 2-Moderate, 3-Severe).

6.4 Discussion

6.4.1 Yield gap patterns at different spatial arrangements

The highly diverse smallholder farming conditions implies yield gap mapping need to acknowledge the existence of variability on smallholder farms (João et al., 2018). That is, mapping should indicate yield gaps at different levels; high, low, average. The results demonstrate the potential use of spatial arrangements on smallholder farms to show yield gap variability and field specific utilization of factors of production; management, socio-economic and biophysical factors. Patterns of high, median and low yield gaps mapped on spatial arrangements closer to the homestead was an indication of heterogeneous yield patterns. The findings coincide with Lobell and Ortiz-Monasterio, (2006) who have shown spatial yield variability patterns on smallholder farms and attributed to management, soil and climatic factors. As the distance increased from the homestead, the high and low yield gap patterns stretched towards nearly homogenous maize yield gap patterns; an indication of better performing fields. The results are incongruent with Tabu et al. (2005) which show better managed and performing fields with increasing distance from the homestead.

Heterogeneous patterns at the near house spatial arrangements which were also shown by high variance in yield gaps indicated unequal use of management and socio-economic factors. Some sections of near house spatial arrangements received better management practices such as high organic fertilizer application and had high plant density (Figure 6.7). This contributed to high maize yields and low yield gaps. Other fields or sections of the near house spatial arrangements had delayed management practices such as late land preparation, untimely weed control, utilization of short maize variety, less land allocation, low proportion of credit facility use (Figure 6.7 and

6.8). This contributed to high yield gaps compared to mid and far farm spatial arrangements. The inconsistency in utilization of field level management practices and socio-economic factors thus contributed to heterogeneous patterns of low and high yield gaps. Patterns of high yield gap could also have resulted from sections of the near house spatial arrangements having high phyto-diversity which contributed for soil nutrients resulting in low yield (Endale et al., 2016).

Nearly homogenous patterns of yield gaps on the mid and far farm spatial arrangements resulted from consistent in utilization of management and socio-economic factors such as high weed frequency, inorganic fertilizer use, early land preparation, long and medium maize variety use (Figure 6.7). Smallholder farmers operate under resource constraints and tend to minimize management and socio-economic resources to achieve large coverage (Onubuogu et al., 2014). Therefore the nearly homogenous yield gap patterns could also have resulted from minimal resource use spread over the entire field due to the large land size allocated to the mid and far farm spatial arrangements (Figure 6.8). All sections within the fields received almost nearly equal treatment.

Studies have shown that farmers manage certain fields within farming systems according to certain perceived benefits (Sanginga, N. and Woomer, 2009). The consistency in utilization of management practices and socio-economic factors at mid and far farm spatial arrangements indicated preferential treatment of these fields over the near house spatial arrangements which could be due to certain perceived benefits that need to be investigated. This was corroborated by the positive correlation of biophysical factors; phosphorus, nitrogen and chlorophyll (SPAD values) and negative correlation of weed pressure and weed height with increasing distance from the homestead (Figure 6.A.1 and 6.A.2-see Appendices).

6.4.2 The production opportunities for the different spatial arrangements to enhance maize yields

The different spatial arrangements also depict production opportunities regarding management, socio-economic and biophysical factors that could be utilized to improve maize yields. The high proportion of organic fertilizer use at the near house plots indicates high nutrient supply and water retention (Achieng et al., 2010). This can be utilized to increase maize production by improving timely execution of agronomic activities such as land preparation, weed control and use of long duration maize varieties. The high proportion of inorganic fertilizer use at the mid and far farm plots is an indication of increased nutrient supply which can efficiently be utilized by timely management of weeds to achieve high yield. Increasing plant density of the plots at mid and far farm which have large land sizes by adopting an optimal plant spacing can also help maximize land use and resources.

The low lying terrain of the far farm fields in Mukuyu is an indication of increased nutrient accumulation washed down from the mid and near house plots when there is a heavy downpour (Zhang et al., 2011). This benefit can be utilized to enhance yields by increasing plant density of the far farm fields. Family labor provides supervisory role to ensure resources such as fertilizer, seeds and time are used efficiently to increase productivity (Kabubo-Mariara and Kabara, 2015). In Mukuyu, the reliance on utilization of hired labour at the mid and far farm fields could indicate reduced resource use efficiency with subsequent effect on soil fertility and productivity. There is need to increase utilization of family labour for the mid farm plots to maximize on resource utilization. Scheduling farm activities such as planting and weed control to coincide with availability of family members to provide supervisory role will help improve labour utilization and resource use efficiency.

6.4.3 Method application

Mapping of yield gaps at different spatial arrangements on smallholder farms using spatial analysis methods showed yield gap patterns. The focal statistics analysis further differentiated fields to yield gap patterns based on distance from the homestead. Heterogeneous yield gaps on spatial arrangements closer the homestead, showed highly diverse fields. Nearly homogenous patterns on spatial arrangements further the homestead showed less diverse farming systems. Survey investigation using management and socio-economic factors further explained the occurrence of the yield gap patterns. The findings show that fine spatial analysis can allow the differentiation of smallholder fields based on yield gap patterns which can aid the assessment of specific factor association. Delineating smallholder farms based on yield gap patterns into units that can be managed uniformly can enhance site specific land management and improve resource use efficiency.

6.5 Conclusion

The study demonstrated the use of spatial arrangements found on smallholder farms as a unique approach to identify patterns of yield gap variability and survey data to reveal field specific utilization of management, socio-economic and biophysical factors as scope for enhancing site specific land management. The findings demonstrated different patterns of low, median and high maize yield gaps. When yield gaps were mapped on spatial arrangements closer the homestead highly heterogeneous patterns; low, median and high yield gaps were realized. As distances increased from the homestead, nearly homogenous patterns; median to high yield gaps were found. Delineating management zones based on yield gap patterns at the different spatial arrangements on smallholder farms, could contribute to site-specific land management and enhance yields. The findings also revealed that smallholder farmers preferentially manage spatial arrangements further the homestead with regard to application of socio-economic and management factors. The challenge now remains upon how to increase the consistency in utilization and replication of these factors on spatial arrangements further and closer the homestead respectively to enhance yields. Investigating the value smallholder farmers attach for each spatial arrangement can further enhance the spatial understanding of yield gap variation on smallholder farms.

CHAPTER SEVEN

GENERAL DISCUSSION

This research makes a novel contribution to yield gap analysis by studying maize yield gaps and the causal factors at a farmer level as a scope for enhancing yields on smallholder farms. There are different types of yield gaps; modelled, experimental and farmer level that can be studied. Most yield gaps have been computed using modelled and/or experimental potential yields which assume perfect socio-economic and management conditions and may not represent the ideal smallholder farming situation. This has led to high yield gaps which may not be exploited by smallholder farmers given their current low resource endowment. The study utilizes a site-specific approach to compute maize yield gaps at a farmer level by comparing yields on the 90th percentile of farms to other farm yields. This provides an opportunity to measure yield gaps and compute unachievable yields at a farmer level for each study site. The yield gaps obtained 1.8 t ha^{-1} and 2.6 t ha^{-1} for Mukuyu and Shikomoli represents 35% and 54% of unachieved yields on smallholder farms. This shows that high yield gaps greater than 30% exist at a farmer level. It is of essence that these yield gaps are closed to enhance food security on smallholder farms.

Most yield gap studies have also used a single data collection and analysis method such as survey and linear regression respectively to determine factors influencing maize yield gaps. The collection of data and analysis of factors influencing yield gaps is achieved using a multi-disciplinary approach; where biophysical, management and socio-economic factors are inclusively studied using different data collection (soil sampling, field measurements, household surveys, on farm experiments, satellite imagery) and analysis methods (FA, CART, GLMM, LMER). The use of different data collection methods helps overcome spatial and temporal data limitations which is common when one method such as survey or field measurements is used to collect data. The different data analysis methods provide complementary findings which have relevance at different scales of decision making and cropping seasons on smallholder farms. The FA identified overarching factors while GLMM and CART analysis showed consistent factors across the two sites that influenced maize yield gaps. The high proportion of variance of socio-economic factors demonstrated by Factor Analysis indicates the high contribution and commonality of these factors to influence maize yield gaps over biophysical and management factors in both Mukuyu and Shikomoli. The GLMM identified education, age, membership to groups, access to markets, family labour, gender, credit facility, maize variety, crop residue utilization insitu, quantity of organic and inorganic fertilizer use, while CART identified maize density, chlorophyll values, maize height, and depth to compact layer as consistent factors affecting yield at both sites. Prioritizing measures to increase yields in staple crops is one of the relevance for carrying out yield gap studies and is particularly important for policy implementation. These findings are therefore important to policy implementers who can focus on a limited number of factors in designing measures to enhance yields.

Optimizing resource use which can be achieved by identifying most limiting agroecology specific factors as well as a combination of high yielding management practices, is the aim of smallholder farmers who operate under financial constraint. In this study, the GLMM analysis showed a two way significant interaction effect between socio-economic, management and biophysical factors on maize yield gaps which was agro-ecology specific. In Mukuyu inorganic fertilizer use and gender of operator as female, weed coverage at early maize stages and crop residue utilization as animal feed, positively interacted to influence maize yield gaps. While low weed coverage at early maize stages and phosphorus, depth of compaction and crop residue use *insitu*, number of organic fertilizer and cation exchange capacity, negatively interacted to influence maize yield gaps. In

Shikomoli, membership to groups and timeliness in execution of agronomic activities such as land preparation, planting and weeding negatively interacted to influence maize yield gaps. The CART analysis also identified a combination of factors that resulted in low and high yield gaps that were agro-ecology specific at different levels. For instance, in Mukuyu, these factors included; lower weed cover at early maize stages below 28%, high depth to compact layer of more than 10 cm, high maize density above 32000 plants per hectare and high manganese content above 83 ppms. In Shikomoli, high plant density above 32000 plants per hectare, high depth to compact layer more than 24 cm and low sand content resulted in low yield gaps. Also, according to CART weed cover at early stages and maize density at late stages was the most limiting factor in maize production in Mukuyu and Shikomoli, respectively. This information is important to local government authorities at the county level and to smallholder farmers who can choose to focus on a single factor or a combination of factors in designing soil and crop intervention measures. The information also indicates that socio-economic, management and biophysical factors conjunctively influence maize yield gaps and hence they should not be disentangled in studying causes of yield gaps.

The assessment of crop status at key maize stages by taking field measurement of SPAD values (chlorophyll content), maize height, crop vigour and weed pressure identified within season field and crop conditions that contributed to maize yield gaps. Maize yield gaps were influenced by weed cover during early maize stages, SPAD values and maize density at late maize stages. This demonstrates that having within season information on crop conditions is important to assess if a crop is being supplied with nutrients and is growing under favorable environmental conditions. This information can be linked to socio-economic conditions to help adjust within soil and crop management practices on smallholder farms.

The study further highlighted the use of remote sensing to overcome spatial data limitations common with surveys or experimental research by mapping yield gap patterns within and between fields. Heterogeneous patterns of high and low yield gaps were found on fields that were closer to the homestead. As distance increased from the homestead, nearly homogenous patterns were observed. The yield gap patterns revealed preferential treatment of certain spatial arrangements over others regarding utilization of socio-economic and management factors and occurrence of biophysical factors which could be exacerbating yield gaps. This information can aid in delineating management zones based on yield gap maps that can assist in site specific land management. Complementing management practices derived from past survey findings on on-farm trial experimentation also helped assess spatial and temporal causes of yield variation on smallholder farms. On-farm trials showed high spatial variability between best and average management practices within farms resulting from nutrient supply, weed cover and plant density. When yields of best management practices were compared to yields of 10% top producing farms from past survey findings, the study found high temporal yield variations attributable to seasonal differences in climate.

The analysis of yield gaps and the causal factors in this study was done in two contrasting regions regarding agro-ecology, market access and population density. The regions have agro-ecology, market access and population density characteristics representative of other maize growing regions in Kenya and Sub Saharan Africa. The findings of this study are therefore applicable to other maize growing regions with similar characteristics as the study sites.

GENERAL CONCLUSION

The findings show that high yield gaps at a farmer level >30% exists indicating a huge scope for farmers to exploit the gap. The findings also demonstrate that an integrated approach can result in overarching, consistent, agroecology specific, interacting and field specific factors influencing yield gaps. In this study, socio-economic were the overarching factors influencing maize yield gaps over biophysical and management across the two sites. Consistent factors across the two agro-ecologies influencing maize yield gaps were; education, age, membership to groups, access to markets, family labour, gender, credit facility, maize variety, crop residue utilization insitu, quantity of organic and inorganic fertilizer use, maize density, chlorophyll values, maize height, and depth to compact layer. Agro-ecology specific factors that were important included; weed cover at early stages and phosphorus in Mukuyu and maize density at late stages and zinc in Shikomoli. The interaction between inorganic fertilizer use and gender of operator as female, weed coverage at early maize stages and crop residue utilization as animal feed influenced maize yield gaps in Mukuyu. While in Shikomoli, membership to groups and timeliness in execution of agronomic activities such as land preparation, planting and weeding negatively interacted to influence maize yield gaps. There was also field specific utilization in management, socio-economic and biophysical factors on smallholder farms with respect to distance from the smallholder homestead as reflected by yield gap patterns. There was higher use of inorganic fertilizer, high frequency of weed control, early land preparation, high proportion of hired and family labour use and allocation of large land sizes on fields that were located away from the smallholder homestead. High proportion of organic fertilizer and family labour use was utilized on fields closer to the homestead. Socio-economic, management and biophysical factors operate at different levels and also interact to influence maize yield gaps hence they should be studied jointly to fully divulge into causes limiting yields in order to identify comprehensive solutions for improving yields on smallholder farms.

GENERAL RECOMMENDATION

- The study presents findings from different viewpoints which can be applied at different scales of decision making; farmer, local, county, national and regional in improving yields.
- This will require general measures that address the soci-economic conditions of smallholder farmers, soil fertility status and within season field management in maize production while simultaneously considering agro-ecology specific.
- General measures aimed at improving the socio-economic welfare such as; improving market accessibility, relaying agricultural information, encouraging family involvement in agronomic activities as well as motivating youth participation in farming are required.
- Also measures aimed at improving soil fertility such as sufficient and timely application of fertilizer at early maize stages, having a supply chain for suitable fertilizers, crop residue utilization *in situ*, manure application, planting of cover crops and availing soil testing services within reach of smallholder farmers will also be useful.
- There is need to invest in low cost technologies that disintegrate crop residues for easier incorporation in soils to help increase soil organic matter and improve soil fertility.
- Improving field management of maize fields by building capacity of smallholder farmers in diagnosing and managing plant macro and micro nutrients e.g investing in technologies such SPAD equipment will be helpful.
- Innovations that utilize mobile phones to create web applications that show different macro and micro-nutrient deficiencies can also help farmers to scout and correct crop anomalies.

- Remote sensing technologies such as use of satellite imagery to delineate fields based on yield gap patterns can also enhance field specific utilization of management, socio-economic and biophysical factors and this will enhance resource use efficiency.
- In areas with high agro-ecological potential and large land sizes such as Mukuyu, there is need to develop labor-saving technologies such as low-cost tillage equipment to help in weed management. Extension education on the significance of early land preparation in controlling weeds will also be helpful.
- In areas with low agro-ecological potential and smaller land size such as Shikomoli, maintaining an optimal and health plant density through proper soil nutrition is needed to enhance yields.
- This research was limited to investigating agronomic practices; from land preparation to harvesting in maize production and how they affect yield gaps. There is need to understand the effect of post-harvest handling on yield gaps in maize production.
- Research should also be done to establish different plants densities that can result in high yield at different fertilizer levels and in identifying weed species to develop weed management strategies. Further research in yield gap studies could also focus on using crowd sourcing methods via innovatively developed mobile application to collect data.

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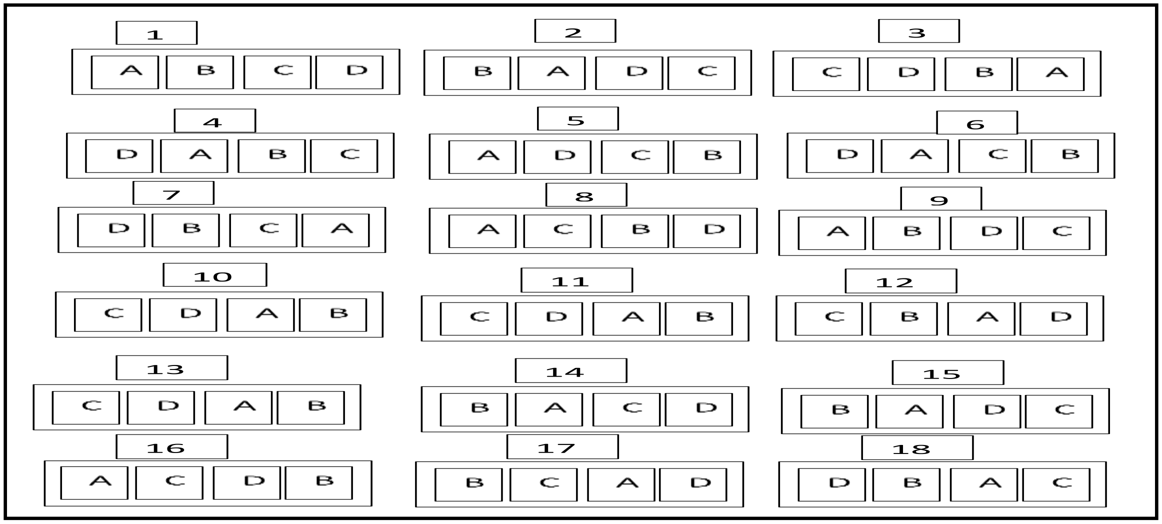
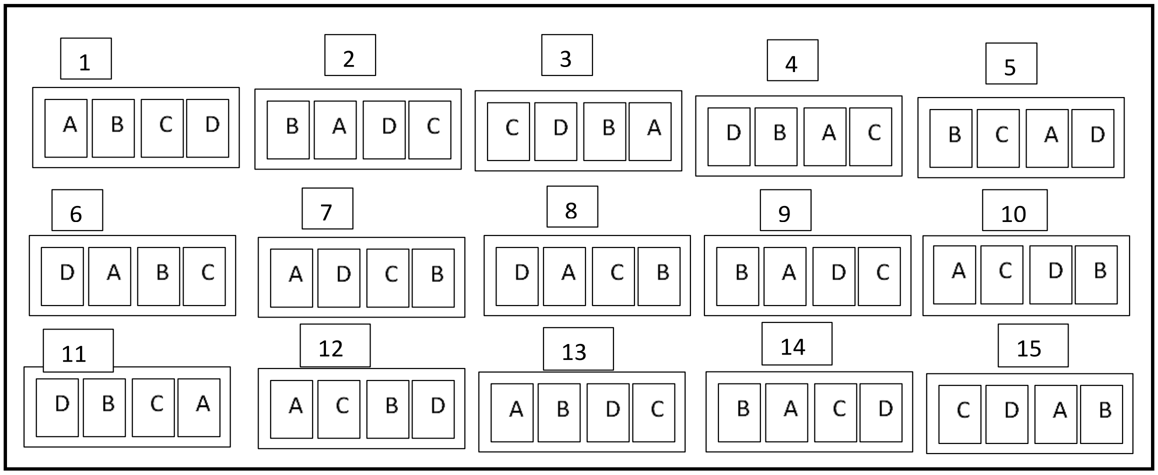
Appendices



Legend: A-Best management, B-Low nutrient, C-Delayed weeding, D-Low pant density

Figure 4.A. 1: Randomized complete block design of treatments in Mukuyu



Legend: A-Best management, B-Low nutrient, C-Delayed weeding, D-Low pant density

Figure 4.A. 2: Randomized complete block design of treatments in Mukuyu

Table 4.A. 1: Best farmer derived management practices in Mukuyu and Shikomoli

	Percentile rank	Yields t/ha	Yield gaps t/ha	Number of application	Quantity of fertilizer Kg/ha	Number of weed control	Time of 1st fertilizer application	Time of 2nd fertilizer application	Time of 3rd fertilizer application	Time of 1st weed control	Time of 2nd weed control	Plant density
Mukuyu	90	5.17	-0.07	3.0	192	1.95	Planting	3rd week	6th week	3.6	6.2	59000
Shikomoli	90	4.8	0.00	3.0	171	2.0	Planting	3rd week	7th week	3.0	5.0	70000

Survey findings from Yield gap project 2016 in the two study sites representing management practices on fertilizer use, weed control and plant density among the 10% top yielding farms.

Table 4.A. 2: The mean values for maize density, maize height, weed height, weed cover, flowering status and maize yield

Site/treatment	Maize yield t/ha	SPAD values			Maize vigor			Maize density (count)			Maize height (cm)			Weed cover (%)			Weed height (cm)			Flowering status (%)
		Stg1	Stg3	Stg4	Stg1	Stg3	Stg4	Stg1	Stg3	Stg4	Stg1	Stg3	Stg4	Stg1	Stg3	Stg4	Stg1	Stg3	Stg4	Stg4
Shikomoli																				
Best management	6.7a	47a	51a	56a	3.9a	4.1a	4.1a	62^{e3}a	57^{e3}a	57^{e3}a	72a	154a	244a	3.9a	10a	16a	5b	9b	11b	79a
CL-Upper	7.1	49	54	59	4.2	4.2	4.4	63^{e3}	59^{e3}	58^{e3}	87	174	256	4.6	14	20	7.5	10.6	12	84
CL-Lower	6.3	43	49	53	3.5	3.7	3.9	61^{e3}	57^{e3}	55^{e3}	59	146	229	3.2	4.8	10	2.2	5.3	7.7	73
Low nutrient	3.5b	43a	41bc	39b	3.8b	3.5b	3.5b	62^{e3}a	51^{e3}b	48^{e3}c	70a	135b	227a	3.8a	12a	16a	5b	9b	13b	24c
CL-Upper	3.8	47	47	41	3.8	4.0	3.7	63^{e3}	53^{e3}	49^{e3}	84	157	240	4.6	16	20	7.2	11.9	16.7	29
CL-Lower	2.9	41	40	35	3.1	3.4	3.2	61^{e3}	50^{e3}	46^{e3}	57	109	213	2.9	6.8	10	2.0	6.7	11.9	19
Delayed weeding	4.6c	44a	44b	53ab	3.5b	3.7b	3.7ab	59^{e3}b	52^{e3}b	51^{e3}b	67a	137b	224a	65b	19a	16a	30a	15a	13b	54b
CL-Upper	5.0	48	46	56	3.8	4.2	4.0	60^{e3}	53^{e3}	52^{e3}	80	140	238	69	23	21	32	16	15.8	59
CL-Lower	4.2	42	39	50	3.1	3.5	3.5	58^{e3}	51^{e3}	47^{e3}	53	104	210	60	13	12	26	11	10.5	49
Low plant density	4.9c	45a	53a	55a	3.8b	4.1a	4.1a	50^{e3}c	48^{e3}c	45^{e3}c	66a	134b	234a	4.6a	12a	17a	6b	13a	16a	81a
CL-Upper	5.4	49	56	59	4.1	3.8	4.4	51^{e3}	50^{e3}	46^{e3}	80	165	248	5.0	17	21	8.0	15	17.8	86
CL-Lower	4.5	43	49	53	3.5	3.0	3.9	48^{e3}	46^{e3}	44^{e3}	52	120	220	4.1	7.5	17	2.7	10	12.6	75
Mukuyu																				
Best management	7.8a	47a	59a	59a	4.2a	4.9a	4.9a	63^{e3}a	61^{e3}a	59^{e3}a	97a	221a	290a	3.4a	10a	15a	4b	8b	10a	77a
CL-Upper	8.1	49	61	62	4.3	4.5	4.9	64^{e3}	62^{e3}	60^{e3}	110	233	303	5.2	14	19.1	6.3	10.5	12.7	82
CL-Lower	7.3	43	56	57	3.8	4.0	4.7	62^{e3}	59^{e3}	56^{e3}	84	208	278	1.4	5.2	10.4	1.6	5.7	7.9	73
Low nutrient	4.3b	42a	48b	45b	3.6a	3.6b	3.6b	65^{e3}a	56^{e3}b	55^{e3}b	92a	209a	279a	3.0a	23b	15a	5b	9b	10a	26b
CL-Upper	4.7	47	51	49	4.1	3.8	3.8	66^{e3}	57^{e3}	56	105	222	292	4.6	26.6	19.5	6.7	11.5	13.3	31
CL-Lower	3.9	41	46	43	3.5	3.4	3.4	64^{e3}	55^{e3}	52	79	196	267	1.5	18.4	10.6	2.0	6.7	8.5	22
Delayed weeding	4.8b	42a	49b	57a	3.6a	3.8b	3.8b	64^{e3}a	57^{e3}b	53^{e3}b	82a	203a	276a	67b	23b	16a	29a	14a	11a	55b
CL-Upper	5.2	44	52	59	4.2	3.9	4.0	66^{e3}	59	53	95	216	289	72	26	19	30	17.1	13.8	60
CL-Lower	4.4	39	47	54	3.5	3.4	3.6	63^{e3}	56	49	70	191	263	63	17	11	26	12	9.1	51
Low plant density	5.0b	44a	61a	60a	4.3a	4.8a	4.8a	51^{e3}b	50^{e3}c	49^{e3}c	95a	222a	288a	2.2a	14c	17a	4b	10b	12a	80a
CL-Upper	5.4	47	64	63	4.4	4.9	4.9	52^{e3}	51^{e3}	50^{e3}	111	235	300	3.3	18	20	6.6	11	14	85
CL-Lower	4.6	41	58	58	4.0	4.1	4.6	48^{e3}	47^{e3}	46^{e3}	85	209	275	0.9	9.1	13	1.2	7	9	76

Different letters denote lmer test statistics at 0.95 significant (p=0.001) and same letters show no statistical difference between treatments. Stg1, Stg2, Stg3 represent stages 1, 2 and 3 of maize development respectively.

Table 4.A. 3: The effect of treatment, site, stage and the interaction on crop performance variables

	Maize density	Maize height	Weed height	Weed cover	SPAD Value	Maize vigour	Flowering status	Maize yield
Treatment	<0.001*	0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0001*	0.0001*	0.0001*
Site	0.00046*	<0.0001*	0.01*	0.1885	<0.0001*	<0.0001*		0.0001*
Stage	<0.0001*		0.0001*	0.1	<0.0001*	<0.0001*		
Treatment × Site	<0.0001*	0.3484	0.3297	0.08	0.2424	0.62586		0.0001*
Treatment × Stage	<0.0001*	0.3	<0.0001*	<0.0001*	<0.0001*	0.54085		
Site × Stage	<0.0001*	0.0001*	0.2	0.1	<0.0001*	0.0001*		
Treatment × Site × Stage	<0.0001*	<0.0001*	0.957	0.667	0.9284	0.813		

Legend: Crop performance measures (maize density, maize height, weed height, weed cover, SPAD values, maize vigour, flowering status and maize yield)

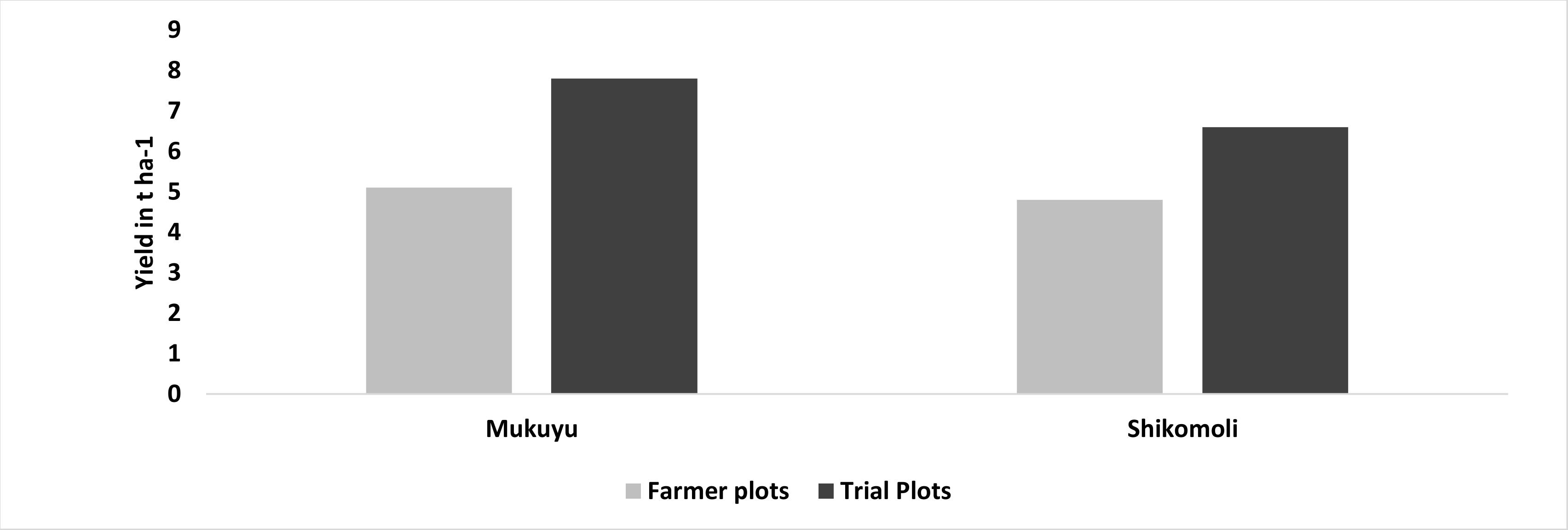
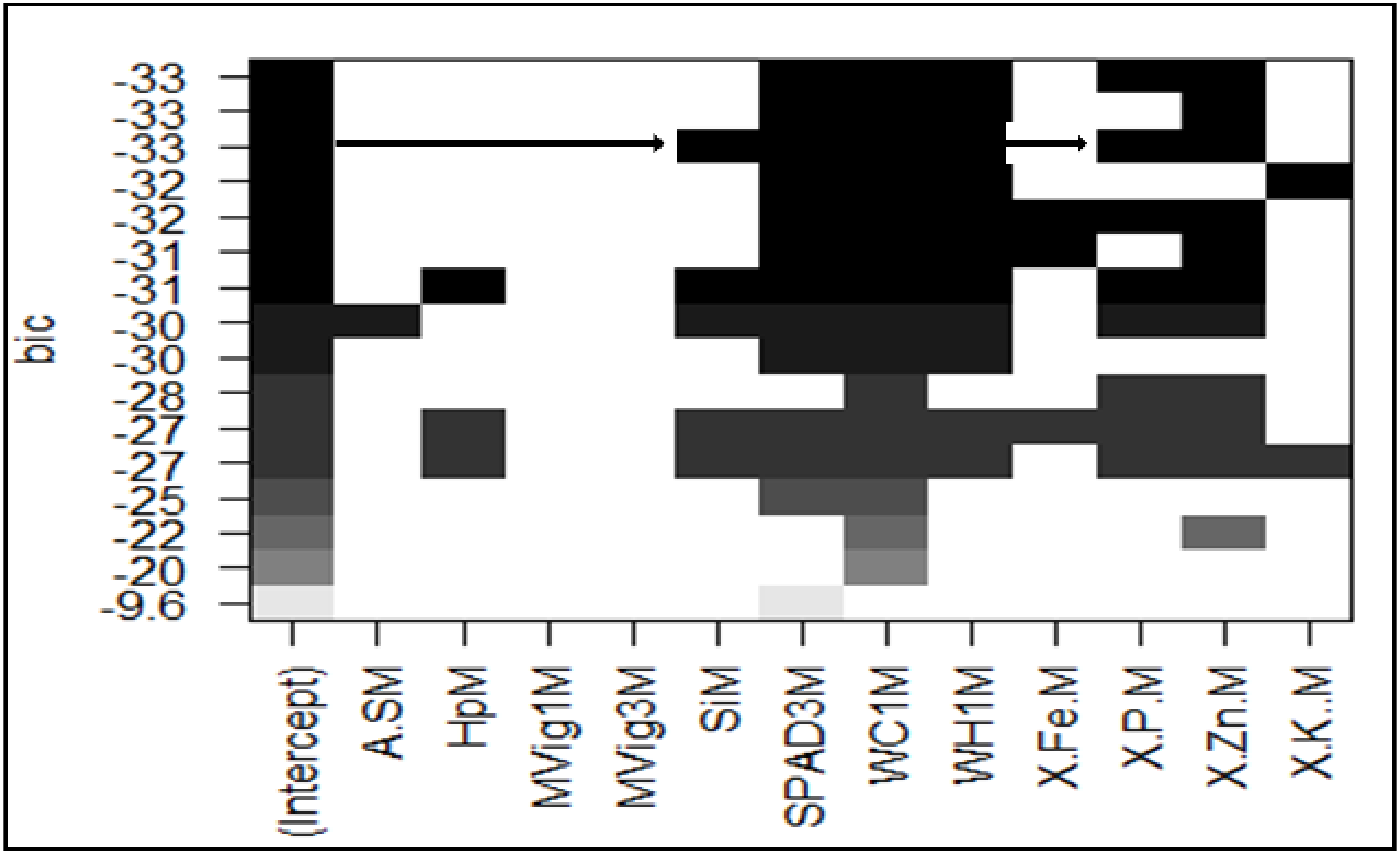
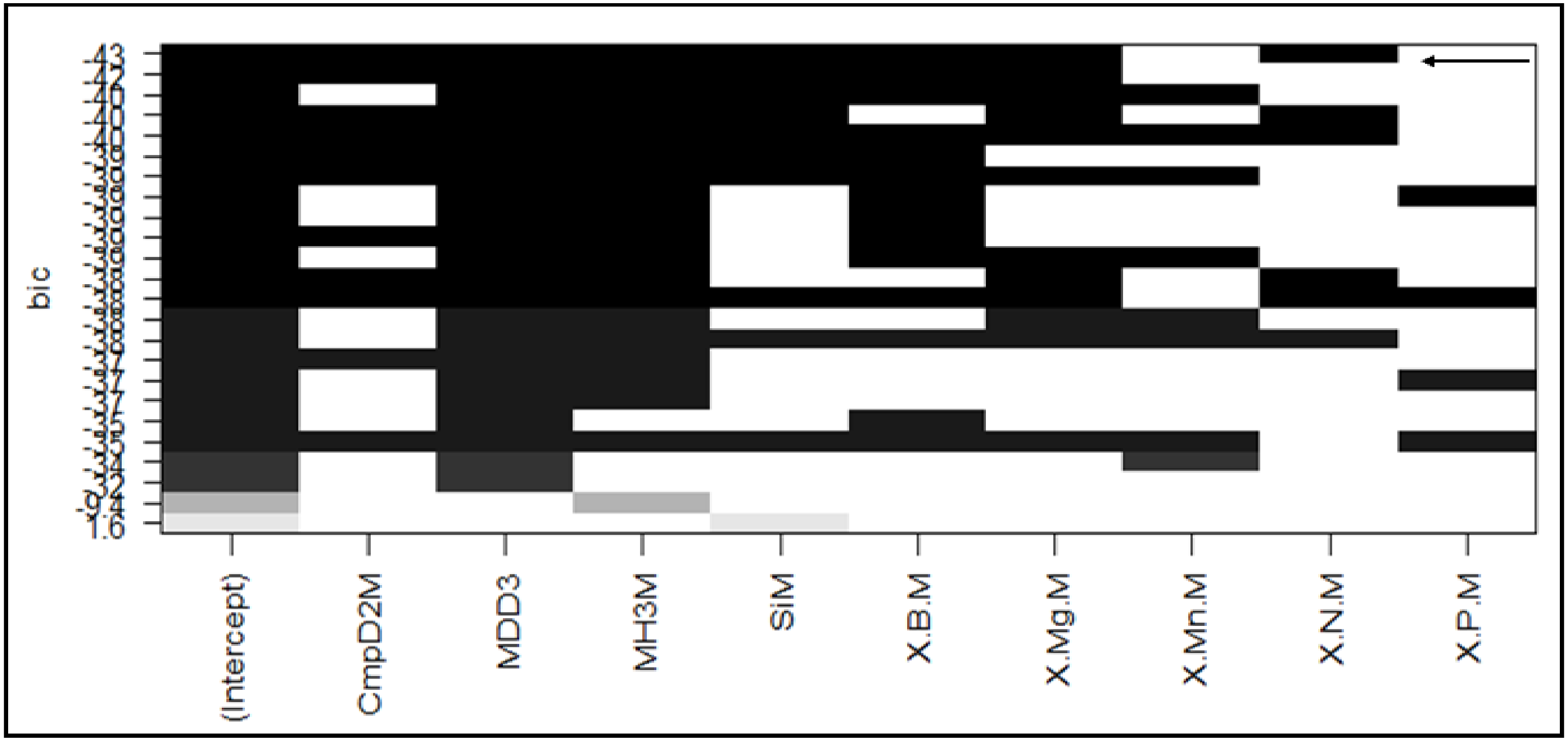


Figure 4.A. 3: Comparison of farmer yields (previous survey findings from 10% top yielding farms) and on farm trial yields.



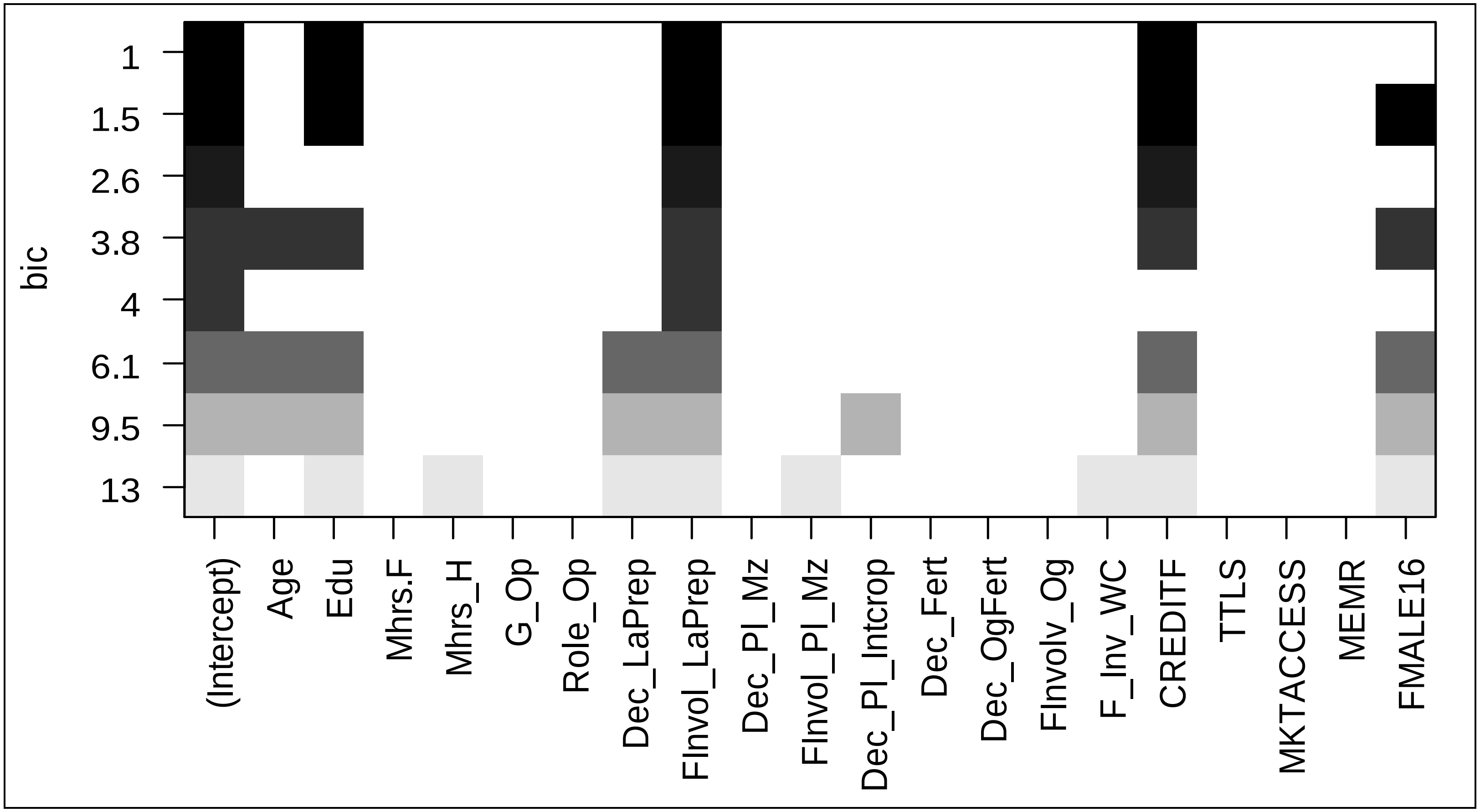
Legend: Silt (SiM), SPAD Readings in stage 3 (SPAD3M), Weed coverage in stage 1(WC1M), Weed height in stage 1(WH1M), Phophorus (X.P.M), and Zinc (X.Zn.M) shown by the two arrows. The intercept represents maize yield gaps.

Figure 5. A. 1: Biophysical factors in Mukuyu selected for GLMM model



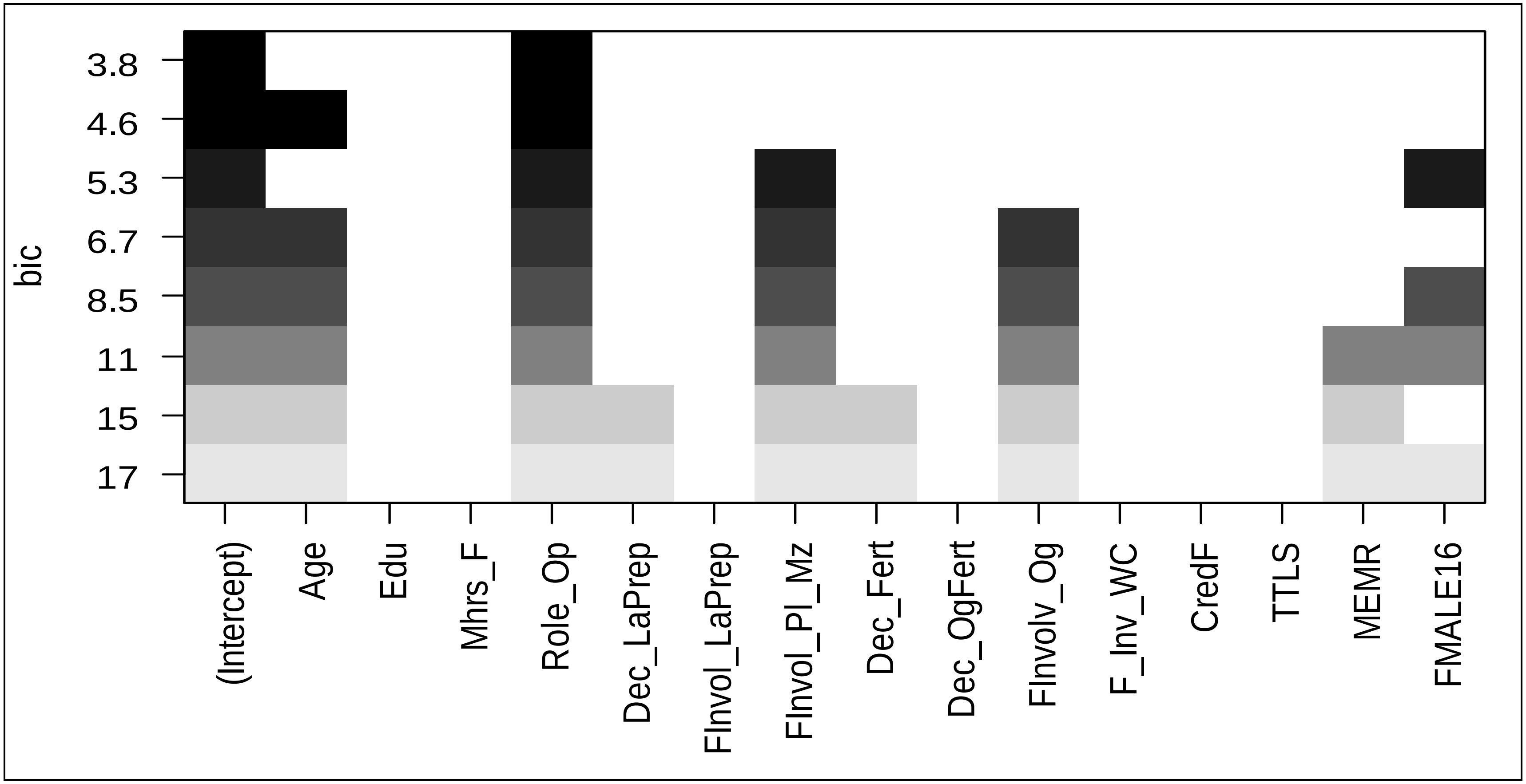
Legend: Depth of compaction (CmpD2M), Maize density at harvest (MDD3), Maize height in stage 3 (MH3M), Silt (SiM), Boron (X.B.M), Magnesium (X.Mg.M), Nitrogen (X.N.M). The intercept represents maize yield gaps

Figure 5. A. 2: Biophysical factors in Shikomoli selected for GLMM model



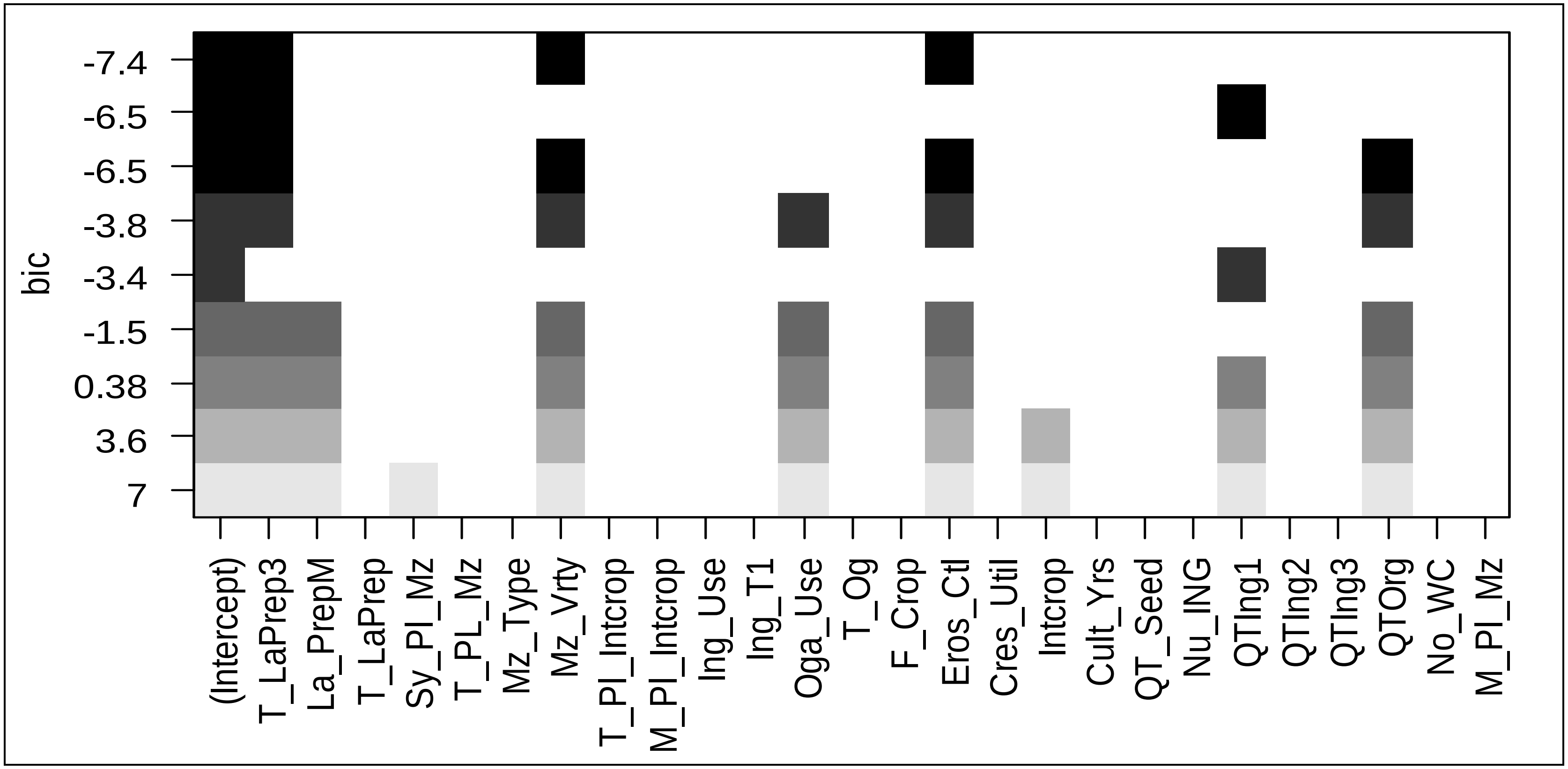
Age, Education (Edu), Man hours hired (Mhrs.F) Decision on land preparation (Dec_LaPrep), Credit facilitation (CREDITF), Female involvement above 16 years (FMALE16)

Figure 5. A. 3: Socio-economic factors in Mukuyu selected for GLMM model



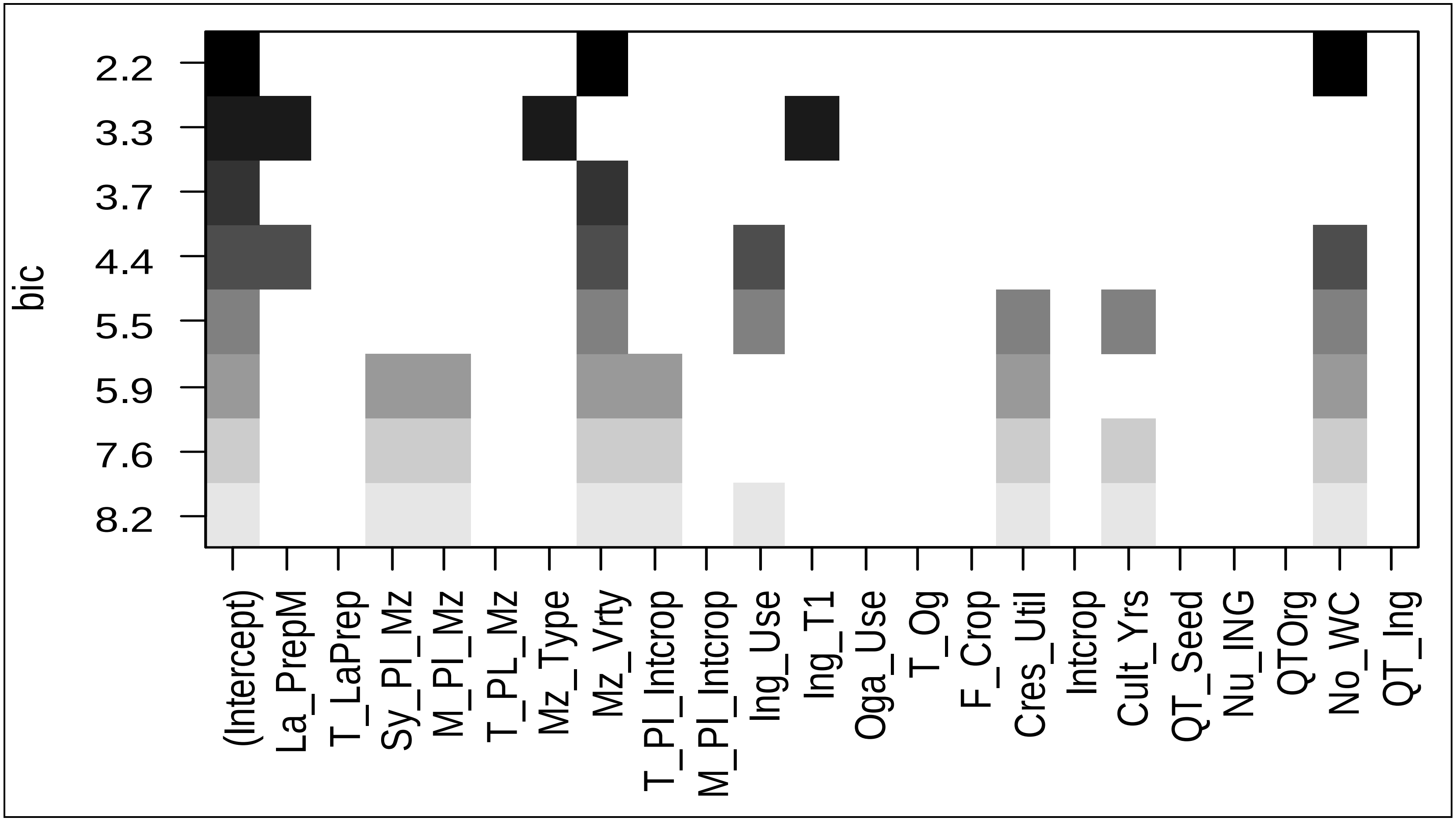
Age, Role of operator (Role_Op), Dec on land preparation (Dec_LaPrep), Family involvement in planting maize (FInvol_LaPrep), Family involvement in organic fertilizer application (FInvolv_Og), Membership to groups (MEMR), Female above 16 years (FMALE16)

Figure 5. A. 4: Socio-economic factors in Shikomoli selected for GLMM model



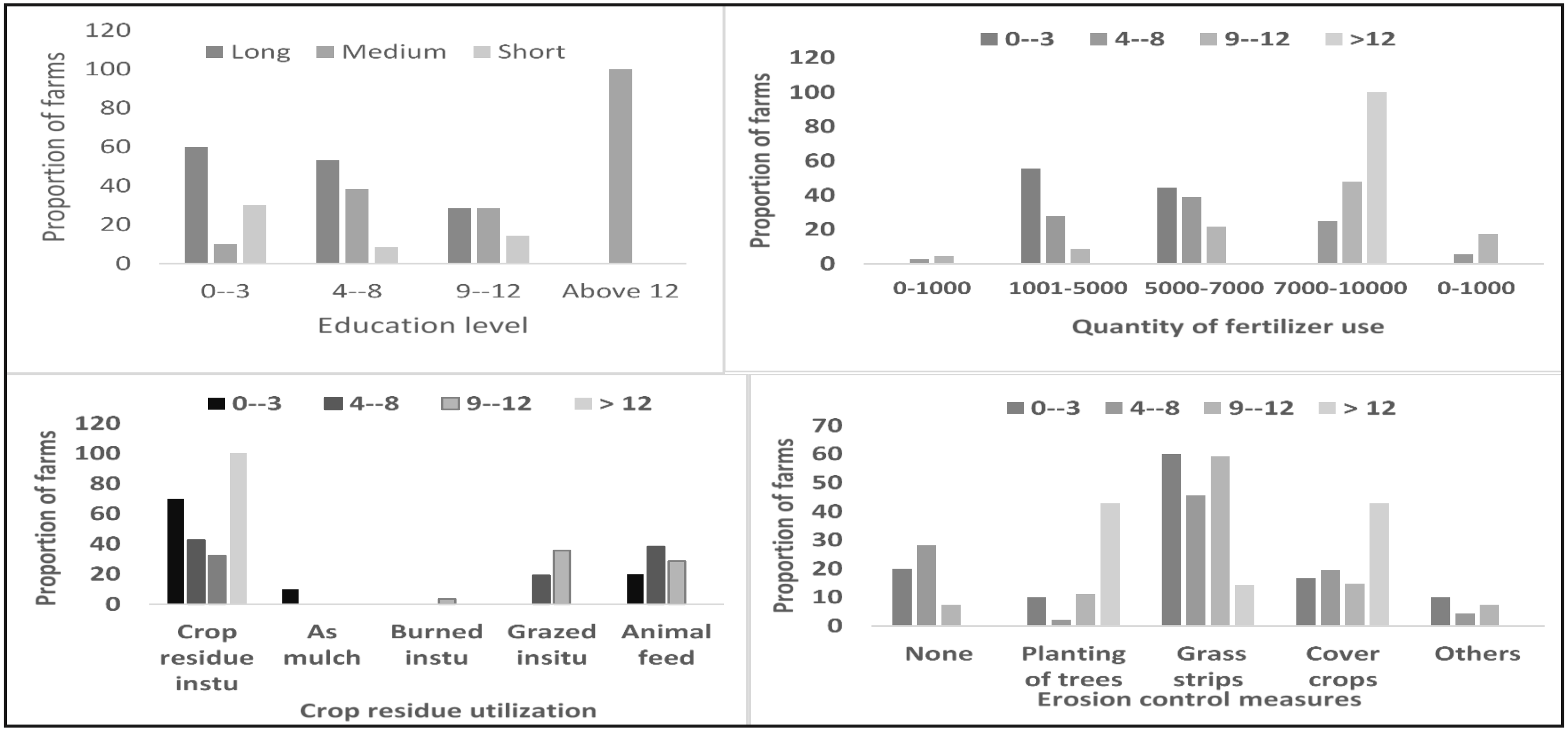
Legend: Time of land preparation (T_LaPrep3), Land preparation method (La_PrepM), Maize variety (MZ_Vrty), Organic fertilizer use (Oga_Use), Erosion control (Eros_Ctl), Intercrop use, Quantity of inorganic application (QTIng1), Quantity of organic fertilizer application (QTOrg)

Figure 5. A. 5: Management factors in Mukuyu selected for GLMM model



Legend: System of planting maize (Sy_Pl_Mz), Method of planting maize (M_Pl_Mz), Maize variety (Mz_Vrty), Time of planting intercrops (T_Pl_Intcrop), Crop residue utilization (Cres_Util), Cultivation years (Cult_Yrs), Number of weed control (No_WC)

Figure 5. A. 6: Management factors in Shikomoli selected for GLMM model



Legend: 0-3, 4-8, 9-12, >12 represent different education levels. 0-3 is primary education to level 3, 4-8 is primary education to level 8, 9-12 is secondary education to level 4, and >12 is college/university education. Long medium and short is the duration of maize growth.

Figure 5. A. 7: Education level versus maize variety (top-left), quantity of organic fertilizer use (top-right), erosion control (bottom-left) and crop residue utilization (bottom-right)

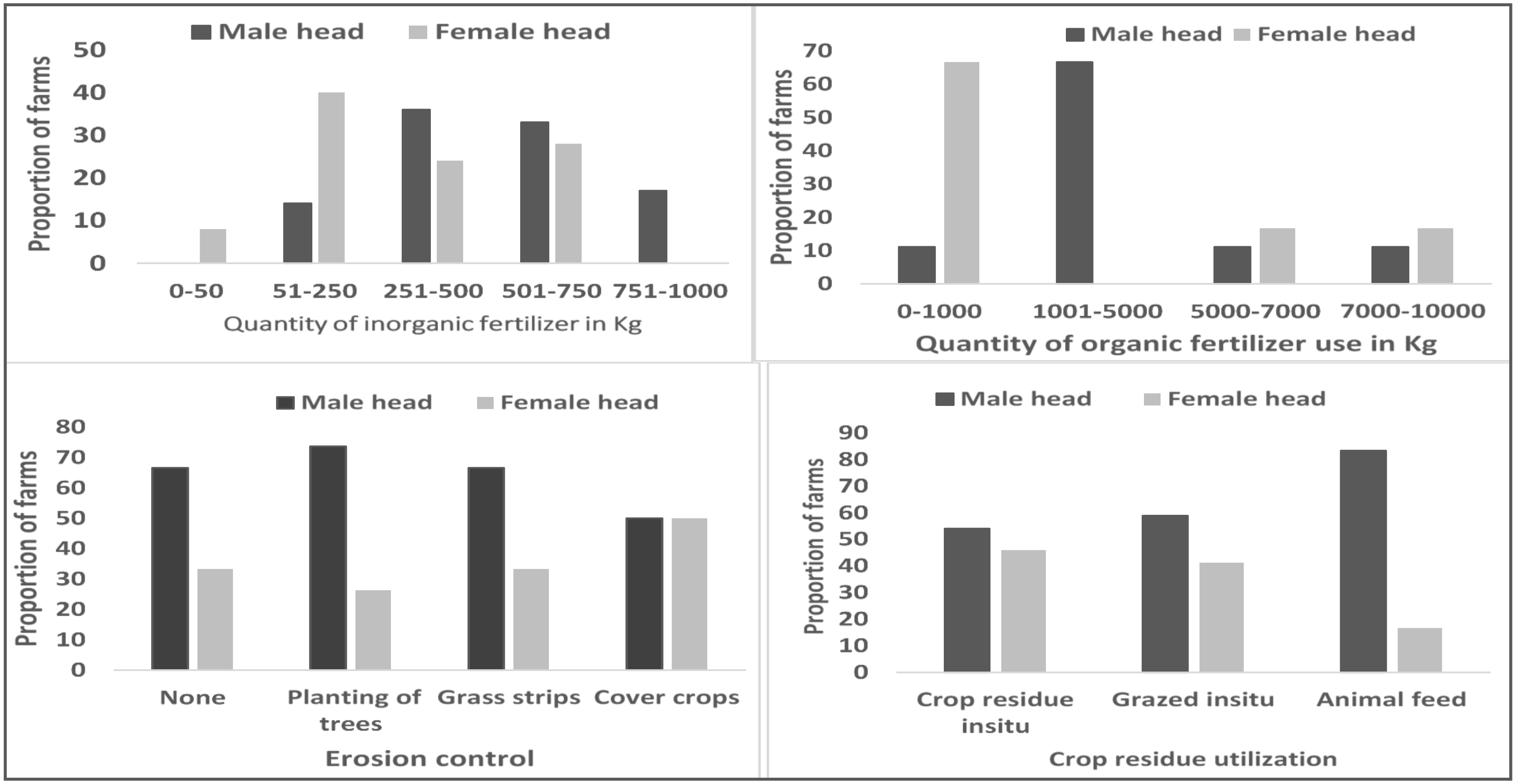
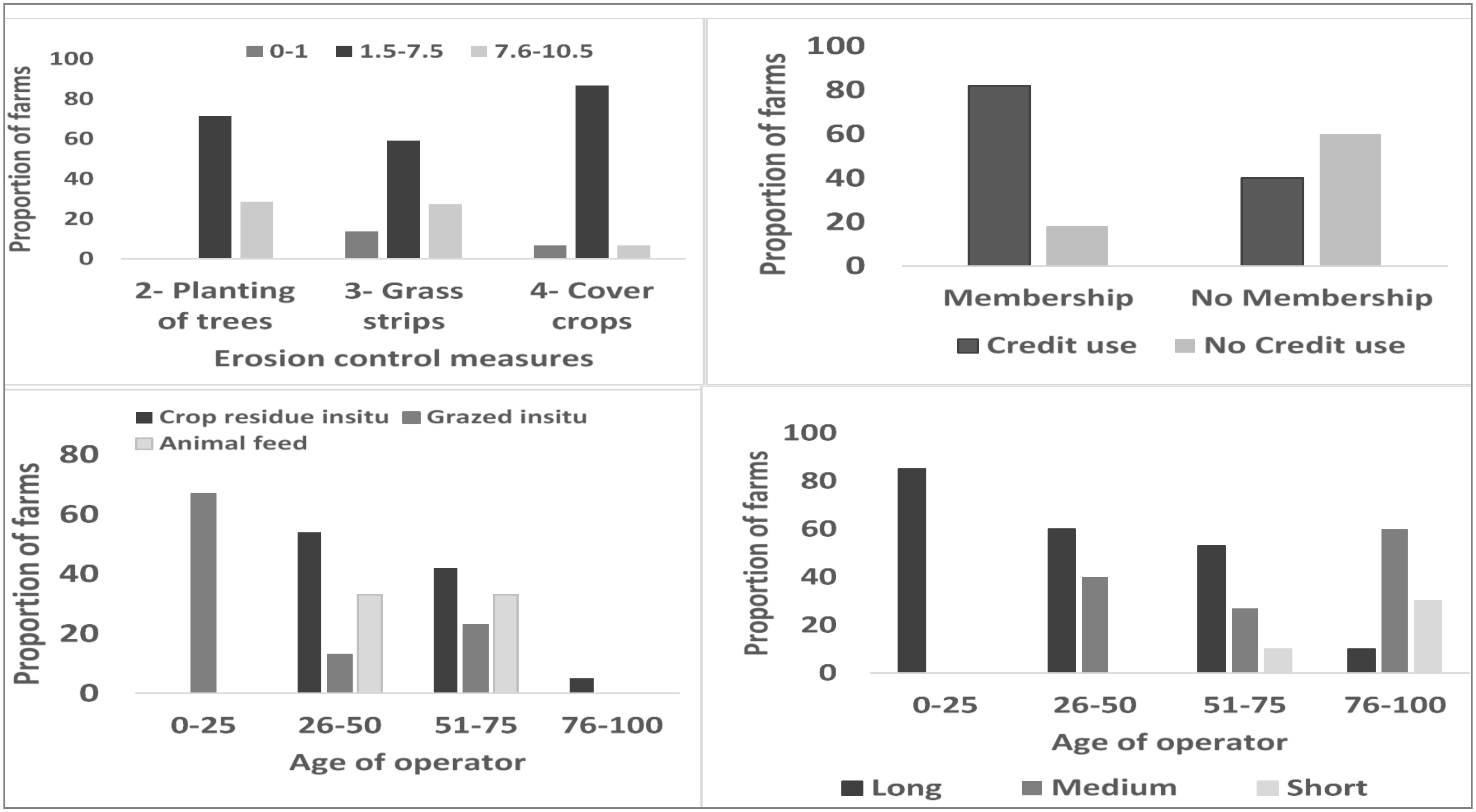


Figure 5. A. 8: Gender versus quantity of organic fertilizer use, erosion control and crop residue utilization



Legend; 0-1, 1.5-7.5, 7.6-10.5 is land size, long medium and short are maize varieties

Figure 5.A. 9: Figure Land size versus erosion control measures (Top left), Membership in groups versus credit facility utilization (Top-right), Crop residue utilization versus age of operator (Bottom left), Maize variety use versus age of operator (Bottom right)

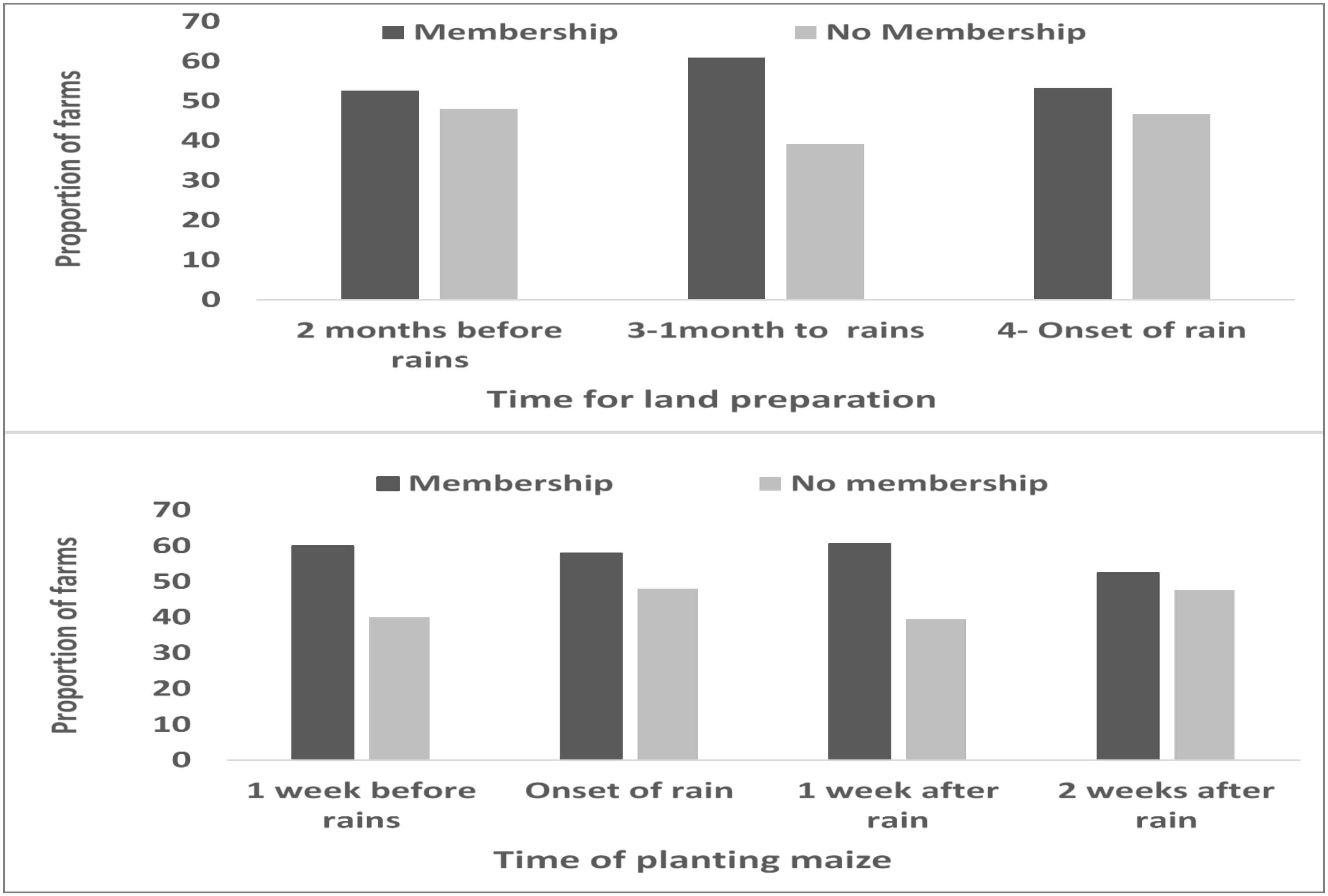


Figure 5.A.10: Time of land preparation and time of planting versus membership to groups

	Intercept	P	N	WC1	WH1	MDD1	MH3	SPAD3	SPAD1	MH1	WC3	PLOTDist	QTIng	TTLS	MDD3	B
	1															
P	-0.052	1														
N	-0.158	-0.078	1													
WC1	0.262	-0.136	-0.112	1												
WH1	0.172	-0.037	-0.025	-0.27	1											
MDD1	-0.517	-0.021	-0.242	-0.114	0.176	1										
MH3	-0.136	-0.02	-0.328	0.044	-0.043	0.129	1									
SPAD3	-0.487	-0.246	0.014	-0.391	0.098	0.195	0.181	1								
SPAD1	-0.49	-0.105	0.269	-0.016	0.245	-0.001	-0.486	0.158	1							
MH1	-0.365	0.058	-0.077	-0.117	-0.725	-0.171	-0.058	0.259	-0.26	1						
WC3	0.224	0.049	-0.015	-0.169	0.04	0.18	0.178	-0.043	-0.076	-0.049	1					
PLOTDist	-0.336	0.256	0.238	-0.108	-0.141	0.269	0.241	0.069	0.027	0.015	0.121	1				
QTIng	-0.108	0.158	-0.142	-0.074	-0.117	0.216	0.064	-0.227	-0.007	0.185	0.172	0.192	1			
TTLS	-0.182	-0.063	-0.121	-0.121	-0.128	0.026	-0.01	-0.163	-0.234	0.106	-0.169	-0.349	-0.017	1		
MDD3	0.059	-0.053	0.034	0.153	0.089	-0.681	-0.275	0.061	0.092	-0.053	-0.13	-0.033	-0.08	-0.26	1	
B	-0.055	-0.052	-0.209	-0.02	-0.062	-0.075	0.044	0.057	-0.048	0.082	0.021	0.121	0.119	0.25	-0.031	1

P-Phosphorus, N-Nitrogen, WC1-Weed cover in stage 1 of maize development, WH1-Weed height in stage 1, MDD1-Maize density in stage 1, MH3-Maize height in stage 3, Soil Plant Analysis Development (SPAD3)-Chlorophyll content in stage 3, SPAD 1-Chlorophyll content in stage 3, MH1-Maize height in stage 1, WC3-Weed height in stage 3, PLOTDist-Distance of the spatial arrangement form the homestead, TTLS-Total land size, MDD3-Maize density in stage 3, B-Boron

Figure 6.A 1: Correlation Matrix for Mukuyu

	Intercept	**P**	**N**	**WC1**	**WH1**	**MDD1**	**MH1**	**SPAD3**	**SPAD1**	**MH1**	**WC3**	**PLOTDs**	**QtIng**	**TTLS**	**MDD3**	**B**
Intercept	1															
P	-0.08	1														
N	-0.358	-0.357	1													
WC1	0.164	0.27	-0.055	1												
WH1	0.045	0.054	-0.089	-0.155	1											
MDD1	-0.279	0.12	-0.066	-0.232	-0.022	1										
MH1	0.157	-0.064	-0.144	-0.042	-0.054	-0.171	1									
SPAD3	0.034	0.007	-0.067	-0.154	0.104	0.105	-0.014	1								
SPAD1	-0.699	0.232	0.069	0.117	-0.042	0.299	-0.225	-0.143	1							
MH1	-0.186	-0.138	0.111	-0.088	-0.415	-0.006	-0.401	-0.145	-0.079	1						
WC3	-0.178	-0.069	0.074	-0.285	-0.087	-0.053	0.125	-0.211	0.082	0.136	1					
PLOTDs	0.001	-0.065	0.048	-0.122	-0.028	-0.025	-0.048	-0.195	-0.038	0.138	-0.091	1				
QtIng	-0.031	-0.047	0.031	0.055	0.043	-0.147	0.173	0.119	-0.119	-0.118	-0.127	-0.035	1			
TTLS	-0.363	0.257	-0.069	0.094	0.063	-0.021	-0.144	-0.256	0.319	0.089	0.176	-0.188	0.159	1		
MDD3	-0.114	0.032	-0.02	-0.04	0.06	-0.365	-0.198	-0.239	-0.192	0.059	0.098	-0.056	0.038	0.179	1	
B	-0.006	0.138	-0.164	0.135	0.02	0.006	-0.129	-0.036	0.027	0.014	0.113	-0.049	-0.022	0.175	0.23	1

P-Phosphorus, N-Nitrogen, WC1-Weed cover in stage 1 of maize development, WH1-Weed height in stage 1, MDD1-Maize density in stage 1, MH3-Maize height in stage 3, Soil Plant Analysis Development (SPAD3)-Chlorophyll content in stage 3, SPAD 1-Chlorophyll content in stage 3, MH1-Maize height in stage 1, WC3-Weed height in stage 3, PLOTDist-Distance of the spatial arrangement form the homestead, TTLS-Total land size, MDD3-Maize density in stage 3, B-Boron

Figure 6.A 2: Correlation matrix for Shikomoli