Potato-Legume Intercrop Effects on Water and Nutrients Use Efficiency, Crop Productivity and Soil Fertility in a Humic Nitisol, Kenya

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A80/50528/2016

A Research Thesis Submitted to the Graduate School in Fulfilment of the Requirements for the Award of Degree of Doctor of Philosophy in Soil Science

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2018

DECLARATION

This thesis is my original work and has not been presented for degree award in any other University.

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DEDICATION

To Prof. Charles K. K. Gachene and Prof. Nancy N. Karanja:

Thank you for capturing my attention a decade ago while I was just an undergraduate student and incentivising me in advance to consider pursuing postgraduate studies. Without your inspiration, I may not have discovered this great potential. Be blessed.

To all postgraduate students:

Whenever you feel like quitting, remember

Quitters never win and since you are a winner, quit not.

Whenever you feel discouraged, remember

The best source of encouragement is within you.

Whenever others say 'you cannot make it', remember

To say to yourself 'I am more than a conqueror, therefore I must make it'.

Above all, remember

To trust God in all your endeavours and work diligently.

ACKNOWLEDGEMENTS

First, I am sincerely grateful to my supervisors: Prof. Charles K. K. Gachene and Prof. Nancy N. Karanja (University of Nairobi) and Dr. Elmar Schulte-Geldermann (International Potato Center) for the unreserved critique and guidance they accorded to me throughout the study period, without which, completion of this thesis would have taken ages. Secondly, I acknowledge the International Potato Center for supporting this study with the funds from the Federal Ministry for Economic Cooperation and Development (BMZ) of Germany, Consultative Group for International Agricultural Research (CGIAR), Research Program on Roots, Tubers and Bananas (RTB) and the CGIAR Fund Donors. I am also indebted to Dr. Solomon Kamau and Dr. Kalpana Sharma for their valuable inputs during the publication process. I recognize the fellow Ph.D. students (Shadrack Nyawade, Joyce Aguk, James Mugo and Bruce Obura) who were supportive and always encouraged me to remain focused on this academic journey. In addition, I am appreciative of the excellent technical support from Boniface Muliro, John Kimotho and Ferdinand Anyika during laboratory analyses. Special regards to Herman Simidi, Michael Ngumo, Mary Atieno and Veneza Gesare for playing a key role in field trial management and data collection.

Lastly but not least, I acknowledge the moral support from my family members; mum Lena, the late dad Gitari, brothers (James, Timothy and Jamlick) and sisters (Janet, Anjoy, Jackline and Jane). Specifically, I am indebted to my immediate family members, Doris (wife), Abigael (daughter) and Caleb (son).

Above all, I thank the Almighty God for the immeasurable love, protection and guidance throughout this journey.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIC	Akaike Information Criterion
BBCH	Biologische Bundesanstalt Bundessortenamt and Chemical Industrie
BCR	Benefit: Cost Ratio
BD	Bulk Density
CEC	Cation Exchange Capacity
CGIAR	Consultative Group for International Agricultural Research
CIP	International Potato Center
DAP	Days After Planting
ET_o	Reference Evapotranspiration
GLM	Generalized Linear Models
HSD	Tukey's Honest Significant Difference
N	Nitrogen
NUE	Nitrogen Use Efficiency
NuPE	Nitrogen uptake Efficiency
P	Phosphorous
PEY	Potato Equivalent Yield
pH	A measure of the Hydrogen ion's concentration in the soil solution
PUE	Phosphorous Use Efficiency
PuPE	Phosphorous uptake Efficiency
RCBD	Randomized Complete Block Design
SD	Sampling Depth
SMC	Soil Moisture Content
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
θ_v	Volumetric soil water content

GENERAL ABSTRACT

Integration of legumes into potato-based cropping systems is a common practice in developing countries presumably as a water and nutrient management strategy. This study was conducted to assess the effect of incorporating legumes into the potato production system on soil water conservation, economic returns, nutrients (N and P) use efficiency, and soil physical and chemical properties. Field-based trials were conducted for four consecutive seasons between 2014 short rains and 2016 long rains at the Field Station, University of Nairobi. The treatments comprised of; a pure stand of potato (PS), potato-dolichos (*Lablab purpureus*) (PD), potato-bean (*Phaseolus vulgaris*) (PB) and potato-garden pea (*Pisum sativum*) (PG) intercrops, which were laid out in a randomized complete block design with each treatment replicated four times. The generated data on ground cover, soil moisture content, yield, economic returns, nutrient uptake and use efficiency, and soil physical and chemical properties were analysed using generalized linear models (GLM) in R software version 2.2.3, while means were separated using Tukey's Honest Significant Difference (HSD) at ($p \leq 0.05$). Pearson correlation analyses were applied to determine the relationship between the measured variables.

The highest ground cover of 69% was recorded at tuber initiation stage (56 days after planting) in PD compared to 66% in PG and PB and 56% in PS. Similarly, the highest soil moisture content (SMC) values were recorded at tuber initiation stage: 230, 207, 201 and 188 mm m^{-1} for PD, PG, PB and PS, respectively with significant ($p \leq 0.05$) differences between treatments. Nutrient uptake by potato was significantly higher in PS and PD than in PB and PG, which was a reflection of tuber yield that followed the trend of PS (36 t ha^{-1}) = PD (35) < PB (30) = PG (29). When tuber and legume grain yield were converted into potato equivalent yield (PEY), the intercropping systems outperformed the potato pure stand. For instance, PD had

significantly ($p \leq 0.05$) the highest economic returns of US$ 9,174 ha^{-1}, nitrogen use efficiency of 43 kg PEY kg^{-1} N supply and phosphorous use efficiency of 169 kg PEY kg^{-1} P supply.

After two years of potato-legume cultivation and incorporation of crop residues into the soil, soil physical and chemical properties at 0.3 m depth such as sand, silt and clay were only influenced by slope position with sand decreasing down the slope whereas, the opposite was observed for silt and clay. Bulk density (BD) was significantly ($p \leq 0.05$) above the initial value (1.03 g cm^{-3}) recorded before the start of the experiment and increased down the slope in all treatments with averages of 1.21, 1.14, 1.13 and 1.07 g cm^{-3} in PS, PB, PG and PD, respectively. PD recorded significantly ($p \leq 0.05$) higher pH (5.9), total nitrogen (3.7 g kg^{-1} N), organic carbon (37 g kg^{-1}), available P (26 mg kg^{-1}) and cation exchange capacity (34 $cmol_c$ kg^{-1}) compared to all other intercropping systems. Sand and BD were inversely (r = 0.33–0.84; $p \leq$ 0.05) correlated with the soil chemical properties such as pH, P, N OC and CEC which in turn were directly (r = 0.38–0.49; $p \leq 0.001$) correlated with clay. The data in this study indicate that intercropping potato with *L. purpureus* is a sustainable production practice that would ensure high tuber yield and improved soil fertility.

Keywords: Potato-legume intercropping systems; Potato equivalent yield; Economic returns; Nutrient uptake efficiency, Nutrient use efficiency; Crop residue incorporation; Soil fertility; Slope position; Spatial variation; Soil physico-chemical properties.

CHAPTER ONE

General Introduction

1.1 Background information

Potato (*Solanum tuberosum* L.) traces its origin in southern Peru, South America where its domestication started about a millennium ago (Burke, 2017; Levy and Rabinowitch, 2017). Since then, the crop has been distributed globally taking the fourth position as the most consumed staple food crop after maize, wheat, and rice (Devaux et al., 2014; FAOSTAT, 2017). Its demand is rising at a greater rate than any other food crop and it is projected to surpass that of wheat and rice by 2020 in terms of production volume and human consumption (IPC, 2009; Raei, 2015). In Kenya, potato is the most grown root crop mainly in the highlands by smallholder farmers for income generation and as a key source of starch (Kaguongo et al., 2007; Schulte-Geldermann et al., 2012; Muthoni et al., 2013; Demo et al., 2015; Okello et al., 2017). However, the average potato yield in the country is about three times lower than the 30–40 t ha^{-1} attainable under normal field conditions (Muthoni et al., 2013; Gitari et al., 2018a and b; Harahagazwe et al., 2018). This is attributed to unreliable rainfall patterns, low soil fertility compounded with potato's shallow rooting system, which makes it susceptible to drought (Mugo et al., 2016; Reyes-Cabrera et al., 2016; Burke, 2017).

Potato production takes place in highlands that are characterized by mountainous terrain, which are prone to erosion due to high-energy rainfall storms that are common in those areas (Gachene et al., 1997; Burke, 2017; Nyawade et al., 2018). Given that potato cultivation involves a lot of soil movement particularly during hilling up, the soil is exposed to erosion processes. With continuous cultivation, the soil in such hilly areas become degraded with varying fertility gradients across the slope (Sadeghi and Sasanfar, 2013; Selassie et al., 2015; Rosemary et al., 2017). Cultivating potato on such degraded soils results in not only low yield due to the variability in soil fertility but also denies the soil its natural ability to revitalize (Mallory and Porter, 2007; Gitari, 2013; Nyiraneza et al., 2015; Usowicz and Lipiec, 2017). Therefore, research on water and nutrient utilization and the residual effect on soil chemical properties under potato-legume intercropping systems are important in informing on the best soil fertility management practises.

Various strategies have been proposed to promote water and nutrient utilization such as increasing the amount of fertilizer applied and/or synchronizing the application with crop's requirement, supplementing rainfall with irrigation and mulching using plastic film (Carli et al., 2014; Zhang et al., 2016b; Lam et al., 2017; Yactayo et al., 2017; Zhang et al., 2017b; Rens et al., 2018). Nevertheless, even though these strategies have yielded positive results in developed countries, their adoption in Kenya are hindered by poverty and ignorance. Thus, development of other innovative strategies, tailored for the smallholder farmers who are dependent on agriculture for their livelihood is vital.

Integration of legume crops into potato production systems might be a viable opportunity that could address these challenges. Intercropping has many advantages such as increased yield, reduced erosion and accelerated nutrient recycling, particularly when crop residues are ploughed back (Ogindo and Walker, 2005; Sharaiha and Hadidi, 2008; Rezig et al., 2013; Nyawade, 2015; Singh et al., 2017). Nevertheless, the role of legumes in influencing water and nutrient utilization under potato-legume-based intercropping systems is not well understood. Thus, this study aimed at assessing the performance of potato when intercropped with selected grain legume crops in order to identify a viable potato-legume intercropping systems that would improve crop productivity and nutrient use efficiency under tropical rain-fed agriculture.

1.2 Problem statement and justification of the study

The potato sector in Kenya is still underdeveloped with low production of 8–15 t ha^{-1}, against the attainable yield of 30–40 t ha^{-1} under field conditions (Muthoni et al., 2013; Gitari et al., 2018a and b). Although potatoes are commonly grown in the wet highland zones, dry periods with soil moisture deficit often occurs due to erratic rainfall patterns (Muthoni et al., 2013; Mugo et al., 2016; Nyawade et al., 2018). This is an indication that rain-fed potato-based intercropping systems in Kenya are vulnerable to climatic variability and therefore, focus on maximizing yield per unit of water and fertilizer applied is imperative. Diversification of the potato-based cropping systems to include intercrops could be fundamental in addressing these challenges as it improves crop productivity through a more effective use of natural resources such as rainfall and externally added inputs like fertilizers.

Although potato has previously been intercropped with various crops such as maize (*Zea mays* L.), beans (L.), spinach (*Spinacia oleracea* L.), sulla (*Hedysarum coronarium* L.), and radish (*Raphanus raphanistrum* L.) (Sharaiha and Hadidi, 2008; Rezig et al., 2013; Fan et al., 2016; Singh et al., 2016; Zhang et al., 2016b), there is a dearth of information on potato–legume intercrops. The few studies available that have been carried on potato-legume intercropping systems; only focused on either the effect on light interception and/or the dry matter production efficiency (Rezig et al., 2013) or were carried under advanced technologies such as plastic film mulch, which poor farmers cannot afford (Zhang et al., 2016b). Legumes play significant roles in the potato-based cropping systems contributing to family nutrition, income generation and building fertile soils for a sustainable future. Their inclusion in such systems will lead to productive potato farming system, hence contributing to the goal of crop diversification.

1.3 Study objectives

1.3.1 General objective

To evaluate the effects of intercropping potato with legumes on soil water conservation, crop productivity and economic returns, nutrients use efficiency and soil physico-chemical properties.

1.3.2 Specific objectives:

i. To determine yield and economic returns as influence by soil moisture conservation under different potato-legume intercropping systems.
ii. To evaluate the nitrogen and phosphorous use efficiency under potato-legume intercropping systems.
iii. To assess the effect of potato-legume intercropping systems and incorporation of crop residues on selected soil physico-chemical properties.

1.4 Hypotheses

i. There is significantly higher soil water conservation under potato-legume intercropping systems compared to pure potato stand, which results in higher yield and economic returns.
ii. Nitrogen and phosphorous use efficiency under potato-legume intercropping systems are higher compared to pure potato stand.
iii. Intercropping potato with legumes and incorporation of residues improves soil physico-chemical properties.

1.5 Structure of the Thesis

This is a seven-Chapter thesis with Chapter 1 giving a general introduction, problem statement and justification, objectives and the hypotheses of the study. General materials and methods are presented in Chapter 2 whereas literature review is presented in Chapter 3. Chapter 4 examines the effects of integrating legumes into potato-based cropping system on soil water conservation, yield and economic returns while Chapter 5 focuses on the effect of the legume intercrops on nutrient (N and P) uptake and use efficiency. Chapter 6 covers the effects of crop residue incorporation on selected soil physical and chemical properties. Chapter 7 presents a synopsis of the results obtained in different experiments, conclusions and recommendations.

CHAPTER TWO

Literature Review

2.1 Potato production systems and their geographical distribution in Kenya

About 83% of the national potato production in Kenya takes place mainly in highland areas with an altitude of between 1,200 and 3,000 m above sea level by smallholder farmers on small pieces of land, which rarely exceeds 0.5 ha (Kaguongo et al., 2007; Janssens et al., 2013; Okello et al., 2017). Production areas include the slopes of Mt. Kenya, such as Meru and Embu, parts of Laikipia and Nyandarua counties. In addition, potatoes are grown in Cherangani hills and in the highlands of Mau and Nandi escarpments. There is also small-scale potato production in Kericho, Kisii and Taita Hills (Janssens, et al., 2013). Among the varieties preferred in the country are Shangi, Asante, Unica, Dutch Robijn and Konjo (Schulte-Geldermann et al., 2012; Kaguora et al., 2015; Harahagazwe et al., 2018).

Potato production is usually carried out continuously resulting in decreasing land productivity (Sadeghi and Sasanfar, 2013; Elias, 2017; Nyawade et al, 2018). These researchers noted that more than 60% of the soil loss occurs from cultivated, moderate to steep slopes that are tilled repeatedly and generally left without vegetation cover. Potato production in farms with 10–30% slope is faced with much soil moisture variability that is influenced by factors, such as topography, vegetation, land uses and precipitation (Selassie et al., 2015; Usowicz and Lipiec, 2017). Potato cultivation on such sloping terrain can be sustained by intercropping hence reducing the loss of soil and nutrients through water erosion (Nyawade, 2015; Fan et al., 2016).

2.2 Potato cultivation under intercropping systems

Declining soil fertility and food insecurity coupled with high poverty levels have compelled farmers to look for alternative interventions of increasing crop production. In addition to sole potato cropping systems, farmers intercrop it with other crops such as maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), sulla (*Hedysarum coronarium* L.) and radish (*Raphanus raphanistrum* L.) (Sharaiha and Hadidi, 2008; Rezig et al., 2013; Fan et al., 2016; Singh et al., 2016; Zhang et al., 2016b). Intercropping is an agricultural practice involving cultivation of multiple crops in the same land either concurrently or within the same cropping season (Sharaiha and Hadidi, 2009; Singh et al., 2016). It differs from mono cropping, which entails cultivation of only one crop in pure stands. Such multiple cropping systems have existed for decades in both advanced and developing nations playing a vital role in subsistence food production (Lithourgidis et al., 2011; Rezig et al., 2013; Sadeghi and Sasanfar, 2013).

Intercropping systems have several benefits over sole cropping systems including increased crop yields with higher combined returns and profitability per unit area of cultivated land (Hinsinger et al., 2011; Zhang et al., 2016b; Gitari et al., 2018a). In an intercropping system, both negative and positive interactions occur simultaneously between the crops grown (Mariotti et al., 2009; Kibunja et al., 2010). With positive interaction, crops performance is improved since the microenvironment for utilizing available resources is improved while with negative interaction, crops compete for the limited resources leading to restrained growth (Brooker et al., 2008). Thus, when competition between crops is minimized, intercropping systems can use environmental resources more efficiently hence improving the sustainability of crop production (Mucheru-Muna et al., 2010). According to Onuh et al. (2011), greater yield stability and land use efficiency, which is an index that embraces economic returns from the same piece of land within a specified period, including better use of growth resources are derived from intercropping systems. The difference in use of above and below ground growth resources by the component crops in an intercropping systems leads to yield advantages.

Intercropping increases competitive ability of crops towards weeds due to the better soil cover leading to reduced soil erosion and nutrient leaching (Mucheru-Muna et al., 2010). Legumes can rely on atmospheric N; therefore, they are less likely to compete for N with potato leading to improved soil fertility due to the addition of fixed nitrogen and excretion from the component legumes (Ojiem et al., 2007; Hauggaard–Nielsen, 2009; Sitienei et al. 2017). The fixed nitrogen can be relocated to the non-legume intercrop such as potato.

Leguminous crops can provide food and fodder for smallholder farmers (Valbuena et al., 2015; Whitbread et al., 2011; Sennhenn et al., 2017) and their inclusion in potato-based cropping systems could boost among other dietary supply: carbohydrate, protein, fats and vitamins for the rural household. In fact, legumes contain about three times more food protein than tubers (Maass et al., 2010; Onuh et al., 2011). Intercropping potato with legumes will further enhance a better use of environmental resources besides providing better yield stability, reducing pests and diseases hence diversifying rural income (Njoku et al., 2007).

2.3 Water conservation and nutrients (N and P) use efficiency under potato-legume intercropping systems

Soil moisture plays a vital role in ecological processes like infiltration, run-off and transportation of solutes (Daly and Porporato, 2005; Okeyo et al., 2014; Kalinda et al., 2015). Water is the most important compound in an active plant and makes up more than 80% of the growing tissue (Alaa et al., 2012; Paredes et al., 2018). It varies in space and time depending on topography, land use, soil type, rainfall amount and ground cover (Xiao et al., 2014). Such variations in soil moisture generally have adverse impacts on crop productivity (Kumar et al., 2000; Purcell et al., 2007). Therefore, to boost potato production, there is a need to maintain adequate water levels throughout most part of crop's growth stages (Yactayo et al., 2017).

Potato has a shallow rooting system with nearly 85% of its roots being concentrated on the upper 0.4 m of the soil, hence, making it very sensitive to drought conditions, particularly during the tuber initiation and filling stages (Tourneux et al., 2003; Reyes-Cabrera et al., 2016; Burke, 2017). In order to boost potato yields, regular water supply is required to meet about 500-700 mm requirement in a growing season (Sood and Singh, 2003; Ierna and Mauromicale, 2012; Levy et al., 2013). However, under rain-fed agriculture, potato production is jeopardized by the erratic rainfall patterns that are common in sub-Saharan counties (Mugo et al., 2016). This calls for viable interventions to conserve soil moisture and boost tuber yield. Some strategies that have been used to increase crop productivity include supplemental irrigation, use of plastic film, use of crop residues as mulch, increased amount of fertilizer applied and synchronizing fertiliser application with crop needs (Carli et al., 2014; Mahinda et al., 2016; Zhang et al., 2016b; Zhang et al., 2017b). Nevertheless, although such strategies have been proofed to yield positive results in developed countries, high poverty levels coupled with ignorance deter farmers in sub-Saharan Africa from adopting them.

Integration of intercrops into potato production systems could be an option to address these challenges. Through intercropping, evaporation from the soil surface can be checked due to increased canopy cover hence promote higher moisture retention leading to increased crop production (Ogindo and Walker 2005; Karuma et al., 2011, 2014; Nyawade, 2015; Singh et al., 2017). The higher canopy under intercropping systems creates a microenvironment with reduced solar radiation reaching the soil surface and low temperatures (Webb et al., 2010; Gericke et al., 2012; Zhaohui et al., 2012). Similar findings have been reported under other intercropping systems such as dolichos-sweet potato (*Ipomea* batatas L.) (Chepkemoi et al., 2014) and dolichos-cassava (*Manihot esculanta* Crantz) (Namoi et al., 2014) and potato-maize

(*Zea mays* L.). The component crops in such intercropping systems utilize water better leading to increased crop productivity as compared to sole cropping systems. For instance, Sharaiha and Hadidi (2008) reported a significant increase in crop water productivity ranging from 0.83 to 0.96 kg m^{-3} attained when potato was intercropped with bean over the values obtained under sole cropping systems of potato. Crops that have been integrated into potato cropping systems include maize, sulla, spinach, radish and beans resulting in increased water use efficiency (Sharaiha and Hadidi, 2008; Rezig et al., 2013; Fan et al., 2016; Singh et al., 2016; Zhang et al., 2016b).

Besides improved water utilization under intercropping systems, there is also enhanced nutrients exploitation resulting in higher nitrogen and phosphorous uptake and use efficiency. In this case, nutrient uptake efficiency reflects the portion of the applied nutrients, which after being taken up by potato plant is used for tuber development (Dobermann, 2007; White et al., 2018). On the other hand, nutrient use efficiency denotes the balance between the harvested economic yield and the available nutrients (Weih et al., 2017). Nitrogen helps in balancing between the vegetative and reproductive growth of potato resulting in increased tuber yield (Alva, 2004). Nitrogen improves tuber size hence increasing the overall yield as attested by Singh and Lal (2012), who obtained a 40 t ha^{-1} yield of potato with an application N at the rate of 225 kg ha^{-1}. Phosphorous is also needed in large quantities by potatoes, and it plays a big role in increasing plant height, marketable tuber yield as well as the tuber number (Zelalem et al., 2009; Hopkins et al., 2014; Manschadi et al., 2014). Adequate soil P availability is important for early crop development, tuber initiation and maturity, and increasing water-use efficiency (Fernandes and Soratto, 2012; Manschadi et al., 2014).

Proper selection of crops to be used as candidates for intercropping can result in improved nutrient uptake and use efficiency, hence reducing not only cost on fertilizers but also nutrients losses due to erosion (Hinsinger et al., 2011; Nyiraneza et al., 2017). This is achievable when crops complement one another especially when the companion crops have different rooting depths (Richardson et al., 2009; Zhang et al., 2017a; Gitari et al., 2018a and b). According to Kutu and Asiwe (2010) and Franco et al. (2015), there is a complementary relationship among the components crops when they have different rooting depths and growth characteristics. For instance, roots of legumes such as dolichos can grow up to 2 m deep into sub-soil and extract nutrients and water, hence reducing competition with shallow-rooted crops for such resources at the surface soil strata (Ojiem et al., 2007; Whitbread et al. 2011; Gitari et al., 2018a and b). Such enviable characteristics make dolichos a drought tolerant and multipurpose legume as it is cultivated for green pods and grain, and as fodder (Whitbread et al., 2011; Sennhenn et al., 2017). However, little is known of this crop as an intercrop in potato-based intercropping systems.

Part of the nutrients applied through fertilizer may not be taken up by the plants, hence are susceptible to losses pathways such as erosion and leaching, which results in dire environment effects such as eutrophication of surface water bodies (Zhaohui et al., 2012; Jones et al., 2013; Hopkins et al., 2014; Rens et al., 2018). This results in spatial variability of soil properties within a farm field as the eroded materials are transported from higher parts of the slopes and finally are deposited at lower sides (Selassie et al., 2015; Rosemary et al., 2017). Ploughing back of crop residues can help replenish lost nutrient hence restoring soil fertility (Mugwe et al., 2009; Kibunja et al., 2010; Nyiraneza et al., 2015; Walia and Dick, 2018). Such a management practice has been shown to improve crop production with positive effects on yield, soil physical and chemical properties (Mallory and Porter, 2007). This could be a promising option for enhancing the productivity of potato-based intercropping systems as well as protecting the environment (Selassie et al., 2015; Usowicz and Lipiec, 2017). The assimilated crop residues decompose, hence release the nutrients bound in them to the succeeding crop (Cheruiyot et al., 2007; Ojiem et al., 2007). However, due to other uses of crop residues such as fuel and fodder, farmers rarely incorporate them after crop harvest (Valbuena et al., 2015). Therefore, there is a need to enlighten the farmers on the importance of such a practice, which would not only improve crop productivity but also, promote environmental health.

CHAPTER THREE

General Materials and Methods

3.1 Study site

This study was conducted at Kabete Field Station located in the University of Nairobi at 1° 15' S, 36° 44' E and 1860 m above sea level for four consecutive rainy seasons between 2014 short rains and 2016 long rains. The soil is dominated by kaolinite clay minerals derived from Nairobi trachyte and is well drained, deeply weathered with moderate inherent fertility, hence classified as a Humic Nitisol (Gachene et al., 1997; Karuku et al., 2012; Gitari et al., 2015; IUSS Working Group WRB, 2015). The area receives a bimodal rainfall with an annual average of about 1000 mm with long rains typically occurring from March to June and short rains from October to December whereas the minimum and maximum temperatures are 16 °C and 28 °C, respectively. Besides potato, other horticultural crops cultivated in the area include, carrots (*Daucus carota* L.), cabbages (*Brassica oleracea* L.), onions (*Allium cepa* L.) kales (*Brassica oleracea* L.) and tomatoes (*Solanum lycopersicum* L.) while coffee (*Coffea Arabica* L.) is the main cash crop.

3.2 Rationale for choosing the study site

Between 2014 and 2016, the International Potato Center (CIP) and the University of Nairobi were implementing a project that aimed at improving soil fertility in potato-based cropping systems mainly in Kenyan highlands. Kabete Field Station, which is based at the University of Nairobi, was therefore chosen to generate data for this project under different objectives in a more integrated approach. Specifically, the site is a typical representative of Kenyan highlands where potato cultivation takes place and there was no other study done in the same area on potato-legume intercropping systems. In this case, it was advantageous to have the current study conducted on the same site and generate plot-scale data to inform on the most viable potato-legume intercropping systems, which has the potential of being upscaled to potato growing regions in sub-Saharan Africa for improved crop productivity and soil fertility.

3.3 Research approach

This study adopted a field-based trial, which was conducted for four consecutive seasons between 2014 and 2016. The treatments, which were potato (*Solanum tuberosum* L.) - legume intercropping systems, included potato-dolichos (*Lablab purpureus* L.), potato-bean (*Phaseolus vulgaris* L.) and potato-garden pea (*Pisum sativum* L.) and a control with a pure stand of potato. These were laid out in a randomised complete block design (RCBD) with each treatment replicated four times. The inter-row spacing for seed potatoes was 0.9 m and inter-seed spacing was 0.3 m whereas legumes were planted in between in a single row with two seeds per hill and spaced at 0.25 m. Fertilizer application was only done on potato with NPK (17:17:17) fertilizer at the planting time at the rate of 200 kg ha^{-1} and with calcium ammonium nitrate (CAN) at the same rate 28 days after planting (DAP). All other appropriate cultural practices such as weeding, spraying, hilling up and staking were also performed accordingly. Harvesting was done between 65 and 75 DAP for peas, 84 DAP for potato and beans and 120 DAP for dolichos, after which all plant residues were ploughed back into the soil. Soil sampling for post-crop analyses was carried out in September 2016.

For the first objective, on crop water conservation and utilization, the data collected included potato tuber and legume grain yield (which were converted into potato equivalent yield), soil moisture and ground cover based on different potato development stages (stolon development, tuber initiation, tuber bulking, and tuber maturity). To address the second objective, the data on nitrogen and phosphorous uptake by potato tissues were obtained by analysing tuber and shoot tissues in the laboratory. The residual effects of the potato-legume intercropping systems coupled with the incorporation of crop residues were assessed by analysing selected soil physical and chemical properties after the four seasons. The data generated in this study were analysed using general linear models in R software version 2.2.3 (R Core Team, 2015) and the means were separated using Tukey's Honest Significant Difference (HSD) test at $p \leq 0.05$ (Abdi and Williams, 2010).

CHAPTER FOUR

Optimizing yield and economic returns of rain-fed potato (*Solanum tuberosum* L.) through water conservation under potato-legume intercropping systems

Abstract

Even though potato (*Solanum tuberosum* L.) - based intercropping systems are widely practised in developing countries, only a few studies have focused on legumes as the companion intercrops. This study was conducted to assess the effect of incorporating legumes into the potato production system on ground cover, soil moisture content (SMC), tuber and legume yield, potato equivalent yield (PEY), gross and net income and benefit: cost ratio (BCR). The treatments comprised of pure potato stand (PS), potato-dolichos (*Lablab purpureus* L.) (PD), potato-garden pea (*Pisum sativum* L.) (PG) and potato-bean (*Phaseolus vulgaris* L.) (PB). Results indicated a significantly ($p \leq 0.05$) higher (69%) ground cover at tuber initiation stage in PD compared to 66% in PG and PB and 56% in PS. Similarly, the highest SMC values were recorded at tuber initiation stage: 230, 207, 201 and 188 mm m^{-1} in PD, PG, PB and PS, respectively. Fresh tuber yield was highest in PS (36 t ha^{-1}) and PD (35 t ha^{-1}) and lowest in PG (29 t ha^{-1}). PEY was higher under intercropping than monocropping systems. Potato-dolichos was the most profitable intercropping system with a net income of US\$ 9174 ha^{-1} and a BCR of 5.7 compared to PS (US\$ 7436 ha^{-1}) with a BCR of 5.1. The study showed that dolichos is a promising legume crop that could be integrated into potato cropping systems to improve on water utilization without compromising the tuber yield.

Published in Agricultural Water Management Journal - Elsevier:

https://doi.org/10.1016/j.agwat.2018.06.005

4.1 Introduction

Potato (*Solanum tuberosum* L.) is an important food security crop and a major source of household income for smallholder farmers in Kenya. The country's area under potato production is 145,967 ha with an annual production of approximately 1.3 Tg (where 1 Tg = 10^{12} g) (FAOSTAT, 2017). Nevertheless, potato sector in Kenya is still underdeveloped and is faced with low productivity of 8–15 t ha^{-1}, despite the attainable yield of 30–40 t ha^{-1} under normal field conditions (Muthoni et al., 2013; Gitari et al., 2018b). The low productivity is mainly ascribed to the erratic rainfall patterns (Mugo et al., 2016). Potato is mainly affected due to its superficial and fibrous root system of which about 85% is concentrated in the upper 0.3 m zone of the soil profile making the crop very susceptible to drought (Reyes-Cabrera et al., 2016; Burke, 2017; Aliche et al., 2018).

Potato production under rain-fed agriculture thus requires a focus on water use efficiency (Pereira et al., 2012). Various interventions that have been promoted to increase water use efficiency in rain-fed agriculture, include increasing the amount of fertilizer applied to crops, supplemental irrigation, use of plastic film and use of crop residues as mulch (Kumar et al., 2000; Essah et al., 2012; Carli et al., 2014; Zhang et al., 2016b, 2017b). Nevertheless, the first three interventions are far beyond the financial ability of most resource-constrained farmers in Kenya. On the other hand, one challenge of using crop residues as a moisture conservation strategy in potato production is their availability in adequate quantities coupled with their competitive uses such as fuel and fodder (Karuku et al., 2014; Gachene et al., 2015). In addition, under tropical conditions, organic mulches decompose rapidly besides being susceptible to termite infestation (Gachene et al., 2015; Kamau et al., 2017). Systematic integration of legume crops into potato production systems could be a viable option for addressing these challenges. These crops can enhance soil moisture conservation by covering the soil surface, which significantly reduces water loss through run-off and evaporation (Ogindo and Walker, 2005;

Karuma et al., 2011; Chepkemoi et al., 2014; Namoi et al., 2014; Gitari et al., 2017; Singh et al., 2017). Various crops such as maize, sulla, spinach, radish and beans have been intercropped with potato, resulting in increased water use efficiency (Sharaiha and Hadidi, 2008; Rezig et al., 2013; Fan et al., 2016; Singh et al., 2016; Zhang et al., 2016b). However, most of these studies focused on potato under non-legume intercropping systems. Sharaiha and Hadidi (2008) reported higher water use efficiency under potato-bean intercropping under irrigation, and Singh et al. (2016) observed higher potato equivalent yield when potato was intercropped with radish. In Kenya, intercropping of potato with legumes (dolichos, garden peas and beans) has been reported to reduce run-off and soil loss compared with the pure stand of potato (Nyawade, 2015). However, the author did not monitor the soil moisture dynamics under those intercropping systems.

Lower soil moisture occurring during tuber formation and bulking stages is very critical and can reduce yield more than when it happens at any other growth stage of the potato (Steduto et al., 2012). To attain the potential potato yield, adequate soil moisture should be available in the rooting zone, particularly during tuber formation stage (Reyes-Cabrera et al., 2016). Depending on the soil type, climatic conditions and growth period, potato requires about 500−700 mm of water in a growing season (Sood and Singh, 2003; Ierna and Mauromicale, 2012).

Given the importance of potato as a food security crop in the most sub-Saharan farming system, there is a need to understand how the integration of different legumes into potato production system affects the tuber yield. Therefore, the aim of this study was to assess ground cover and soil moisture content under potato-legume intercropping systems, and the effects of these systems on economic yield and returns.

4.2 Materials and methods

4.2.1 Experimental site description

The experiment was conducted at Kabete Field Station, College of Agriculture and Veterinary Sciences, University of Nairobi. The site falls in the sub-humid agro-ecological zone (Jaetzold et al., 2006), and lies at 1° 15' S, 36° 44' E, and at 1860 m above sea level. Rainfall occurs in a bimodal pattern, from October to December and March to June, and locally referred to as short and long rains, respectively.

4.2.2 Soil physical and chemical properties of the experimental site

The soil is classified as a Humic Nitisol, which is dark red to dark reddish-brown, well-drained, clayey and very deep (more than 1.8 m) with low to moderate inherent soil fertility (Gachene et al., 1997; Karuku et al., 2012; Gitari, 2013; Gitari et al., 2015; IUSS Working Group WRB, 2015). Before establishing this experiment, twelve soil samples were taken as described by Pennock and Yates (2008) at 0−0.3 m depth, and they were composited, air-dried and ground to pass through a 2 mm sieve. Soil pH (soil: water ratio of 1: 2.5) was measured using a pH meter (Ryan et al., 2001), total N by modified micro-Kjeldahl method (Bremner, 1996) and organic carbon (OC) by modified Walkley and Black method (Nelson and Sommers, 1996). Phosphorous was extracted by Mehlich-1 method (Mehlich, 1978) then measured using a UV-vis spectrophotometer (Murphy and Riley, 1962). Cation exchange capacity was analysed following procedures provided by Rhoades and Polemio (1977). Flame photometry method was used to analyse K and Na while Atomic Absorption Spectrophotometry was used for Ca and Mg analyses (Jackson, 1967). Soil texture was measured using the hydrometer method (Gee and Bauder, 1979). Undisturbed soil samples were also collected in core rings for bulk density determination as described by Doran and Mielke (1984). Saturated hydraulic conductivity was determined following Reynolds and Elrick (2002) method. The total available water, saturation, field capacity, permanent wilting point and matric potential were estimated using the hydraulic properties' calculator (Saxton and Rawls, 2006). The soil physical and chemical properties of the experimental site are presented in Table 4.1.

Table 4.1: Soil physical and chemical properties of the experimental site at 0−0.3 m depth.

Physical Properties		Chemical Properties	
Sand (g kg^{-1})	306.12	pH (water) 1:2.5	5.64
Clay (g kg^{-1})	422.80	Exchangeable Na ($cmol_c$ kg^{-1})	1.21
Silt (g kg^{-1})	271.08	Exchangeable K ($cmol_c$ kg^{-1})	1.81
Bulk density (g cm^{-3})	1.03	Exchangeable Ca ($cmol_c$ kg^{-1})	8.98
Matric potential (bar)	14.92	Exchangeable Mg ($cmol_c$ kg^{-1})	2.51
Hydraulic conductivity (mm hr^{-1})	20.81	Cation exchange capacity ($cmol_c$ kg^{-1})	30.78
Total available water (mm m^{-1})	130.5	Base saturation (%)	47.14
Field capacity (mm m^{-1})	386.2	Organic C (g kg^{-1})	29.02
Permanent wilting point (mm m^{-1})	256.3	Total N (g kg^{-1})	2.71
Saturation (mm m^{-1})	480.7	Available P (mg kg^{-1})	17.09

4.2.3 Experimental design

The experiment was laid out using a randomized complete block design with four replications in 4 m x 6 m plots (Fig. 4.1). Treatments consisted of four cropping systems, namely, pure potato stand (var. Shangi) (PS), and potato intercropped with dolichos (*Lablab purpureus* L. var. Uncinatus) (PD), garden pea (*Pisum sativum* L. var. Green feast) (PG) and climbing bean (*Phaseolus vulgaris* L. var. Kenya tamu) (PB). 'Shangi' is the most common potato cultivar in Kenya with an early maturity of 3−4 months and an attainable yield of 30−40 t ha^{-1} (Gitari et al., 2018b). The experiment was conducted for four consecutive seasons, from short rains season in 2014 to long rains season in 2016. Planting was done manually at the onset of each rainy season with pre-sprouted seed tubers planted at a spacing of 0.3 m within rows and 0.9 m between rows at a depth of 0.1 m to give a plant density of 36,400 plants ha^{-1}. Legumes were planted between the rows of potato with two seeds per hill spaced at 0.25 m to give a plant density of 88,000 plants ha^{-1}. The seed rates were 1.8 t ha^{-1} and 20 kg ha^{-1} for potato and legumes, respectively. Fertilizer application was done twice only on potato, at planting with 200 kg ha^{-1} of NPK (17:17:17) fertilizer and 28 days after planting (DAP) with 200 kg ha^{-1} of calcium ammonium nitrate (27% N) fertilizer to supply the crop with 88 kg N ha^{-1}, 34 kg P_2O_5 ha^{-1} and 34 kg K_2O ha^{-1}.

Potato was sprayed to control blight with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) alternated with Daconil 720 SC (Chlorothalonil 720 g L^{-1}) four times in a fortnight interval starting at 14 DAP. Dolichos were sprayed with Duduthrin 1.7 EC (Lambda-cyhalothrin 17.5 g L^{-1}) alternating with Bestox 100 EC (Alpha-cypermethrin 50 g L^{-1}) to control aphids. Weeding was done by hand hoeing at 28 and 56 DAP. At 28 DAP, beans were staked using wooden sticks whereas, potatoes were ridged with soil that was drawn gently from up to 0.35 m from each side of the potato rows.

Block one				Block two				Block three				Block four			
PB	PD	PS	PG	PS	PB	PG	PD	PG	PS	PB	PD	PB	PS	PD	PG

Fig. 4.1: Schematic illustration of how treatment's randomization was done in the four blocks. The plots measured 4 by 6 m with an inter-plot spacing of 0.5 m. PS, PD, PG and PB represent potato pure stand, and potato-dolichos, potato-garden peas and potato-bean intercropping system, respectively.

4.2.4 Data collection

Soil moisture and ground cover were measured on a weekly basis starting from the planting date and seven DAP, respectively, until the 84th day when potato had attained the physiological tuber maturation. The data were taken from three different points per plot and subsequently grouped into four-potato development stages based on the Federal Biological Research Center Bundessortenamt and Chemical Industry scale normally referred to as Biologische Bundesanstalt Bundessortenamt and Chemical Industrie (BBCH) (Hack et al., 2001).The stages were stolon development, tuber initiation, tuber bulking, and tuber maturation with BBCH of 21–29, 41–49, 60–73 and 93–95, respectively. Ground cover (GC) was measured using a sighting frame and expressed in percentage as described by Elwell and Wendelaar (1977) (Eq. 4.1).

$$\text{GC (\%)} = \frac{\text{No. of tubes in which vegetation cover is sighted}}{\text{Total no. of sighted tubes}} \times 100 \qquad (4.1)$$

Soil moisture content was measured using a digital handheld moisture sensor meter-HSM50 (Omega®). Moisture readings (volumetric soil water contents - θ_v) were taken from between and within the crop rows, and then they were converted to mm using Eq. (4.2).

$$\text{Soil moisture content (mm)} = \theta_v \times \text{SD} \qquad (4.2)$$

Where θ_v is the volumetric soil water content (%) and SD = the sampling depth (300 mm).

The tuber and legume yield were estimated from the central 3 m by 2 m area of each plot. Harvesting was carried out manually at 85 days after planting (DAP) for potato and bean, and 120 days for dolichos. Potato plants were dehaulmed by cutting at 0.1 m above the ground level, and then tubers were dug out using a fork hoe. Dolichos and beans were harvested when 80% of the pods had turned brown. The whole plant was uprooted, sun-dried for three days and threshed to obtain the grains. Peas were harvested twice between 65 and 75 DAP when the pods were filled but still green. The yield (tubers and legumes) was expressed in t ha^{-1} then converted into potato equivalent yield (PEY) terms using Eq. (4.3).

$$\text{PEY (kg ha}^{-1}) = \text{PY (kg ha}^{-1}) + \frac{\text{LY (kg ha}^{-1}) \text{ x LP (US\$ kg}^{-1})}{\text{PP (US\$ kg}^{-1})} \tag{4.3}$$

Where PEY = potato equivalent yield, PY = potato yield, LY = legume yield, PP = market price of potato (0.34 US$ kg^{-1}) and LP = market price of the legume (0.78, 0.97 and 1.17 US$ kg^{-1} for bean, pea and dolichos respectively).

For economic analysis, net income for each cropping system was estimated using Eq. (4.4).

$$\text{Net income} = \text{Gross income} - \text{Total cost of cultivation} \tag{4.4}$$

Where total cost of cultivation included the cost of inputs and labour. The cost of inputs (seed, fertilizers, fungicides and pesticides) was estimated based on the local market prices. Labour was valued by recording the time taken to carry out various cultural activities (land preparation, planting, weeding, earthing up, staking and harvesting) and paid at the rate of US$ 4.85 man-day^{-1} of 8 h. Gross income was taken as the total value of economic yield (tubers and grains) per cropping systems.

4.2.5 Data analysis

Generalized linear models (GLM) were used to assess the effects of intercropping systems on ground cover, soil moisture content, yield and economic returns. The 2.2.3 version of R software (R Core Team, 2015) was used for statistical analyses using the package lme4 (Bates et al., 2015). Several models were fitted by sequentially adding the explanatory variables into the base model. The choice of the best model was based on the lowest Akaike Information Criterion (AIC). Means were separated using the Tukey's HSD test at $p \leq 0.05$ (Abdi and Williams, 2010).

4.3 Results

4.3.1 Rainfall, reference evapotranspiration and temperature during the study period

Rainfall was above 500 mm in all the seasons except 2014 short rains, which had a cumulative amount of 381 mm (Fig. 4.2). The average seasonal rainfall was 547 mm for short rains and 788 mm for long rains, respectively. Higher rainfall was received during tuber initiation and bulking potato development stages compared to sprout development, stolon development and tuber maturation stages. Similarly, reference evapotranspiration was relatively higher especially during bulking potato development stage with an average of 170 mm compared to 40 mm recorded in tuber maturation stage. Temperature ranged from 20 to 25 °C across the seasons with the warmest (23.3 °C) season being 2015 short rains and the coolest (21.4 °C) was 2016 long rains.

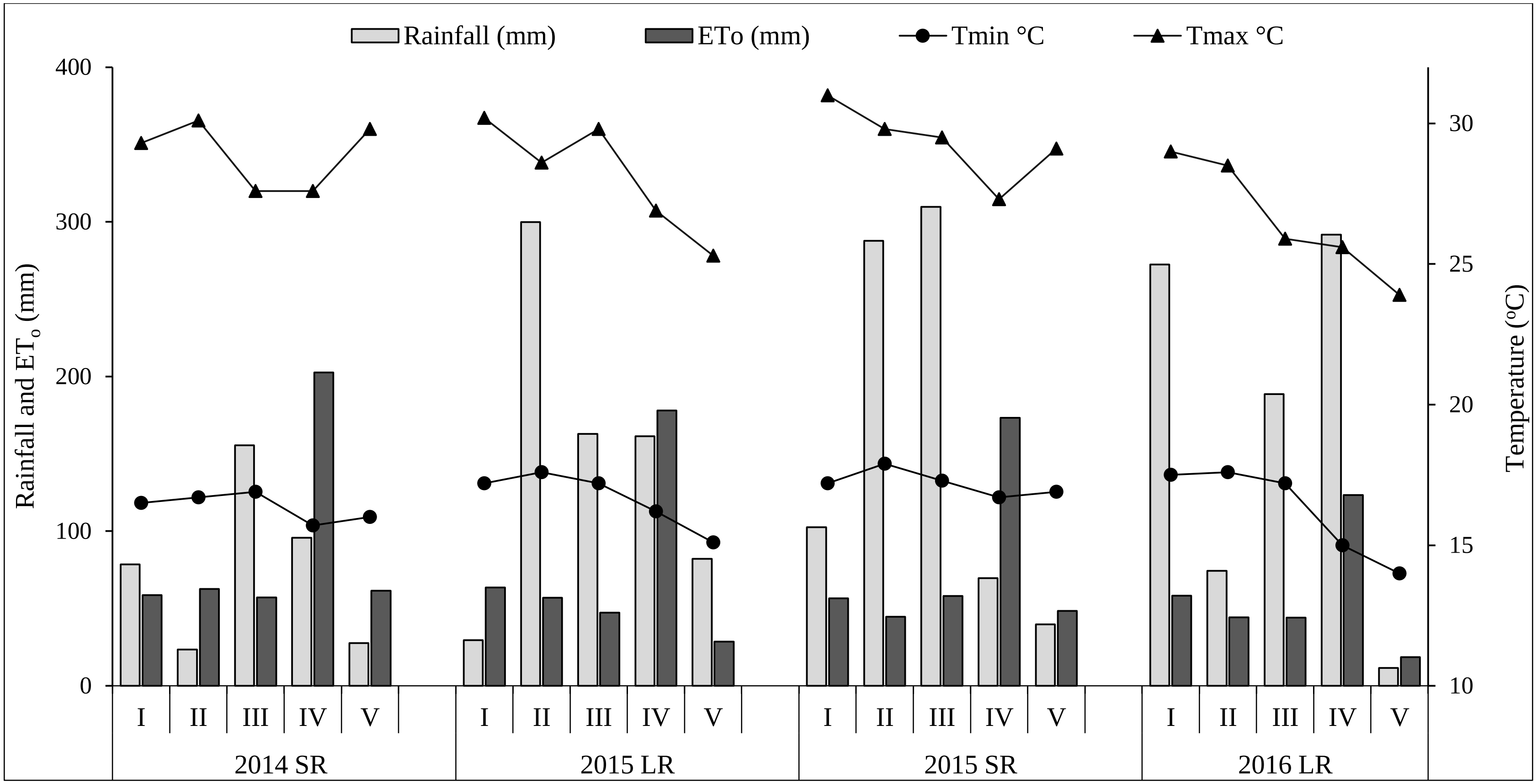

Fig. 4.2: Rainfall, reference evapotranspiration (ET_o) minimum (Tmin) and maximum (Tmax) temperature recorded for different potato development stages namely, sprout development (I), stolon development (II), tuber initiation (III), tuber bulking (IV) and tuber maturation (V) from 2014 short rains (SR) to 2016 long rains (LR).

4.3.2 Effect of intercropping systems on ground cover and soil moisture content at different potato development stages and seasons

There were significant ($p \leq 0.05$) effects of intercropping systems (CS) on ground cover and soil moisture content at different potato development stages (PDS) and seasons (S) (Table 4.2). The effect of these factors on ground cover was in the decreasing order of PDS (F = 974) > CS (F = 237) > S (F = 100). Across the potato development stages and seasons, ground cover was significantly highest and lowest under PD (56%) and PS (39%), respectively, while intermediate values were recorded in PG (51%) and PB (50%) intercropping systems. Regardless of the season, ground cover at the stolon development stage (BBCH: 21–29) was significantly higher in PG and PB than PD and PS. At tuber initiation stage (BBCH: 21–29), PS had significantly less ground cover compared to the intercropping systems whereas, at tuber bulking stage (BBCH: 60–73), PD had the highest ground cover, although the difference between PD and PB was not significant. At the tuber maturation stage (BBCH: 93–95), PS and PG had the lowest percentage ground cover while PB and PD had an intermediate and highest cover, respectively.

Interaction of CS by PDS and CS by S were significant ($p \leq 0.05$) for soil moisture content (SMC), but there was no three-way interaction (Table 4.3). The effects of these factors on soil moisture content was in a decreasing order of PDS (F = 893) > S (F = 319) > CS (F = 132). Across the potato development stages and seasons, SMC varied significantly ($p \leq 0.05$) between intercropping systems with the highest value in PD (207 mm m^{-1}), lowest in PS (168 mm m^{-1}) and intermediate in PG (183 mm m^{-1}) and PB (179 mm m^{-1}) (Table 4.3). Depending on potato development stages, at stolon development, SMC was significantly higher in PD than PS but the differences between PD and either PG or PB were not significant. At tuber initiation stage, SMC recorded in PD was 10, 13 and 18% higher than in PG, PB and PS, respectively. Soil moisture content value recorded in PD at tuber bulking stage was significantly higher than those in PS and

PB by 18 and 17%, respectively. At tuber maturation, PG and PB resulted in intermediate SMC values, which were 25% lower than in PD and 12% higher than in PS.

4.3.3 Effect of potato-legume intercropping systems on yield and economic returns

Intercropping systems had significant ($p \leq 0.05$) influences tuber and legume yield and potato equivalent yield, and they varied with growing seasons. Across the seasons, fresh tuber yield was significantly ($p \leq 0.05$) highest in PS (36 t ha^{-1}) and PD (35 t ha^{-1}) and lowest in PB (30 t ha^{-1}) and PG (29 t ha^{-1}) (Fig. 4.3a). When intercropped with potato, dolichos grain yield was lowest compared to the other legumes ranging from 1.8 to 1.9 t ha^{-1} whereas beans and peas recorded yield ranging from 2.5 to 2.7 t ha^{-1} and 3.1 to 3.5 t ha^{-1}, respectively (Fig. 4.3b).

When all yields (grain and tubers) were expressed in potato equivalent yield, the highest values were observed in PD and PB at 43 and 40 t ha^{-1}, respectively, whereas in PG and PS were lowest at 38 and 36 t ha^{-1}, respectively (Table 4.4). The highest cost of production was incurred under potato-legume intercropping systems ranging from US$ 1550 ha^{-1} in PG to US$ 1600 ha^{-1} in PD, compared to US$ 1450 ha^{-1} in PS. Nevertheless, these potato-legume intercropping systems were the most profitable with net income of US$ 9174, 8496, 7884 ha^{-1} for PD, PB and PG, respectively compared to PS (US$ 7436 ha^{-1}). This resulted in significantly ($p \leq 0.05$) higher benefit: cost ratios in PD and PB (5.7 and 5.4, respectively) compared to 5.1 in PS and PG.

Table 4.2: Ground cover (means ± standard error) as influenced by intercropping systems (CS) at different potato development stages (PDS) and seasons (S).

Potato development stage	Intercropping System	Ground cover (%)			
		2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Stolon development (BBCH 21–29)	PS[1]	29.2 ± 5.6^{b}[2]	36.7 ± 6.6^{b}	35.0 ± 8.0^{b}	30.8 ± 4.7^{c}
	PD	34.6 ± 8.6^{ab}	37.1 ± 6.9^{b}	43.3 ± 8.1^{ab}	34.2 ± 3.3^{bc}
	PG	39.2 ± 4.2^{a}	47.1 ± 4.5^{a}	44.6 ± 6.6^{a}	40.8 ± 4.2^{a}
	PB	37.5 ± 7.8^{a}	45.0 ± 9.3^{a}	51.3 ± 9.3^{a}	38.3 ± 6.9^{ab}
Tuber initiation (BBCH 41–49)	PS	54.6 ± 3.3^{c}	65.0 ± 4.3^{b}	54.6 ± 3.3^{b}	49.6 ± 7.2^{b}
	PD	70.0 ± 6.7^{a}	75.8 ± 5.6^{a}	65.0 ± 4.8^{a}	65.4 ± 6.2^{a}
	PG	67.9 ± 5.4^{ab}	74.6 ± 5.4^{a}	61.7 ± 6.2^{a}	59.2 ± 6.3^{a}
	PB	64.2 ± 4.2^{bc}	73.8 ± 4.3^{a}	64.6 ± 3.3^{a}	62.5 ± 8.7^{a}
Tuber bulking (BBCH 60–73)	PS	48.8 ± 4.8^{b}	58.3 ± 8.9^{b}	40.8 ± 7.9^{b}	40.8 ± 7.9^{b}
	PD	67.1 ± 5.8^{a}	75.4 ± 7.5^{a}	60.0 ± 8.1^{a}	60.0 ± 8.0^{a}
	PG	59.2 ± 9.3^{a}	71.3 ± 4.3^{a}	52.5 ± 5.1^{a}	52.5 ± 5.4^{a}
	PB	64.2 ± 4.2^{a}	72.1 ± 4.5^{a}	54.2 ± 7.2^{a}	54.2 ± 7.2^{a}
Tuber maturation (BBCH 93–95)	PS	13.3 ± 2.5^{c}	28.3 ± 6.2^{b}	13.3 ± 2.5^{c}	27.9 ± 4.5^{c}
	PD	48.3 ± 6.2^{a}	65.4 ± 7.8^{a}	48.3 ± 6.2^{a}	52.1 ± 5.4^{a}
	PG	31.7 ± 7.8^{b}	37.5 ± 5.8^{b}	31.7 ± 7.8^{b}	38.8 ± 4.3^{b}
	PB	20.0 ± 6.4^{bc}	31.3 ± 6.8^{b}	20.0 ± 6.4^{bc}	41.7 ± 2.5^{b}

	Summary of analyses of variance				
	CS	PDS	S	CS x PDS	CS x PDS x S
Degrees of freedom	3	3	3	9	27
F value	237.1	974.4	99.5	42.7	2.7
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[1]PS, pure potato stand; PD, potato-dolichos; PG, potato-garden; PB, potato-bean.

[2]Means followed by the same superscript letter (down the column within a potato development stage) are not significantly different ($p \leq 0.05$) by Tukey's HSD test.

Table 4.3: Soil moisture content (means ± standard error) as influenced by intercropping systems (CS) at different potato development stages (PDS) and seasons (S).

Potato development stage	Intercropping system	Soil moisture content (mm m^{-1})			
		2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Stolon development (BBCH 21–29)	PS[1]	191.8 ± 14^{b2}	162.6 ± 8^{d}	197.5 ± 44^{b}	242.4 ± 16^{b}
	PD	199.3 ± 14^{a}	192.6 ± 22^{a}	245.9 ± 29^{a}	294.4 ± 15^{a}
	PG	170.9 ± 19^{c}	173.8 ± 6^{c}	221.6 ± 42^{a}	278.7 ± 20^{ab}
	PB	186.5 ± 6^{bc}	183.5 ± 12^{b}	200.0 ± 35^{ab}	267.8 ± 15^{ab}
Tuber initiation (BBCH 41–49)	PS	156.7 ± 13^{b}	205.6 ± 17^{b}	206.0 ± 17^{b}	184.5 ± 11^{b}
	PD	190.9 ± 19^{a}	250.3 ± 19^{a}	253.0 ± 33^{a}	225.0 ± 10^{a}
	PG	165.2 ± 16^{b}	228.6 ± 11^{a}	244.6 ± 41^{a}	190.6 ± 27^{b}
	PB	150.9 ± 7^{b}	230.7 ± 13^{a}	221.8 ± 22^{ab}	201.3 ± 20^{ab}
Tuber bulking (BBCH 60–73)	PS	117.9 ± 24^{b}	201.0 ± 14^{b}	225.1 ± 19^{b}	176.2 ± 13^{b}
	PD	155.3 ± 14^{a}	233.3 ± 20^{a}	270.3 ± 29^{a}	217.3 ± 13^{a}
	PG	124.2 ± 9^{b}	227.9 ± 11^{a}	253.0 ± 32^{ab}	183.8 ± 44^{b}
	PB	121.3 ± 9^{b}	216.9 ± 12^{ab}	228.3 ± 20^{b}	191.8 ± 24^{ab}
Tuber maturation (BBCH 93–95)	PS	91.3 ± 13^{b}	133.4 ± 15^{c}	100.7 ± 20^{b}	88.1 ± 4^{c}
	PD	126.4 ± 5^{a}	166.9 ± 12^{a}	149.8 ± 33^{a}	141.2 ± 17^{a}
	PG	99.1 ± 4^{b}	149.0 ± 6^{b}	120.2 ± 21^{ab}	102.3 ± 17^{b}
	PB	96.0 ± 5^{b}	149.6 ± 6^{b}	110.5 ± 18^{b}	109.3 ± 10^{b}

	Summary of analyses of variance				
	CS	PDS	S	CS x S	PDS x S
Degrees of freedom	3	3	3	9	9
F value	132.3	893.3	318.6	5.6	117.5
p value	< 0.001	< 0.001	< 0.001	< 0.001	0.043

[1]PS, pure potato stand; PD, potato-dolichos; PG, potato-garden; PB, potato-bean.

[2]Within a column for each potato development stage, means followed by different superscript letters differ significantly at $p \leq 0.05$ by Tukey's HSD test.

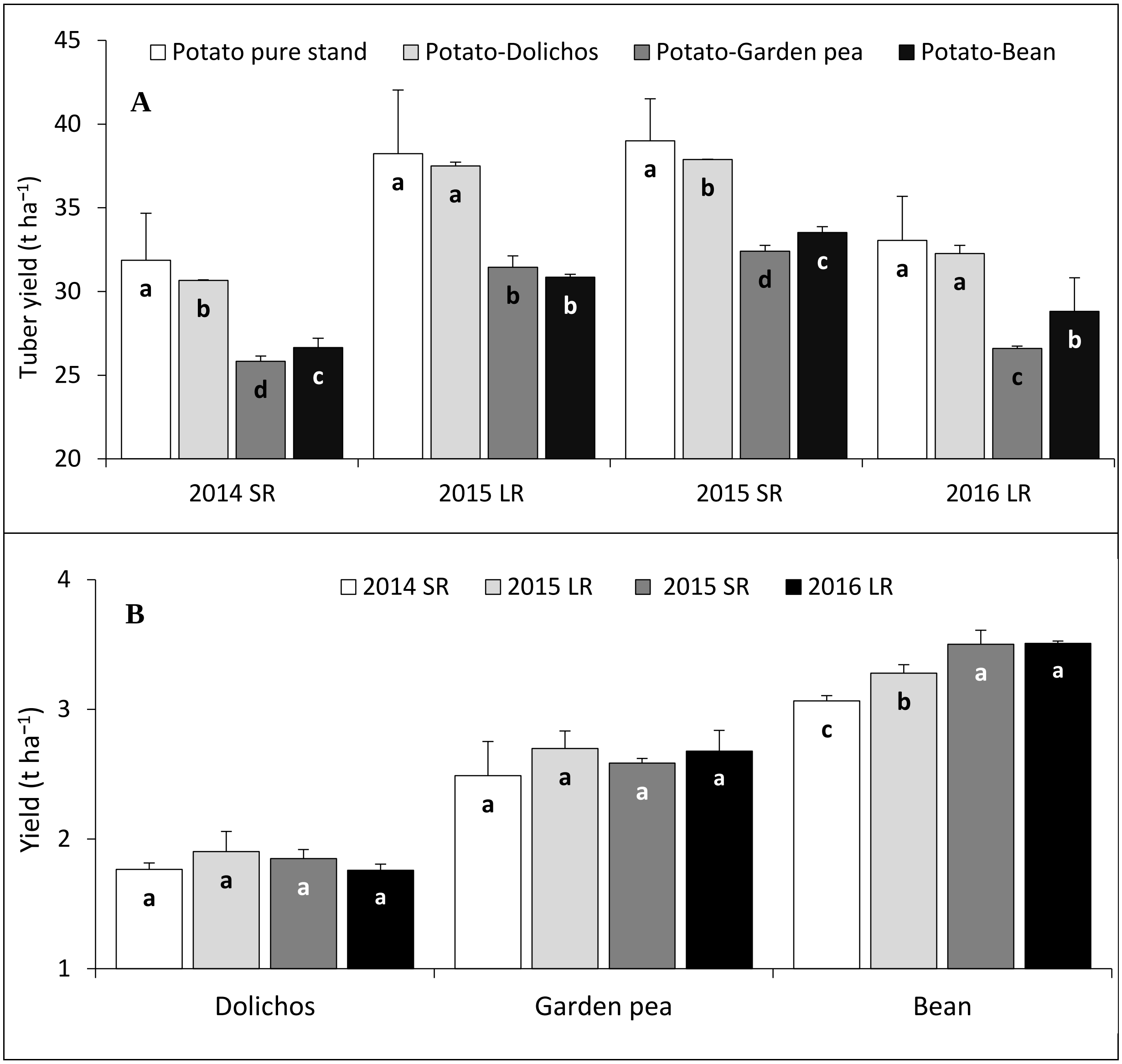

Fig. 4.3: Potato tuber yield (A) and legume grain yield (B) as influenced by intercropping systems at different seasons. SR and LR denote short and long rains seasons, respectively. Bars bearing the same letter across the treatments and within the same season for tuber yield, and across the season and within the same treatments for grain yield are not significantly different at $p \leq 0.05$. Error bars signify standard error of the means.

Table 4.4: Potato equivalent yield (PEY), gross and net income and benefit: cost ratio as influenced by intercropping systems (CS) at different seasons (S).

Season	Intercropping System	PEY ($t\ ha^{-1}$)	Cultivation Cost (US$ ha^{-1})	Gross Income (US$ ha^{-1})	Net Income (US$ ha^{-1})	Benefit: Cost Ratio
2014	PS[1]	31.9[d2]	1449	7968[d]	6519[d]	4.5[c]
Short	PD	38.9[a]	1600	9730[a]	8130[a]	5.1[a]
Rains	PG	34.1[c]	1551	8521[c]	6970[c]	4.5[c]
	PB	36.2[b]	1596	9053[b]	7456[b]	4.7[b]
2015	PS	38.2[c]	1449	9557[c]	8108[c]	5.6[b]
Long	PD	46.4[a]	1600	11601[a]	10001[a]	6.3[a]
Rains	PG	40.4[b]	1551	10100[b]	8550[b]	5.5[bc]
	PB	41.1[b]	1596	10268[b]	8672[b]	5.4[c]
2015	PS	39.0[c]	1449	9752[c]	8303[c]	5.7[b]
Short	PD	46.5[a]	1600	11636[a]	10036[a]	6.3[a]
Rains	PG	41.0[b]	1551	10247[b]	8696[b]	5.6[b]
	PB	45.2[a]	1596	11307[a]	9710[a]	6.1[a]
2016	PS	33.1[c]	1449	8263[c]	6814[c]	4.7[b]
Long	PD	40.5[a]	1600	10128[a]	8528[a]	5.3[a]
Rains	PG	35.5[b]	1551	8872[b]	7321[b]	4.7[b]
	PB	39.8[a]	1596	9938[a]	8342[a]	5.2[a]
CS		< 0.001	-	< 0.001	< 0.001	< 0.001
S		< 0.001	-	< 0.001	< 0.001	< 0.001
CS x S		< 0.001	-	< 0.001	< 0.001	< 0.001

[1]PS, pure potato stand; PD, potato-dolichos; PG, potato-garden; PB, potato-bean.

[2]Within a column, means followed by the same superscript letter are not significantly different at $p \leq 0.05$ by Tukey's HSD test.

4.4 Discussion

4.4.1 Effect of intercropping systems on ground cover and soil moisture

The observed trends of ground cover (Table 4.1) indicate the potential role of legumes in promoting water conservation in these intercropping systems. The high ground cover in potato-dolichos could be attributed to the ability of dolichos to accumulate more biomass than other legumes. For instance, in the 2014 short rains season, the amount of rainfall received was 9% below seasonal average and unevenly distributed with October recording the highest rainfall (148 mm) of which 76% only occurred in 2 days (Fig. 4.2). The crop might have used the available soil water effectively resulting in the high canopy cover and eventually more biomass production. Nyawade (2015) reported that dolichos usually maintain a high ground cover of up to 40% beyond the physiological maturity period of potato. This probably was the reason for the high ground cover especially at early stages of potato development, which could help in intercepting rainfall, thus reducing raindrop impact on the soil surface (Ogindo and Walker 2005; Karuma et al., 2011; Nyawade, 2015; Singh et al., 2017; Zhang et al., 2017; Aliche et al., 2018). This may have increased the infiltration resulting in higher soil moisture content in potato-legume intercropping systems as compared to pure potato stand (Table 4.2).

Increased ground cover, especially in the potato-dolichos intercropping system (Table 4.1), might have created a microclimatic zone by shielding the moist and cool air close to the soil surface, thereby reducing water loss through evaporation. Higher soil moisture contents have also been reported under other intercropping systems such as potato-maize (*Zea mays* L.) (Mushagalusa et al., 2008; Fan et al., 2016), dolichos-cassava (*Manihot esculanta* Crantz) (Namoi et al., 2014) and dolichos-sweet potato (*Ipomea* batatas L.) (Chepkemoi et al., 2014). On the contrary, potato-pea and potato-bean intercropping systems, which had relatively less dense canopy cover than potato-dolichos probably experienced a higher water loss through direct evaporation from the soil surface resulting in lower soil moisture content.

4.4.2 Effect of intercropping systems on yield, economic returns, crop evapotranspiration, and crop water productivity

The almost similar potato yield in PD compared to PS (Table 4.4) would suggest a positive interaction between the two crops, which could be explained by temporal shoot architectural differences. In this case, during the stolon development stage of potato, dolichos had a lower-lying canopy than that of potato. This could have enabled potato to obtain enough solar radiation for photosynthesis, resulting in higher tuber yield. At later stages of potato development, increased ground cover due to relatively higher dolichos biomass could have further benefited potato by reducing water loss through evaporation and lowering the temperature within the canopy (Ogindo and Walker, 2005; Borowy, 2012). These results corroborate earlier findings by Liao et al. (2016) and Burke (2017) that lower temperatures promote translocation of photo-assimilates to the developing tubers leading to higher tuber yield, which was comparable to that in pure stand.

On the other hand, in potato-bean intercropping, higher-lying canopy of bean at very early potato growth stages could have resulted in a decreased light interception by the potato plants, thus reducing their photosynthetic capacity hence the low tuber yield. This concurs with the findings by Fan et al. (2016) and Gitari et al. (2017) who reported that tuber yield is highly dependent on the amount of intercepted solar radiation. In a potato-maize intercropping system, Mushagalusa et al. (2008) reported a 4–26% decrease in potato yield, which they attributed to the shading effect of maize crops.

Apart from the shading effects on potato, the observed variations in potato tuber yield across different cropping systems (Fig. 4.3) may be attributed to the differences in root architecture of these legume crops. The root system of dolichos can grow up to a depth of about 2 m (Gitari et al., 2018a). This might have reduced the competition for available water. In contrast, beans and peas have shallow roots (0.2–0.4 m), which could have increased competition with potato for resources such as water and nutrients, resulting in lower tuber yield. Similar results were obtained when potato was intercropped with maize (Mushagalusa et al., 2008). Similarly, Singh et al. (2016) and Zhang et al. (2016) reported a decrease in tuber yield when potato was intercropped with radish and faba bean, respectively.

In 2014 short rains, there was generally a lower potato tuber yield in all the treatments, which could be attributed to the low rainfall amount received during that season (Fig 4.2). Given that potato cultivation under monoculture requires 500−700 mm of water in a growing season (Sood and Singh, 2003; Ierna and Mauromicale, 2012), the rainfall amount recorded in this season was inadequate to meet the crop’s seasonal water requirement. This might have resulted in water stress condition, which might have resulted in reduced nutrient uptake and translocation of assimilates into the tubers leading to low yield (Fleisher and Timlin, 2008; Gitari et al., 2016, 2018b). This argument is further reinforced by the findings by Ramirez et al. (2016) who reported that tuber yield decreases in response to an increase in water stress. Under water stress conditions, crops close their stomata resulting in decreased transpiration (Ierna and Mauromicale, 2012; Liao et al., 2016).

The higher potato equivalent yield under intercropping systems compared to pure potato cropping system (Table 4.4) could mainly be attributed to the additional legume grain yield. Another possible explanation for this observation could be increased nutrient uptake and translocation of assimilates into potato tubers and legume seeds as observed by Fleisher et al. (2008) and Gitari et al. (2016, 2018b). Higher potato equivalent yields have been reported by

Singh et al. (2016) under radish intercropping system compared to pure potato stand. Notwithstanding the lower grain yield recorded in potato-dolichos plots, the potato equivalent yield was still high due to the high market price of dolichos (US$ 1.17 kg^{-1}) compared to beans and peas whose market prices are less than a dollar per kg. In addition, dolichos has high socio-economic value to many African communities (Maass et al., 2010) as it is consumed by lactating mothers. Higher gross income has also been reported under potato-bean (Zhang et al., 2016) and maize-okra-cowpea (Sharma et al., 2017) intercropping systems compared to the respective pure stands.

The higher productivity observed under intercropping systems especially in potato-dolichos relative to a pure stand of potato (Table 4.4) could imply that there was an efficient use of water as a higher proportion of soil moisture was taken up by the plants and used for transpiration rather than being lost through direct evaporation from the soil surface (Blum, 2012). High canopy cover under potato-dolichos may have reduced evaporative water loss while promoting productive water use. With a high density of roots under the intercropping system, then it is expected that water uptake is accelerated resulting in high transpiration and consequently high yield (Mabhaudhi et al., 2013; Chimonyo et al., 2016). Zhang et al. (2016) reported a better water utilization under potato-legume intercropping systems compared to monocropping systems. Sharaiha and Hadidi (2008) and Rezig et al. (2013) reported higher productivity when potato was intercropped with bean and sulla (*Hedysarum coronarium* L.), respectively compared to the pure stand of potato. The current study, therefore, emphasizes the great potential of potato-legume intercrops that can easily be adopted, especially by smallholder farmers to increase their incomes. Moreover, dolichos shows the potential of being successfully incorporated into the potato production systems without necessarily compromising the yield.

4.5 Conclusions and recommendations

This study has shown that increased ground cover under intercropping systems could be a potential water conservation strategy for increased crop productivity. Therefore, the findings from this study have demonstrated the economic feasibility of intercropping potato with legumes. In this regard, dolichos was the most effective legume that could be integrated into potato cropping systems to improve crop productivity without compromising on potato yield. Increased water conservation and utilization is vital, especially for resource-constrained smallholder farmers who are reliant on rain-fed agriculture for their livelihood. However, given that this was a four-season study and thus is subject to seasonal variations, it will be important to look at the effects of these intercropping systems on crop water productivity, yield and economic returns on a long-term basis.

CHAPTER FIVE

Nitrogen and Phosphorous Uptake by Potato (*Solanum tuberosum* L.) and their Use Efficiency under Potato-Legume Intercropping Systems

Abstract

Competition for nitrogen (N) and phosphorous (P) under potato-based intercropping systems decreases the level of nutrients available for potato and subsequently influences N and P use efficiency. A field trial was conducted for four consecutive seasons between 2014 short rains and 2016 long rains to assess the effect of incorporating legumes as intercrops into potato cropping systems on N and P uptake and, their uptake and use efficiency by the potato. The treatments included potato intercropped with either garden pea (*Pisum sativum* L.) (PG), dolichos (*Lablab purpureus* L.) (PD) or climbing bean (*Phaseolus vulgaris* L.) (PB), and a pure stand of potato (PS) as control. Intercropping potato with beans and peas significantly reduced its N uptake by 22 and 27% relative to PS, but the N uptake was not affected under PD. Phosphorous uptake was 2, 8 and 11 kg P ha^{-1} lower in PD, PB and PG, respectively compared with PS. Nitrogen use efficiency (NUE) was significantly lower in PD, PB and PG by 30, 19 and 9% compared with PS. Similarly, P use efficiency (PUE) was 6, 14 and 21% higher in PG, PB and PD, respectively than PS. The highest tuber yield recorded in PS (36 t ha^{-1}) did not significantly differ from PD (34 t ha^{-1}) whereas tuber yield was significantly ($p \leq 0.05$) lower in PB and PG as compared with PS. The study shows the great potential of dolichos as a promising intercrop that could be integrated into potato cropping systems without negatively affecting potato yield.

Published in Field Crops Research Journal - Elsevier:

https://doi.org/10.1016/j.fcr.2018.03.019

5.1 Introduction

Potato cultivation under intercropping systems has been practised globally due to its effectiveness in soil and water conservation resulting in increased yield and economic returns compared with monocropping system (Hinsinger et al., 2011; Gericke et al., 2012; Nyawade, 2015; Zhang et al., 2016b). High productivity in potato production systems has been achieved by incorporating crops such as radish, maize and bean (Mushagalusa et al. 2008; Zhang et al., 2016b). However, competition between companion crops for the available resources such as moisture, nutrients like nitrogen (N) and phosphorous (P) and light is a common occurrence (Gitari et al., 2017). These two elements are essential nutrients that are important in potato production and their deficiency may result in yield losses (Fernandes and Soratto 2012; Hopkins et al., 2014; Sandana, 2016; Musyoka et al., 2017). Nevertheless, these mineral elements are inherently low in most tropical soils such as Nitisols, which dominate potato-growing areas in Kenya (Jaetzold et al., 2006; IUSS Working Group WRB, 2015). The low available P is also due to its adsorption onto soil constituents such as organic matter, clays and sesquioxides (Hinsinger et al., 2011; Hopkins et al., 2014; Hill et al., 2015).

Nitrogen and phosphorous are usually supplied to crops mainly through inorganic fertilizers, and this takes about 20% of operating costs in potato production (Stark et al., 2004; Rens et al., 2018). In Kenya, as in many other sub-Saharan countries, potato growers are mainly small-scale farmers who primarily use ammonium-based fertilizers such as di-ammonium phosphate and calcium ammonium nitrate. Adding P to a low pH soil renders it unavailable through fixation by Fe and Al (Muindi et al., 2015). In addition, P uptake by most crops largely depends upon root interception due to its low mobility (Hill et al., 2015). However, the potato has a shallow rooting system to exploit fully such P and N hence; they are susceptible to loses principally through immobilization, volatilization, leaching and run-off under poor agronomic management (Hopkins et al., 2014; Rens et al., 2018). This results not only in yield losses but also adversely affect the environment through processes such as eutrophication of surface water bodies (Zhaohui et al., 2012; Jones et al., 2013). This is an indication that potato-based intercropping systems are still vulnerable to nutrient loss pathways resulting in poor crop growth and low tuber yield. For instance, the average tuber yield in Kenya is 8–15 t ha^{-1}, which is more than three times lower than the 30–40 t ha^{-1} that is achievable under field conditions (Muthoni et al., 2013; Gitari et al., 2016). Therefore, identification and integration of suitable intercrops in potato intercropping systems could be a potential strategy to curb such losses.

A number of strategies have been proposed to reduce N and P losses from cropping systems such as the use of crop-specific fertilizers, synchronizing fertilizer application with the crop nutrient demand and use of slow N-releasing fertilizers (Abalos et al., 2014; Venterea et al., 2016; Lam et al., 2017; Rens et al., 2018). Although such strategies have been shown to be viable in developed countries, most farmers in sub-Saharan Africa are reluctant to adopt them because of incomplete or unclear information and most cannot financially afford to apply these strategies. Thus, research on nutrients use efficiency is imperative for feasible potato production systems, especially in tropical soils, which usually are low in N and P. Development of innovative strategies that would enhance availability of N and P from fertilizers applied to a potato crop would contribute greatly to easing the burden of increased cost of production to the resource-poor farmers who are dependent on agriculture for their livelihood.

One potential strategy that could be easily adopted by resource-poor potato growers is identification and integration of suitable intercrops in potato intercropping systems. Intercropping is one of the cultural practices that improve nutrient uptake and nutrient use efficiency without requiring an increase in fertilizer inputs (Hinsinger et al., 2011; Gitari et al., 2016; Nyiraneza et al., 2017). Better nutrient utilization under intercropping systems can be achieved through niche facilitation and complementarity occurring in the rhizosphere of the companion crops, hence minimizing competition for nutrients and thus increasing nutrient use efficiency (Richardson et al., 2009; Zhang et al., 2017a). This is mainly possible when legumes are integrated since they have the ability to fix atmospheric N for their own utilization and subsequently transfer the surplus directly making it accessible for uptake by companion crops (Ojiem et al., 2007; Hauggaard-Nielsen et al., 2009; Sitienei et al. 2017). The roots of legumes can also produce exudates that can solubilize P by competing with phosphate ions for exchange sites, hence making it available for uptake by the non-legume crops in the intercropping systems (Hinsinger et al., 2011; Postma and Lynch, 2012; Wang et al., 2015; Zhang et al., 2016a; Giles et al., 2017).

In intercropping systems, integrating deep-rooted crops such as dolichos results in better exploitation of soil resources such as water and nutrients (Ojiem et al., 2007; Whitbread et al. 2011; Nyawade, 2015; Gitari et al., 2017). In this regard, dolichos can extract water and nutrients from deeper soil horizons thus reducing competition of these resources from the surface horizon to the benefit of shallow-rooted crops such as potato. Dolichos has been established as a drought tolerant and multipurpose legume cultivated for its green pods and grain, and as fodder (Whitbread et al., 2011; Sennhenn et al., 2017). Notwithstanding the potential of dolichos as an intercrop in potato-based intercropping systems, little has been done to assess its effects on nutrient use efficiency. Therefore, this study aimed at assessing the effects of intercropped legumes on N and P uptake by potato and their use efficiency for the intercropping system.

5.2 Materials and Methods

5.2.1 Site Description

A potato-legume intercropping trial was conducted at Kabete Field Station, University of Nairobi, located at 1°15′S, 36°44′E and 1860 m above sea level. The site is a typical Kenyan highland where most of the country's potato cultivation is carried out and is classified as dry sub-humid agro-ecological zone (Jaetzold et al., 2006). The predominant soil type is a Humic Nitisol and is characterized by a homogeneous deep soil profile of up to about 2 m (Jaetzold et al., 2006; IUSS Working Group WRB, 2015). The soil had a bulk density of 1.03 g cm^{-3}, pH of 5.6 (soil to water ratio of 1:2.5), organic carbon of 29 g kg^{-1}, and available N and P of 167 and 53 kg ha^{-1}, respectively. Exchangeable Na, K, Mg and Ca were 1.2, 1.8, 2.5 and 9.0 $cmol_c$ kg^{-1}. The site receives an average annual rainfall of 1000 mm in a bimodal pattern, from March to June, usually referred to as 'long rains', and October to December referred as 'short rains'.

5.2.2 Experimental design and layout

This study was conducted for four consecutive seasons from 2014 short rains to 2016 long rains. The treatments included potato (var. Shangi) as a pure stand (abbreviated as PS) and potato intercropped with either garden pea (*Pisum sativum* L. var. Green feast) (PG), dolichos (*Lablab purpureus* L. var. Uncinatus) (PD) and climbing bean (*Phaseolus vulgaris* L. var. Kenya tamu) (PB). The trial was laid out in a randomized complete block design in four replications for each treatment. The dimension of the experimental unit was 6 by 4 m accommodating six potato rows spaced at 0.9 m. At the onset of each growing season, pre-sprouted seed potato tubers (35–55 mm in diameter) were planted in rows at an inter-seed spacing of 0.3 m, a seed rate of 1.8 t ha^{-1} and a plant density of 36,400 plants ha^{-1}. The legumes were planted between potato rows at a rate of 20 kg of seed ha^{-1} with two seeds sown at a spacing of 0.25 m within a row such that the final plant density was 88,000 plants ha^{-1}. Shangi was preferred for its popularity among smallholder farmers in the country. It matures within 90 days with an attainable yield of 30–40 t ha^{-1} under field conditions (Muthoni et al., 2013; Gitari et al., 2017). The legume varieties used in this study are the most common ones among the local farmers, hence the high chances of adoption of the proposed potato-legume intercropping systems.

5.2.3 Agronomic practices

The potato was supplied with 34 kg ha^{-1} of N, 15 kg ha^{-1} of P and 28 kg ha^{-1} of K using NPK (17:17:17) compound fertilizer at planting and 54 kg ha^{-1} of N using calcium ammonium nitrate (CAN) fertilizer 28 days after planting (DAP). Weeding, earthing-up for potato and staking for beans were done manually 28 DAP. To control late blight, the potato was sprayed twice per month starting from 14 days after the emergence with Daconil 720 SC (Chlorothalonil 720 g L^{-1}) alternated with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}). For the control of aphid that infested only dolichos, the crop was sprayed with Bestox 100 EC (Alpha-cypermethrin 50 g L^{-1}) alternated with Duduthrin 1.7 EC (Lambda-cyhalothrin 17.5 g L^{-1}).

5.2.4 Data collection

Plant canopy cover was measured every seven days starting from 28 to 84 DAP using a sighting frame. The frame was placed between potato rows and the vegetation was observed through each of the ten thin gun sight tubes arranged at fixed intervals along a crossbar. A similar sampling frequency was used for soil moisture content using a digital moisture meter-HSM50 (Omega®). The probe of the meter was inserted at a depth of 0.2 m from different points of the plot. Harvesting was carried out manually from 12 m^2 central area per plot at 65 and 75 DAP for pea, 84 DAP for potato and bean, and 120 DAP for dolichos. From the harvesting area, 10 potato plants were randomly selected and their haulm biomass was harvested, weighed and cut into 5 cm long pieces. The tubers were dug out, weighed and 10 tubers were randomly picked and sliced into 10 mm wide strips. Sub-samples of 500 g for haulm biomass and tubers were oven-dried at 70 °C for 72 h and their weights were recorded. The samples were then ground using a tissue grinder and passed through a 1 mm sieve for N and P analysis. Nitrogen was determined by Kjeldahl method (Bremner, 1996) whereas P was analysed colourimetrically using a UV-vis spectrophotometer (Murphy and Riley, 1962). Nutrient (N and P) uptake for tubers and haulms was determined as the product of tissue's dry weight and nutrient concentration, and summing up the two gave the plant nutrient uptake (Eq. (5.1)).

$$\text{Plant nutrient uptake} = \text{Haulm nutrient uptake} + \text{Tuber nutrient uptake} \tag{5.1}$$

Nutrient (N and P) uptake efficiency was computed as a ratio of total potato nutrient uptake and nutrient supply (Eq. (5.2)) (Valle et al., 2011; Sandana, 2016).

$$\text{Nutrient uptake efficiency} = \frac{\text{Total plant nutrient uptake}}{\text{Nutrient Supply}} \tag{5.2}$$

Where nutrient supply was estimated as the sum of elements (N and P) in the soil at planting time (in 0–0.3 m depth) added to that applied through fertilizers. Nutrient use efficiency, which indicates productivity of the intercropping system, was calculated by dividing potato equivalent yield (PEY) by nutrient supply (Eq. (5.3)).

$$\text{Nutrient use efficiency} = \frac{\text{PEY}}{\text{Nutrient Supply}} \tag{5.3}$$

Where PEY was computed using Eq. (5.4).

$$\text{PEY (kg ha}^{-1}\text{)} = \text{PY (kg ha}^{-1}\text{)} + \frac{\text{LY (kg ha}^{-1}\text{) x LP (US\$ kg}^{-1}\text{)}}{\text{PP (US\$ kg}^{-1}\text{)}} \tag{5.4}$$

Where PY = potato yield, LY = legume yield, PP = market price of potato (US$ 0.34 kg^{-1}), and LP = market price of legume (US$ 1.17, 0.78 and 0.97 kg^{-1} for dolichos, beans and peas, respectively).

5.2.5 Statistical data analysis

The effect of legume intercrops on N and P uptake and use efficiency by potato and its yield was tested using generalized linear models (GLM) in R Software version 2.2.3 using the lme4 package (R Core Team, 2015). All possible models were fitted from where the best were chosen based on the least Akaike Information Criterion (AIC). The treatment means were compared using Tukey's Honest Significant Difference (HSD) at $p \leq 0.05$ (Abdi and Williams, 2010). The relationship between nutrient (N and P) uptake efficiency, N and P use efficiency and potato yield components were determined using Pearson correlation.

5.3 Results

5.3.1 Rainfall and temperature patterns

The 2014 short rains season received a lower amount of rainfall (about 380 mm) compared with the cumulative rainfall of 740, 720, and 840 mm recorded for 2015 long rains, 2015 short rains and 2016 long rains, respectively (Fig. 5.1). Nearly constant temperatures were experienced throughout the four seasons with an average minimum and maximum temperature of 16.2 and 28.9 °C, respectively.

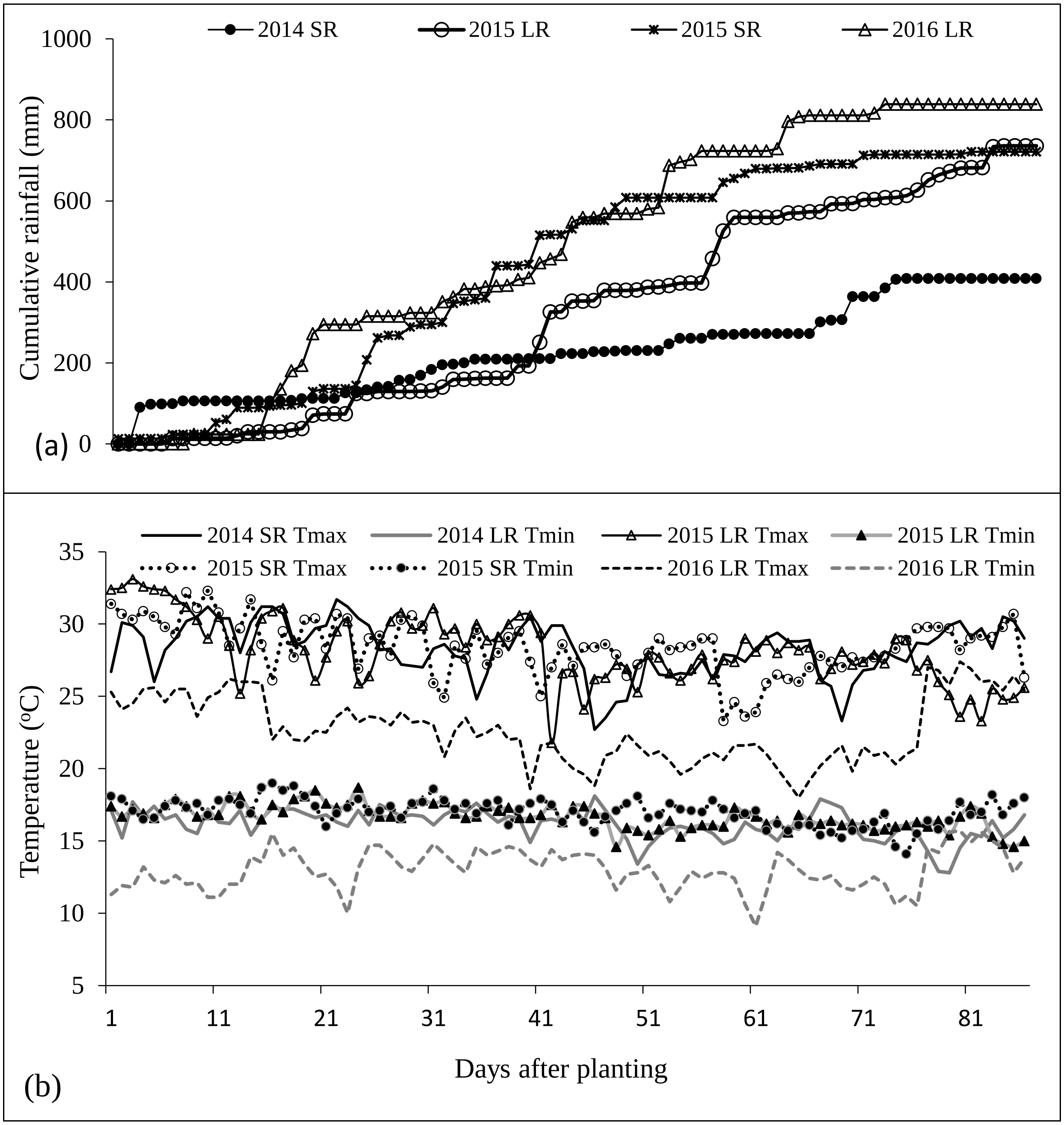

Fig. 5.1: Rainfall and temperature for the period between potato planting and harvesting. Tmax = maximum temperature, Tmin = minimum temperature, LR = long rains and SR = short rains. (Source: Kenya Meteorological Department, Kabete Weather Station).

5.3.2 Crop canopy cover and soil moisture content

All the treatments had developed substantive canopy cover at 28 days after planting (DAP) across the four seasons. The canopy cover increased gradually to reach the peak levels of 73, 69, 67 and 58% for PD, PG, PB and PS, respectively at 56 DAP then started to decline gradually except in potato-dolichos intercropping system, which had maintained a substantial cover of 52% until the potato's physiological maturity stage (Fig. 5.2a). Canopy cover was significantly ($p \leq 0.001$) higher under potato-legume intercropping systems by 47, 29 and 26% in PD, PG and PB, respectively as compared with PS across seasons.

Soil moisture content (SMC) was significantly ($p \leq 0.001$) higher under potato-legume intercropping systems compared with potato pure stand. Across seasons, SMC was 21% in PD, 18% in PG and 17% in PB compared to 16% in PS (Fig. 5.2b). The lowest SMC values were observed in 2014 short rains, and they were less than 20% in all treatments. In 2015 long rains, the highest SMC of 25, 23, 22 and 21% were recorded at 56 and 70 DAP for PD, PG, PB and PS, respectively. All treatments recorded SMC of above 20% between 28 and 70 DAP in 2015 short rains, whereas such a record was made only at 56 DAP in 2016 long rains.

5.3.3 Effect of potato-legume intercropping systems on nutrients (N and P) uptake, uptake efficiency and use efficiency

Nitrogen uptake, N uptake efficiency and N use efficiency were significantly affected by the type of potato-legume intercrop, but these differences differed from season to season (Table 5.1). Either potato N uptake in PB and PG was lower than in PS by 22 and 27%, respectively but comparable in PD. Intercropping potato with peas or beans reduced N uptake efficiency significantly ($p \leq 0.05$) by 37% in comparison with PS. However, intercropping with dolichos resulted in comparable N uptake efficiency of 0.66 and 0.69 kg total N uptake kg^{-1} N supply in

PD and PS, respectively. The N use efficiency (NUE) in PG, PB and PD were significantly significant ($p \leq 0.05$) higher by 6, 14 and 21% than in PS.

Similarly, P uptake, P uptake efficiency and P use efficiency were significantly affected by the type of potato-legume intercrop, and they varied with seasons (Table 5.2). Phosphorous uptake was highest in PS (29 kg P ha^{-1}) and PD (28), but declined by 29 and 39% in PB and PD, respectively compared with PS. Phosphorous use efficiency (PUE) was lowest in PS (321 kg potato equivalent yield kg^{-1} P supply) and it increased by 6, 15 and 22% in PG, PB and PD, respectively compared with PS.

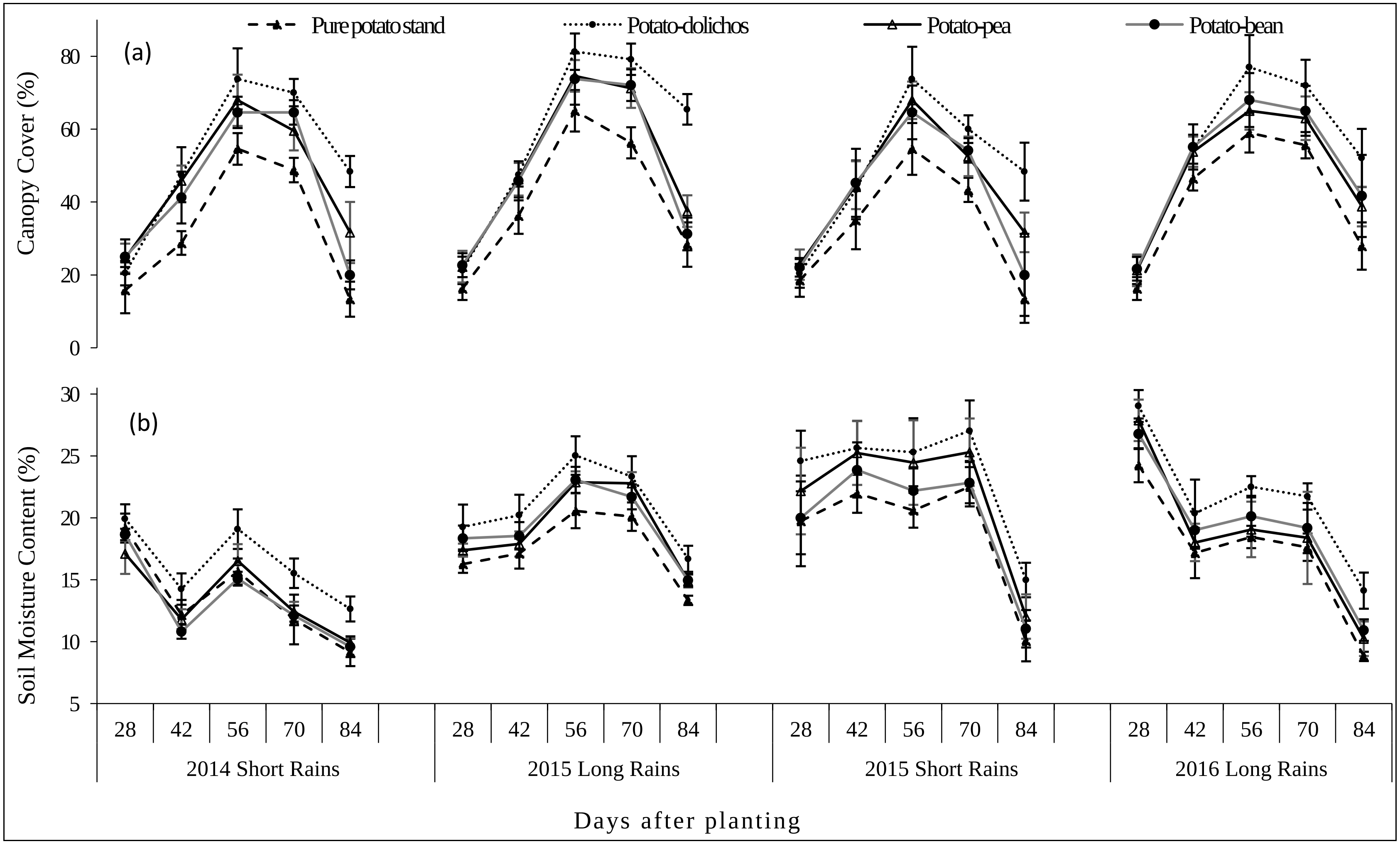

Fig. 5.2: Canopy cover (a) and soil moisture content (b) in different potato-legume intercropping systems.

Table 5.1: Nitrogen uptake, uptake efficiency and use efficiency as influenced by potato-legume cropping systems.

Variable	Intercropping System[a]	2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Plant N uptake ($kg\ ha^{-1}$)	PS	136.88	198.59	204.27	164.02
	PD	136.75	188.85	198.54	148.99
	PG	119.58	154.38	156.04	110.16
	PB	102.31	142.83	168.32	122.89
	Tukey's HSD	13.77	8.91	16.16	11.45
N uptake efficiency (kg total N uptake kg^{-1} N supply)	PS	0.54	0.78	0.80	0.64
	PD	0.54	0.74	0.78	0.58
	PG	0.40	0.56	0.61	0.43
	PB	0.43	0.58	0.66	0.48
	Tukey's HSD	0.05	0.03	0.06	0.04
N use efficiency (kg PEY kg^{-1} N supply)	PS	124.99	149.91	152.97	129.62
	PD	152.62	181.97	182.53	158.87
	PG	133.66	158.44	160.73	139.17
	PB	142.00	161.07	174.30	155.89
	Tukey's HSD	4.51	2.99	2.26	8.14

Analyses of variance (*p* values)

Variable	Intercropping system	Season	System × Season
Plant N uptake	< 0.001	< 0.001	0.032
N uptake efficiency	< 0.001	< 0.001	0.032
N use efficiency	< 0.001	< 0.001	< 0.001

[a]PS (pure potato stand), PD (potato-dolichos), PG (potato-pea) and PB (potato-bean).

Table 5.2: Phosphorous uptake, uptake efficiency and use efficiency as influenced by potato-legume Intercropping systems.

Variable	Intercropping System[a]	2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Plant P uptake ($kg\ ha^{-1}$)	PS	24.79	33.10	30.89	26.75
	PD	23.70	31.77	31.09	24.46
	PG	15.61	20.63	19.19	15.55
	PB	17.55	22.37	22.25	20.12
	Tukey's HSD	1.19	2.01	2.21	3.01
P uptake efficiency (kg total P uptake kg^{-1} P supply)	PS	0.22	0.30	0.28	0.24
	PD	0.21	0.29	0.28	0.23
	PG	0.14	0.19	0.17	0.14
	PB	0.16	0.20	0.20	0.18
	Tukey's HSD	0.01	0.02	0.02	0.03
P use efficiency (kg PEY kg^{-1} P supply)	PS	288.29	345.76	352.81	298.96
	PD	352.01	419.71	420.99	366.42
	PG	308.27	365.43	370.72	320.99
	PB	327.53	371.50	402.01	359.55
	Tukey's HSD	10.40	6.89	5.20	18.78

Analyses of variance (*p* values)

Variable	Intercropping system	Season	System × Season
Plant P uptake	< 0.001	< 0.001	0.049
P uptake efficiency	< 0.001	< 0.001	0.049
P use efficiency	< 0.001	< 0.001	< 0.001

[a]PS (pure potato stand), PD (potato-dolichos), PG (potato-pea) and PB (potato-bean).

5.3.4 Effect of potato-legume intercropping systems on potato and legume yield

Tuber dry yield, number of tubers per plant, fresh tuber yield, legume grain yield and potato equivalent yield were significantly ($p \leq 0.05$) affected by the type of potato-legume intercrop, although these differences differed with seasons (Table 5.3). Dry tuber yield was lower in PD, PB and PG by 2, 16 and 17%, respectively compared with PS. The least number of tubers per plant (7) was recorded in PG and PB, and it differed significantly from the highest (9) in PS and PD. Fresh tuber yield was highest (36 t ha^{-1}) in PS, but this was not significantly different from that recorded in PD. Nevertheless, the yield decreased significantly by 5.6 t in PB and 6.5 t in PG when compared with PS. Among the legumes, dolichos had the lowest grain yield that ranged between 1.8 and 1.9 t ha^{-1} across the seasons. Pea plots recorded intermediate (2.5–2.7 t ha^{-1}) grain yield whereas those of beans had the highest (3.1–3.5 t ha^{-1}).

5.3.5 Relationship between N and P uptake efficiency and use efficiency and potato yield components

Nitrogen uptake efficiency (NUpE) and P uptake efficiency (PUpE) correlated positively and strongly ($p \leq 0.05$) with tuber dry weight, number of tubers $plant^{-1}$ and fresh tuber yield $plant^{-1}$ (Table 5.4). Nitrogen use efficiency (NUE) and P use efficiency (PUE) also indicated significant ($p \leq 0.05$) correlations with tuber dry weight and fresh tuber yield $plant^{-1}$. The relationship between the number of tubers $plant^{-1}$ and NUE and PUE was also significant ($p \leq 0.05$) though weaker ($r = 0.39$).

Table 5.3: Potato tuber yield components, legume grain yield and potato equivalent yield as influenced by potato-legume Intercropping systems.

Variable	Intercropping System[a]	2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Tuber dry matter ($t\ ha^{-1}$)	PS	5.59	6.75	6.92	5.87
	PD	5.55	6.68	6.74	5.77
	PG	4.66	5.65	5.85	4.69
	PB	4.67	5.50	5.93	5.12
	Tukey's HSD	0.19	0.26	0.27	0.29
Tubers $plant^{-1}$	PS	6.65	10.97	10.34	9.06
	PD	7.75	10.73	9.68	9.32
	PG	6.03	7.85	7.08	7.27
	PB	5.38	8.00	7.23	5.98
	Tukey's HSD	1.41	1.67	1.49	1.45
Fresh tuber yield ($t\ ha^{-1}$)	PS	31.87	38.23	39.01	33.05
	PD	31.66	37.50	37.89	32.27
	PG	25.82	31.45	32.51	26.60
	PB	26.65	30.85	33.52	28.81
	Tukey's HSD	0.84	0.74	0.51	1.97
Legume grain yield ($t\ ha^{-1}$)	PS	-	-	-	-
	PD	1.77	1.90	1.85	1.76
	PG	2.49	2.70	2.59	2.68
	PB	3.07	3.28	3.50	3.51
	Tukey's HSD	0.78	2.08	2.03	0.22
Potato equivalent yield ($kg\ ha^{-1}$)	PS	31.87	38.23	39.01	33.05
	PD	38.92	46.40	46.54	40.51
	PG	34.08	40.40	40.99	35.49
	PB	36.21	41.07	44.45	39.75
	Tukey's HSD	1.15	0.76	0.58	2.08

Analyses of variance (*p* values)

Variable	Intercropping system	Season	System × Season
Tuber dry matter	< 0.001	< 0.001	0.138
Tubers $plant^{-1}$	< 0.001	< 0.001	0.006
Fresh tuber yield	< 0.001	< 0.001	< 0.001
Legume grain yield	< 0.001	< 0.001	< 0.001
Potato equivalent yield	< 0.001	< 0.001	< 0.001

[a]PS (pure potato stand), PD (potato-dolichos), PG (potato-pea) and PB (potato-bean).

Table 5.4: Correlation between potato yield components and N and P uptake and use efficiency.

Variable	Tuber dry matter	Tubers plant^{-1}	Fresh tuber yield
N uptake efficiency (NUpE)	0.97^{***}	0.78^{***}	0.98^{***}
N use efficiency (NUE)	0.54^{***}	0.39^{**}	0.52^{***}
P uptake efficiency (PUpE)	0.92^{***}	0.80^{***}	0.92^{***}
P use efficiency (PUE)	0.54^{***}	0.39^{**}	0.52^{***}
NUpE x PUpE	0.89^{***}	0.82^{***}	0.96^{***}
NUE x PUE	0.57^{***}	0.42^{***}	0.57^{***}

Significant at $p < 0.001$ (***) and $p < 0.01$ (**).

5.4 Discussion

Potato production in sub-Saharan countries such as Kenya is mainly carried out by smallholder farmers who are dependent on Agriculture for their livelihood. Incorporating legumes into such production systems would have far-reaching benefits such as enhancing better nutrient utilization, hence improving the productivity of potato-based intercropping systems. Rooting depth and canopy cover are pivotal factors in controlling N and P uptake for potato, and hence productivity of the potato-legume intercropping systems (Mushagalusa et al., 2008; Zhang et al., 2016a). As it has been suggested, any intervention that promotes uptake of these mineral elements may increase their use efficiencies (Zebarth et al., 2008; Wang et al., 2015; Gitari et al., 2016; Sandana, 2016; Musyoka et al., 2017; Nyiraneza et al., 2017). However, in potato-based intercropping systems, the type of companion crop plays a big role in determining nutrient uptake and use efficiency as well as the yield, and this could be partly linked to the growth attributes of these companion crops (Zhang et al., 2016a).

In this study, the higher nutrient (N and P) uptake by potato observed when intercropped with dolichos compared with other legumes (peas and beans) (Table 5.1 and 5.2) could probably be explained by the architecture of the rooting system. Dolichos have been shown to have a deep rooting system, with a taproot that can grow up to a depth of 1.8 m (Cook, 2005; Gitari et al., 2017). The deep rooting system enables the crop to acquire nutrients, outside the zone accessible to the less expansive potato root system, hence minimizing loss through fixation and leaching (Fernandes and Soratto 2012; Hopkins et al., 2014; Gitari et al., 2015). For instance, Ojiem et al. (2007) and Whitbread et al. (2011) reported that dolichos has the ability to capture N and P from the subsoil and pump them to the surface soil strata thus, minimizing the competition for these nutrients. In contrast to dolichos, the rooting system of peas and beans is shallow just like that of potato, which could have increased competition for N and P, hence, contributing to low tuber yield. Lynch and Brown (2012) reported that bean, in particular, tends to localize its roots only at the surface horizon of the soil where P concentration is relatively high due to continual deposition of plant residues. In a potato-maize based intercropping system, Mushagalusa et al. (2008) also reported increased competition of available nutrient by maize crop, which has a shallow rooting system, similar to that of potato.

Besides the deep rooting system by dolichos, higher N and P uptake under potato-dolichos could be attributed to the interaction of the roots between these two crops. It has been suggested that dolichos produce exudates such as phosphatases and carboxylates, which could have a significant influence on the availability of nutrients in its rhizosphere as well as that of the companion crop (Nuruzzaman et al., 2005; Hinsinger et al., 2011). Phosphatases, for instance, may compete with phosphate ions from the charged surfaces, thus releasing P into soil solution (Huang et al., 2005; Hill et al., 2015; Giles et al., 2017). Phosphatases have been shown to assist in degrading organic matter through cleaving phosphate bonds, thus affecting P availability around the rhizosphere (Richardson et al., 2009; Wang et al., 2015). Apart from the legume (companion) crop, rhizodeposition of P could also increase the availability of this element for uptake by potato (Nuruzzaman et al., 2005; Postma and Lynch, 2012). Such a process, to some extent, could explain the high potato P uptake observed in the potato-dolichos intercropping system.

Apart from the root interactions, canopy cover could have played a role in the observed differences in nutrient uptake and use efficiency. For instance, the observed higher canopy cover under potato-dolichos (Fig. 5.2), which could affect the nutrient availability and uptake patterns. Increased moisture, as a result of higher canopy cover, could increase N and P solubilisation as well as reduce their loss hence increasing the available nutrients for potato plant uptake resulting in high tuber yield (Nyawade, 2015; Gitari et al., 2017; Sennhenn et al., 2017). The higher canopy near the soil surface in potato-dolichos intercrop might have also created a microenvironment with reduced solar radiation reaching the soil surface and low temperatures (Webb et al., 2010; Gericke et al., 2012; Zhaohui et al., 2012). Kim et al. (2017) observed lower temperatures due to increased canopy favours tuber initiation process and translocation of the produced sugars from the leaves to the tubers. In turn, this could increase the tuber number and weight, and thus the total tuber yield. In contrast, under potato-bean intercrop, there was increased canopy above the potato plants. This could have promoted more shading than the beneficial covering of soil observed in potato-dolichos intercrop. For instance, in a previous study, Mushagalusa et al. (2008) recorded a 4–26% decline in tuber yield when potato was intercropped with maize, which they ascribed to the shading effect from the maize crop. Shading reduces the photosynthetic capacity of the potato resulting in low yield.

The high N and P uptake efficiency observed in a potato-dolichos treatment similar to the control (Table 5.1 and 5.2) is a clear indication that optimum potato production is feasible under dolichos intercropping systems. This has far-reaching benefits such as reducing environmental hitches related to N and P losses to surface water bodies (Sinclair and Rufty, 2012; Jones et al., 2013; Ruark et al., 2014). Nevertheless, N and P uptake varied with season, which could be attributed to the differences in rainfall patterns (Fig. 5.1). Water plays a great role in determining the plant's ability to take up nutrients in the soil (Ierna and Mauromicale, 2012; Su et al., 2014). For instance, the important role that is played by water in solubilizing P, hence making it available for potato uptake, was clear in the 2014 short rains. This season experienced extremely low rainfall, with cumulative amounts being 380 mm. This was about 25% lower moisture level than the basal potato water requirement of 500 mm (Ierna and Mauromicale, 2012). These findings are in agreement with Zebarth et al. (2008) and Nyiraneza et al. (2017) who reported that P uptake varies from season to season due to differences in rainfall pattern. Thus, weather conditions greatly influence plant's ability to take up nutrients with low uptake occurring in seasons with inadequate rainfall as also observed by other studies (Westermann, 2005; Tein et al., 2014).

The higher productivity (denoted by potato equivalent yield) under intercropping systems than pure potato stand (Table 5.3) is an indication that there was better utilization of resources such as nutrients and water. For instance, legumes could have fixed atmospheric N for their own utilization and subsequently transferred the surplus directly making it accessible for potato uptake. This concurs with earlier findings by Hauggaard-Nielsen et al. (2009), Hinsinger et al. (2011) and Sitienei et al. (2017) who observed that legumes tend to fix N biologically from the atmosphere hence sparing the N supplied from inorganic fertilizers for companion crops such as potato. As a result, this could have improved availability of N for both potato and legume in the intercropping systems. This resulted in additional yield from the legumes, which contributed to higher potato equivalent yield compared to pure potato stand. These results concur with the findings by Singh et al. (2016) and Zhang et al. (2016b) who reported higher potato equivalent yield when potato was intercropped with radish and bean respectively compared to pure potato stand. In turn, the higher potato equivalent yield translated to higher N and P use efficiency under intercropping than pure potato stand. Among the intercropping systems, potato-dolichos recorded the highest nutrient use efficiency, which can further be attributed to dolichos' higher market value of US$ 1.17 kg^{-1}, 30% higher than beans and peas. The current study, therefore, shows the feasibility of intercropping potato with legume intercrops especially dolichos to increase productivity with a negligible penalty on potato yield.

5.5 Conclusions and recommendations

In sub-Saharan African, the vast number of potato growers is smallholder farmers who could improve the productivity of their potato production systems through integrating legumes. This study aimed at determining the most promising legume crop for incorporation into potato production systems without compromising tuber yield. The results of study demonstrate that among the potato-legume based intercrops, potato-dolichos is the most promising in terms of increasing potato productivity. Therefore, farmers can feasibly intercrop potato with dolichos given that it does not compete for nutrients (N and P) besides providing additional yield. Dolichos is a multipurpose drought tolerant legume used as green manure and forage, and its pods, seeds and leaves are used for human consumption. Therefore, integration of such crops as dolichos into potato intercropping systems could hedge against the risk of crop failure, as well as contribute to a balanced diet for farmers who are dependent on Agriculture for their livelihood. Nevertheless, since this study was limited to an altitude of 1860 m, there is needed to explore more legumes for higher potato growing altitudes and determine to what extent such legumes are affected when intercropped with potato.

CHAPTER SIX

Potato-legume intercropping on a sloping terrain land and its effects on potato equivalent yield and soil physico-chemical properties

Abstract

Characterization of soil physical and chemical properties is a fundamental step in understanding soil fertility dynamics under potato-legume-based intercropping systems. A study was conducted in a clayey sub-tropical Nitisol at Kabete Field Station, University of Nairobi to assess the effects of potato-legume intercropping on a sloppy land on potato equivalent yield (PEY) and the spatial variability of selected soil physical and chemical properties following a two-year cultivation coupled with ploughing back of crop residues. The experiment was laid out in a randomised complete block design with four replicates. The treatments were potato-dolichos (*Lablab purpureus* L.) (PD); potato-garden pea (*Pisum sativum* L.) (PG); potato-bean (*Phaseolus vulgaris* L.) (PB) intercropping systems; and a pure stand of potato (*Solanum tuberosum* L.) (PS). Potato-legume intercropping resulted in significantly higher PEY by 25, 17 and 9% in PD, PB and PG compared with PS across the slope positions and seasons. In addition, PEY varied with slope position in all intercropping systems except PD. Under PS, PG and PB, clay and silt increased significant ($p \leq 0.05$) down the slope whereas, an opposite observation was made for sand and bulk density. Nonetheless, under PD, slope position had no significant effect on soil physical properties. In all intercropping systems, a significant increase ($p \leq 0.05$) was observed down the slope for pH and cation exchange capacity (CEC). Similar observations were made for phosphorous (P), nitrogen (N) and organic carbon (OC) under all the intercropping systems except PD. This study has established that PD is a viable intercropping system, which could be adopted by the smallholder potato farmers for higher tuber yield and improved soil fertility.

Submitted to Plant and Soil Journal - Springer.

6.1 Introduction

In Kenya, potato production is done mainly by smallholder farmers as a key food and cash crop on approximately 146,000 ha with an average annual tuber yield of about 1.3 Tg (where 1 Tg = 10^6 tonnes) (FAOSTAT, 2017; Gitari et al., 2018a and b). Due to the exponentially growing human population and decreasing land resources, potato growers are expanding cultivation to marginal areas with steep slopes where frequent high-energy rainstorms occur, hence predisposing soil to erosion (Gachene et al., 1997; Elias, 2017; Nyawade et al., 2018). In these areas, the potato is grown continuously with shortened fallows and without rotations leading to net nutrient mining, which jeopardizes the soil's ability to rejuvenate (Mallory and Porter, 2007; Gitari, 2013; Gitari et al., 2015, 2018a; Nyiraneza et al., 2015; Usowicz and Lipiec, 2017). Thus, heterogeneity in soil physical and chemical properties and declining soil fertility is widespread, resulting in low crop yields. Understanding the spatial heterogeneity of soil physical and chemical properties is very crucial for determining the best management practices that not only improve the productivity of potato-based intercropping systems but also enhance environmental sustainability (Selassie et al., 2015; Usowicz and Lipiec, 2017).

One common way of restoring depleted nutrients is through use of chemical fertilizers (Mugwe et al., 2009; Muthoni et al., 2013; Gitari et al., 2018b). However, high fertilizer prices limit farmers in sub-Saharan countries from applying this input in recommended amounts to support high crop yields (Muthoni et al., 2013; Gitari et al., 2018b). Consequently, such skewed and imbalanced use of fertilizers results in deterioration of soil's ability to support high crop production (Ortiz-Escobar and Hue, 2008; Sharma et al., 2017). Such soil fertility fluctuation can be stabilised through the addition of green manures (Mugwe et al., 2009; Maltais-Landry and Frossard, 2015; Nyiraneza et al., 2015; N'Dayegamiye et al., 2017; Walia and Dick, 2018). Use of green manure particularly from legumes such as *Glycine max, Lablab purpureus, Crotalaria ochroleuca* and *Mucuna pruriens* as a management practice has been proven to have positive effects on yield, soil organic matter content, structure and fertility (Gachene and Wortmann, 2004; Mallory and Porter, 2007; Mugwe et al., 2009; Maobe et al., 2010).

Legumes have an ability to fix atmospheric N, hence sequestering it by immobilizing nitrate-N into plant protein, which provides an appropriate competition to N loss pathways, such as denitrification and leaching (Dabney et al., 2010). This results in less competition for N among the companion intercrops (Ojiem et al., 2007; Hauggaard–Nielsen, 2009; Gitari et al., 2018b; Sitienei et al. 2017). For instance, Ojiem et al. (2007) had earlier reported that dolichos could contribute up to 42 kg N ha^{-1} to soil N fertility, which was mainly attributed to their ability to fix atmospheric N. This is a clear indication that legumes have the ability to recycle nutrients when their residues are incorporated into the soil as they undergo decomposition and mineralization processes, hence contributing to the available soil nutrients (Cheruiyot et al., 2007; Ojiem et al., 2007; Soltangheisi et al., 2018). However, such studies involving incorporation of legume crop residues in potato production to boost soil fertility are rare, especially in sub-Saharan Africa.

Soil moisture content (SMC), texture, bulk density (BD), pH, total nitrogen (N), available phosphorous (P), cation exchange capacity (CEC) and organic carbon (OC) are among the fundamental soil properties that govern soil productivity (Castrignano et al., 2000; Rosemary et al., 2017). Spatial variability of such soil properties within a farm field is primarily attributed to the disparity in transport and deposition of the eroded materials and anthropogenic activities related to soil management practices (Sadeghi and Sasanfar, 2013; Selassie et al., 2015; Rosemary et al., 2017).

Designing alternative intercropping systems remains a key research priority that can address the problem of food scarcity in sub-Saharan Africa to increase the productivity of the existing potato cropping systems given that land resources are diminishing. Ploughing back of crop residues reduces the loss of soil and nutrients through water erosion hence, improve soil fertility (Mugwe et al., 2009; N'Dayegamiye et al., 2017; Walia and Dick, 2018). Such a practice could maintain and replenish soil chemical properties, which are pivotal in crop production. Nonetheless, information on the effect of potato-legume intercropping systems on soil physical and chemical properties is limited. Therefore, this study was carried out with an overarching focus to explore the effect of a two-year potato-legume intercrop on crop production and selected soil physical and chemical properties in a Nitisol. With regard to crop production, potato equivalent yield was determined whereas; the soil physical and chemical properties that were assessed were SMC, texture (sand, silt and clay), BD, pH, total N, OC, available P and CEC.

6.2 Materials and Methods

6.2.1 Site description

This study was carried out between 2014 and 2016 at Kabete Field Station, University of Nairobi, located at 1° 15' S and 36° 44' E, at 1860 m above sea level. The study site falls under the sub-humid agro-ecological zone, which is typical of a Kenyan highland where potato cultivation takes place (Jaetzold et al., 2006; Gitari et al., 2018b). The soil (locally known as Kikuyu red loam) is classified as a Humic Nitisol (IUSS Working Group WRB, 2015). It is derived from tertiary aged Nairobi trachyte lava that is dominated by non-expanding kaolinite clay minerals, is well drained, deeply weathered (> 1.8 m), with diffuse horizon boundaries (Gachene et al., 1997; Karuku et al., 2012). The area receives rainfall in a bimodal pattern, with the first season from March to June often referred to as ‘long rains’ and second season (short rains) from October to December.

6.2.2 Experimental setup and crop establishment

The experiment was laid in a terraced field with a slope of 10% with a well-maintained cut-off drain and embankment on the upper and lower side, respectively (Fig. 6.1). A randomised complete block design in four replicates was adopted with plots whose width was 4 m and while length varied between 10 and 13 m along the contour. The treatments were potato-dolichos

(*Lablab purpureus* L.) (PD); potato-garden pea (*Pisum sativum* L.) (PG); potato-bean (*Phaseolus vulgaris* L.) (PB) and a pure stand of potato (*Solanum tuberosum* L.) (PS).

At the onset of rainfall, pre-sprouted seed potatoes (25–50 g, var Shangi) were manually planted at a spacing of 0.3 m within a row and 0.9 m between rows (plant density = 36,400 plants ha^{-1}). Legumes were planted between the potato rows at a spacing of 0.25 m within a row to give a plant density of 88,000 plants ha^{-1}. At planting, potatoes were supplied with 200 kg ha^{-1} of NPK (17:17:17) fertilizer and an equivalent quantity of calcium ammonium nitrate fertilizer 28 days after planting (DAP). Weeding, hilling-up for potato and staking for bean was carried out manually at 28 DAP. Potatoes were sprayed with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) alternated with Daconil 720 SC (Chlorothalonil 720 g L^{-1}) after every 14 days starting at 28 DAP to control late blight. For data collection, each plot was demarcated into three 2-m slope positions namely: the upper (2 m from the uppermost part of the plot), the middle (2 m at the middle of the plot) and the lower slope position (2 m from the lowest part of the plot) (Fig. 6.1).

6.2.3 Harvesting and biomass nutrient analyses

At crop maturity (75 days after planting for peas, 85 for potatoes and beans and 120 for dolichos), only tubers from potatoes and grains from legumes were taken from the intercropping systems as economic yield, which was recorded per plot and slope position in kg ha^{-1} then converted into potato equivalent yield (PEY) as shown in Eq. (6.1).

$$PEY = PY + \frac{LY * LP}{PP} \tag{6.1}$$

Where PY and LY denote yield (in kg ha^{-1}) of potato and legume, respectively. PP and LP gives the current market price of potato (US\$ 0.34 kg^{-1}) and legumes (taken as US\$ 1.17 kg^{-1} for dolichos, 0.92 for peas and 0.78 for beans), respectively. All crop residues were incorporated in situ as green manure to a depth of 0.3 m. Representative samples for potato and legume crop residues were taken at harvest from every plot, cut into small pieces and 500 g sub-samples were taken, oven dried to constant weight at 70 °C, ground and sieved through a one-millimetre sieve for analysis. Nitrogen and P content were determined using micro-Kjeldahl (Bremner, 1996) and colourimetric (Murphy and Riley, 1962) method, respectively.

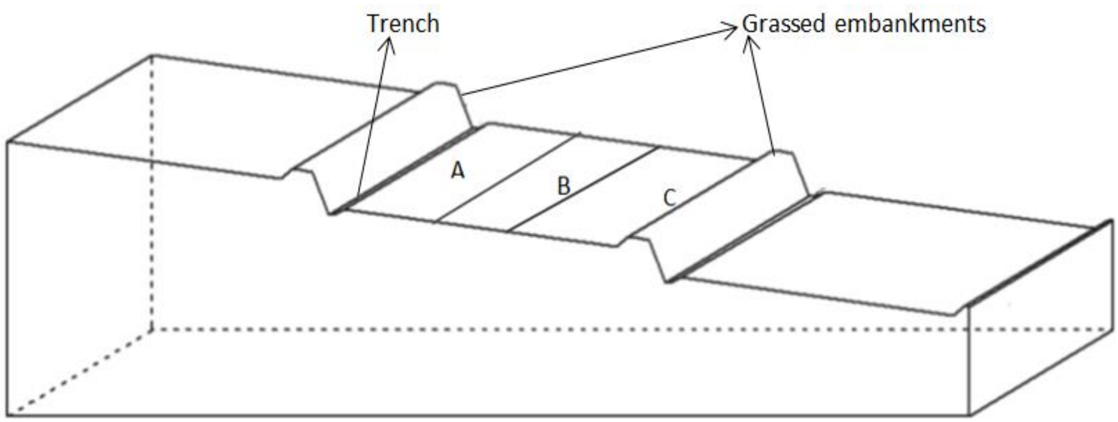

Fig. 6.1: A cross-section sketch drawing of a plot showing the three slope positions, upper (A), middle (B) and lower (C).

6.2.4 Data collection

During each crop-growing season, soil moisture content was measured per slope position and intercropping systems in a weekly basis using a digital soil moisture meter-HSM50. The soil moisture content data were pooled and reported as means for every season. Soil sampling was done at 0−0.3 m depth following the procedures described by Pennock and Yates (2008) using a soil auger (for disturbed samples and in stainless steel core rings (5 cm diameter) (for undisturbed samples). The sampling was done twice, first on October 2, 2014 (before establishing the experiment) and the second sampling was done within each slope position per plot on September 6, 2016, 60 days after incorporating crop residues for the last season (2016 long rains).

For soil physical properties, soil texture analysis was done by hydrometer method (Gee and Bauder, 1979) whereas bulk density was determined as described by Doran and Mielke (1984) from the undisturbed samples. The disturbed soil samples were air-dried and sieved through a 2 mm sieve for chemical analyses. The pH was determined in a 1:2.5 (soil: water) ratio using a pH meter (Ryan et al., 2001). Total N was analysed by the modified micro-Kjeldahl digestion method (Bremner, 1996), and organic carbon by modified Walkley and Black method (Nelson and Sommers, 1996). Cation exchange capacity (CEC) was measured using the NH_4-acetate method as described by Rhoades and Polemio (1977). From the soil extract, available phosphorous was determined using a UV-vis spectrophotometer (Murphy and Riley, 1962).

6.2.5 Statistical data analysis

The effects of potato-legume intercrops on potato equivalent yield and selected physical (sand, silt clay and bulk density) and chemical (pH, phosphorous, nitrogen, organic carbon and cation exchange capacity) soil properties were done using R software version 2.2.3 (R Core Team, 2015). The significant means were separated at $p \leq 0.05$ using Tukey's Honest Significant Difference (HSD). Correlation was done to indicate the relationship between the assessed variables.

6.3 Results

6.3.1 Weather patterns during crop growing period

When compared with the 20-year (1994–2013) average rainfall (994 mm), the amounts received during the two years of the study were 28 mm and 79 mm higher for 2014/15 and 2015/16 years, respectively (Fig. 6.2). The first and second year had an average temperature of 22.2 and 21.9 °C, respectively compared to the long-term average (22.0 °C). In particular, February 2015 and March 2016 were the warmest months, and they were 0.4 °C cooler and 2 °C warmer, respectively when compared to the long-term averages. July remained the coolest month in both years with an average of 19.2 °C and 23.8 °C in comparison to month's 20-year mean of 19.7 °C.

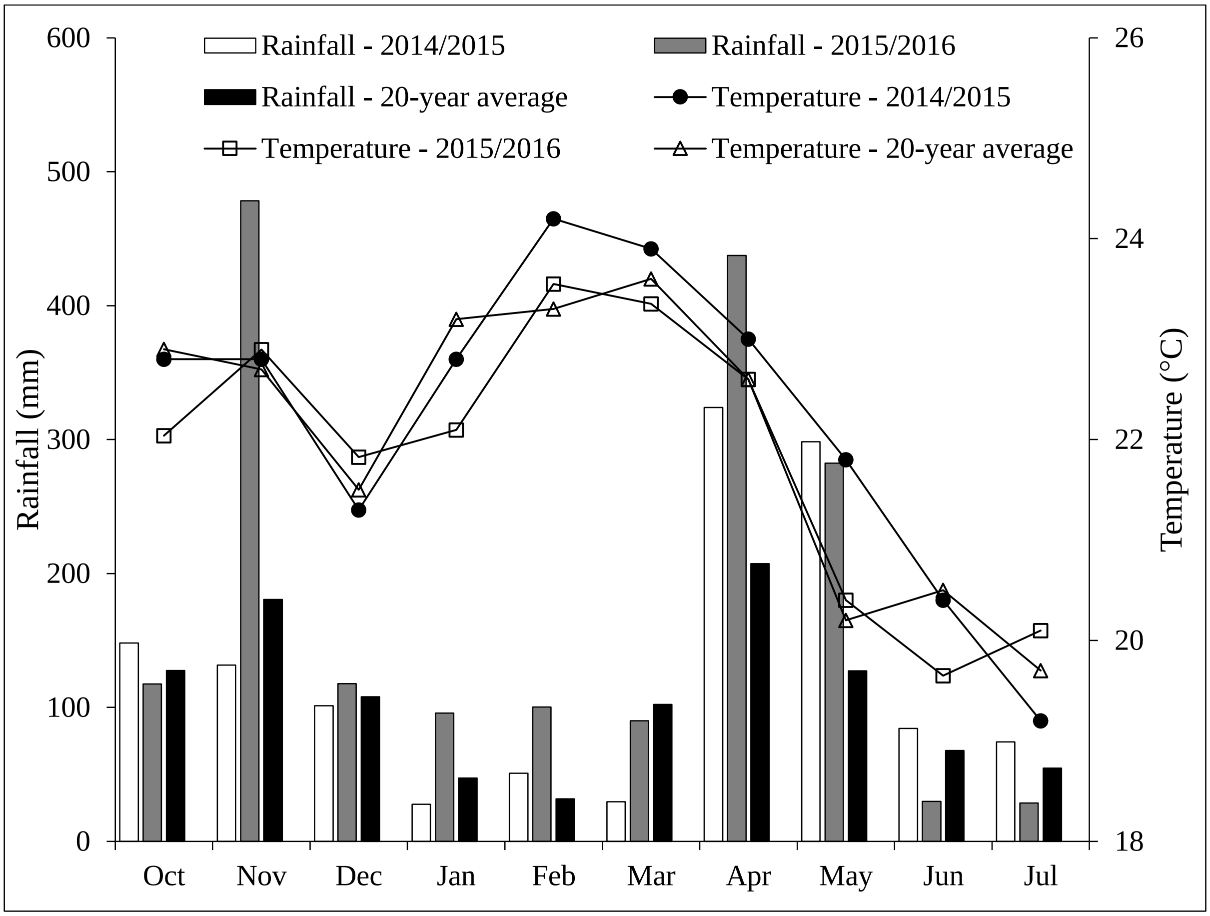

Fig. 6.2: Monthly mean air temperature and the total rainfall during the growing seasons in 2014/15, 2015/16 and 1994–2013 average at Kabete Field Station. (Source: Kenya Meteorological Department, Kabete Weather Station).

6.3.2 Initial soil physical and chemical properties of the study site

Prior to the establishment of this study, the site was fallow for two years and the soil's physical properties at the upper, middle and lower slope position showed no significant ($p \leq 0.05$) differences, with mean bulk density of 1.03 g cm^{-3}, sand of 31%, silt of 27%, and clay of 42%, respectively (Table 6.1). Therefore, the soil could be described as having a clayey texture. The soil was slightly acidic with a mean pH of 5.6, which did not vary down the slope. Available P, total N, organic C and cation exchange capacity (CEC) showed a significant ($p \leq 0.05$) increase down the slope with mean values of 17 mg kg^{-1}, 2.7 g kg^{-1}, 29 g kg^{-1} and 31 cmol$_c$ kg^{-1}, respectively across the three slope positions.

Table 6.1: Initial soil physical and chemical properties of the study site.

	Slope Position			
	Upper	Middle	Lower	*p* Value
Physical properties				
Sand (%)	30.6^{a}	30.6^{a}	30.5^{a}	0.191
Silt (%)	27.0^{a}	27.1^{a}	27.3^{a}	0.101
Clay (%)	42.4^{a}	42.3^{a}	42.2^{a}	0.084
Bulk density (g cm^{-3})	1.04^{a}	1.02^{a}	1.03^{a}	0.068
Chemical properties				
pH	5.6^{a}	5.6^{a}	5.6^{a}	0.155
Available P (mg kg^{-1})	17.2^{b}	17.0^{a}	17.3^{b}	0.044
Total N (g kg^{-1})	2.6^{a}	2.7^{b}	2.7^{b}	0.024
Organic C (g kg^{-1})	28.9^{a}	29.1^{ab}	29.2^{b}	0.006
CEC (cmol$_c$ kg^{-1})	31.0^{a}	31.3^{b}	31.3^{b}	0.004

Values followed by the same superscript letter across the row are not significantly different ($p \leq 0.05$) by Tukey's HSD test.

6.3.3 Potato equivalent yield as affected by slope position and intercropping systems over the four seasons

There was significant ($p \leq 0.05$) influence of slope positions (SP) on potato equivalent yield (PEY) in different intercropping systems (CS) and seasons (S) (Table 6.2). Across the slope positions and seasons, potato equivalent yield was significantly higher by 25, 17 and 9% in PD, PB and PG compared with PS. Regardless of the season, PEY in PS showed significant variation with slope position with a 12 and 14% margin at middle and lower slope position, respectively compared with the upper slope position. Similar observations were made in PB and PG though with smaller differences in values recorded at upper slope compared to those at either middle or lower slope positions. Nevertheless, there was no significant variation in PEY recorded in PD with respect to slope position.

6.3.4 Potato and legume biomass yield and their tissue nutrient contents

Dolichos produced significantly ($p \leq 0.05$) the highest biomass yield of 4.8 t ha^{-1}, which was 35, 54 and 58% higher than that produced by bean, potato and pea residues, respectively (Table 6.3). The dolichos residues had significantly ($p \leq 0.05$) the highest N content contributing an average of 141 kg N ha^{-1} to the soil, which was 56, 89 and 103 kg N ha^{-1} higher than that from the pea, bean and potato residues, respectively. Similarly, P contribution from dolichos residues was significantly ($p \leq 0.05$) higher by 43, 65 and 66% compared to the bean, pea and potato residues, respectively.

Table 6.2: Potato equivalent yield as influenced by slope positions (SP) and intercropping systems (CS) over the four seasons (S).

Intercropping system	Slope position	Potato equivalent yield (t ha^{-1})			
		2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Pure potato stand (PS)	Upper	30.61 ± 0.6[b*]	32.36 ± 1.8[b]	35.64 ± 0.7[b]	27.61 ± 1.7[b]
	Middle	31.87 ± 0.6[a]	38.23 ± 0.2[a]	39.01 ± 0.2[a]	33.06 ± 0.1[a]
	Lower	31.91 ± 0.6[a]	39.32 ± 0.9[a]	39.84 ± 0.2[a]	34.34 ± 0.2[a]
Potato-dolichos (PD)	Upper	39.15 ± 0.9[a]	45.97 ± 0.5[a]	45.63 ± 0.7[b]	40.02 ± 0.6[a]
	Middle	38.92 ± 0.3[a]	46.40 ± 0.7[a]	46.55 ± 0.3[a]	40.51 ± 0.6[a]
	Lower	39.08 ± 0.5[a]	46.89 ± 1.0[a]	47.09 ± 0.6[a]	40.93 ± 0.7[a]
Potato-pea (PG)	Upper	33.44 ± 1.0[b]	39.54 ± 0.7[c]	39.54 ± 0.9[c]	34.43 ± 0.9[c]
	Middle	34.08 ± 0.8[ab]	40.40 ± 0.3[b]	40.99 ± 0.5[b]	35.49 ± 0.5[b]
	Lower	34.64 ± 0.3[a]	40.72 ± 1.0[a]	41.78 ± 0.5[a]	36.06 ± 0.6[a]
Potato-bean (PB)	Upper	37.16 ± 2.4[b]	40.46 ± 0.4[b]	43.58 ± 0.5[c]	38.23 ± 1.8[c]
	Middle	36.21 ± 0.6[a]	41.07 ± 0.3[a]	44.45 ± 0.1[b]	39.76 ± 2.0[b]
	Lower	36.52 ± 0.6[a]	41.18 ± 0.3[a]	45.60 ± 0.3[a]	40.44 ± 2.4[a]

Summary of analyses of variance

	SP	CS	S	SP x CS	SP x S	SP x CS x S
DF	3	3	3	9	9	27
F value	74.9	723.0	637.6	16.9	5.8	2.3
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.003

[*]Means (± standard deviation) followed by different letters down the column differ significantly at $p \leq 0.05$ by Tukey's HSD test.

Table 6.3: Biomass yield for potato and legume residues and their N and P contribution into the soil.

Crop	Biomass yield (t ha^{-1})	Nitrogen		Phosphorous	
		N (%)	N (kg ha^{-1})	P (%)	P (kg ha^{-1})
Potato	2.25^{c}	1.89^{c}	42.53^{d}	0.28^{c}	6.30^{c}
Dolichos	4.84^{a}	3.01^{a}	145.68^{a}	0.38^{a}	18.39^{a}
Pea	2.05^{c}	2.74^{b}	56.17^{c}	0.31^{b}	6.36^{c}
Bean	3.17^{b}	2.82^{b}	89.39^{b}	0.33^{b}	10.46^{b}

Means followed by different superscript letters down the column differ significantly at $p \leq 0.05$.

6.3.5 Soil physical properties as influenced by slope position under different intercropping systems

Potato-legume intercropping systems influenced significantly ($p \leq 0.05$) soil physical properties such as moisture content, bulk density and texture (sand, silt and clay) and their values varied with slope position and growing seasons. Across the slope positions and seasons, SMC was 7, 9 and 23% higher in PB, PG and PD compared with PS (Fig. 6.3). A similar trend was depicted down the slope in all intercropping systems such that SMC at lower and middle slope positions were 17 and 5% higher than at upper slope position.

Bulk density varied significantly ($p \leq 0.05$) between intercropping systems in the order PD (1.07 g cm^{-3}) < PG (1.12) < PB (1.14) < PS (1.21) (Fig. 6.4), which marked percentage increase of 17, 4, 9 and 11, respectively relative to the baseline values (Table 6.1). Significant ($p \leq 0.05$) decrease in bulk density was observed down the slope in all intercropping systems except PD with an average of 1.01 g cm^{-3} at upper slope position, 1.14 g cm^{-3} at the middle slope position and 1.16 g cm^{-3} at the lower slope position and these values were 11, 12 and 8% higher compared to the baseline values recorded prior to the start of this experiment (Table 6.1).

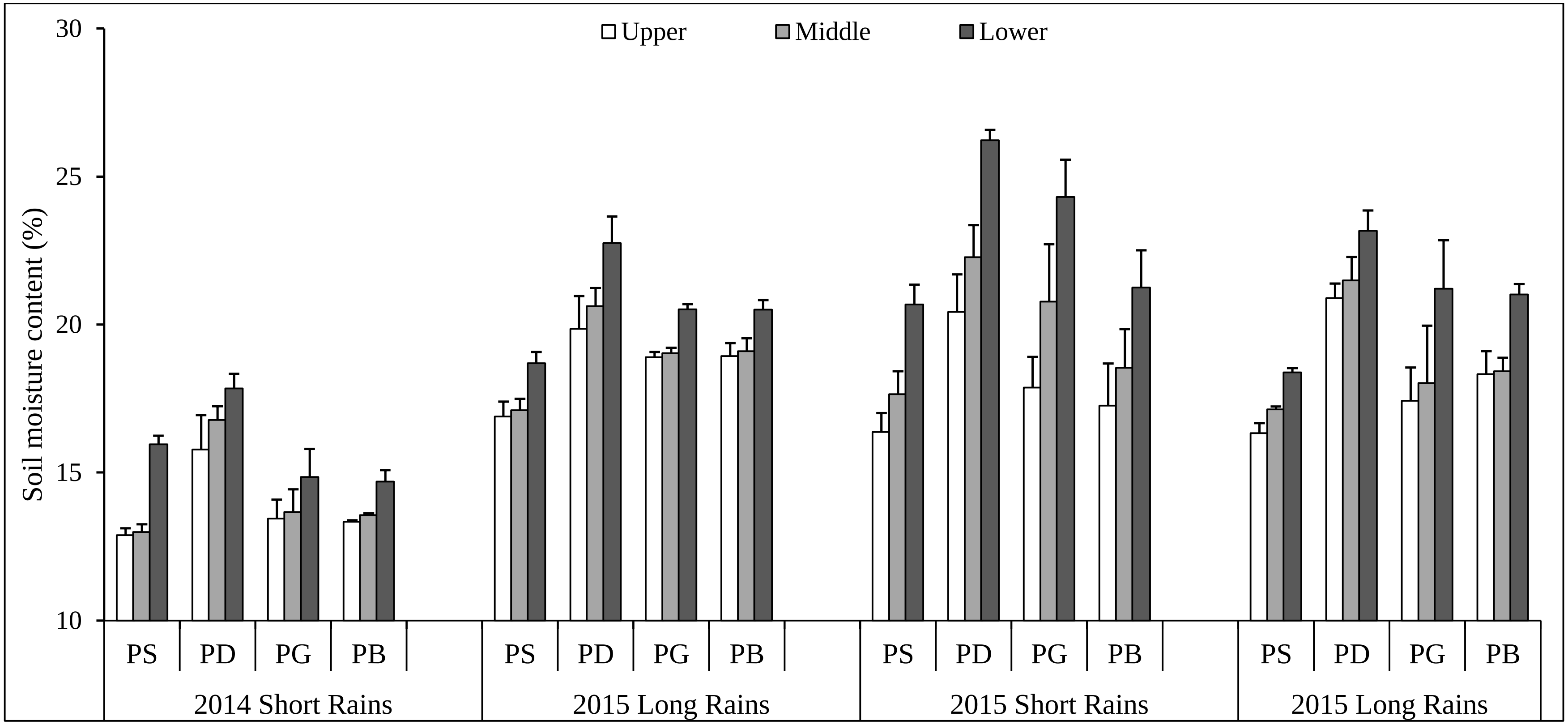

Fig. 6.3: Soil moisture content as influenced by slope position under different potato-legume intercropping systems at different seasons. PS: pure potato stand, PD: potato-dolichos, PG: potato-pea, PB: potato-bean. Bars with the same letter within the same intercropping system and season denote means that are not significantly different at $p \leq 0.05$). Error bars depict standard error of the means.

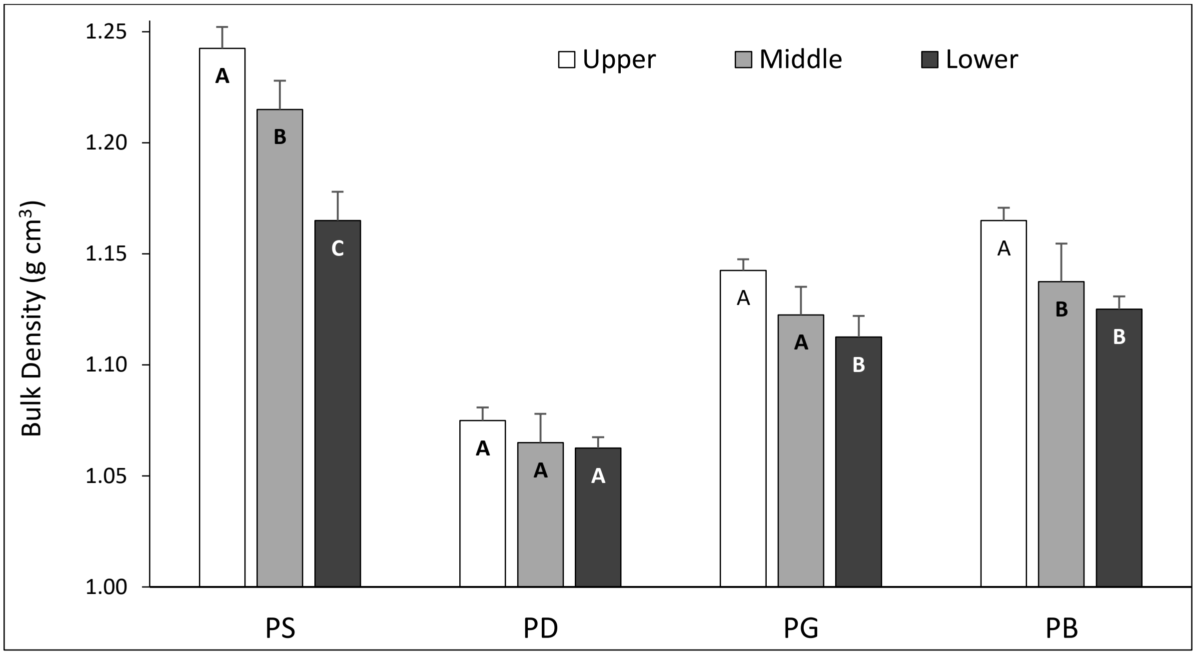

Fig. 6.4: Soil bulk density as influenced by slope position under different potato-legume intercropping systems. PS: pure potato stand, PD: potato-dolichos, PG: potato-pea, PB: potato-bean. Bars with the same letter (by intercropping systems) are not significantly different at $p \leq 0.05$). Error bars signify standard error of the means.

Sand, silt and clay content were significantly ($p \leq 0.05$) affected by slope positions with intercropping systems having a negligible influence (Fig. 6.5). Sand decreased significantly down the slope in PS, PG and PB whereas, in PD, it did not change in all the three slope positions. Averaged across the intercropping systems, sand decreased by 8 and 14% at middle and lower slope positions, respectively compared with upper slope position. When compared with baseline values (Table 6.1), sand content at the upper slope position was 6% higher whereas, at the middle and lower slope positions it was 2 and 8% lower, respectively.

In contrast, silt increased significantly down the slope in all intercropping systems except in PD (Fig. 6.5). Silt was significantly higher at middle slope position by 2% and at lower slope position by 5% compared with the upper slope position across the intercropping systems.

Potato-legume intercropping resulted in a 1% decrease in silt content at upper slope position but at the middle and lower slope positions, it increased by 3% and 6%, respectively compared with baseline values (Table 6.1).

Similarly, clay content increased significantly down the slope in all treatments excluding PD (Fig. 6.5). Irrespective of the intercropping systems, clay content at the upper slope position decreased significantly ($p \leq 0.05$) by 4% whereas at the lower slope position it increased by 3% in comparison with the average value (42.2%) recorded prior to the establishment of this study (Table 6.1). The clay content at the middle and lower slope positions were 5 and 7% higher, respectively than at the upper slope position.

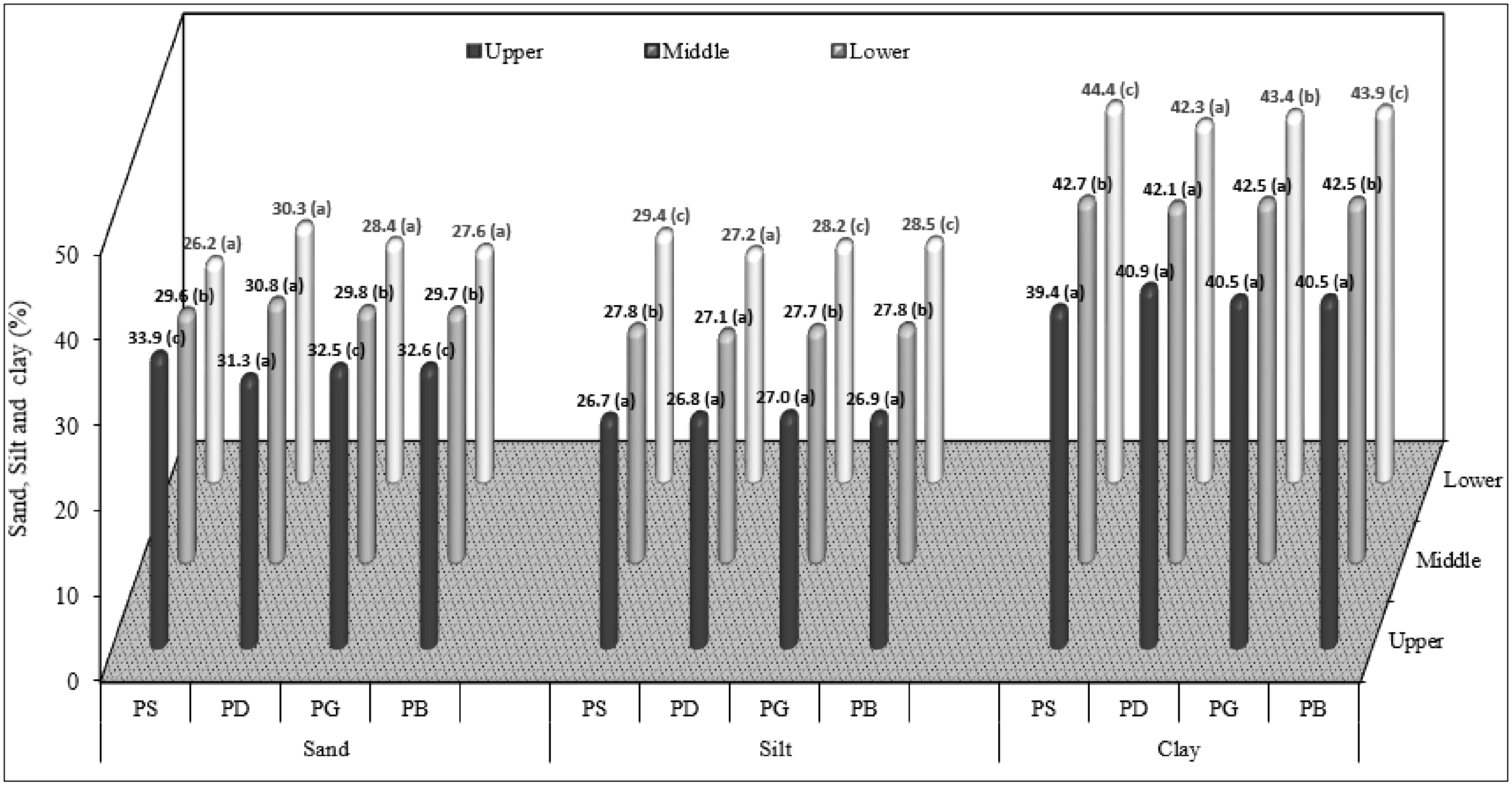

Fig. 6.5: Sand, silt and clay as influenced by slope under different potato-legume intercropping systems. PS: pure potato stand, PD: potato-dolichos, PG: potato-pea, PB: potato-bean. Bars with the same letter (down the slope within the same intercropping system) depict means that are not significantly different at $p \leq 0.05$.

6.3.6 Soil chemical properties as influenced by slope position under different intercropping systems

There was significant ($p \leq 0.05$) influence of slope positions under different potato-legume intercropping systems on soil chemical properties (Table 6.4). The soil pH was higher by 0.1 unit in PG and 0.2 units in PD and PB compared with PS, and it increased significantly down the slope in all the treatments. The P value recorded in PS (23.5 mg kg^{-1}) at the lower slope position was significantly higher than at middle and upper slope positions by > 8 mg kg^{-1}. There was no significant change in P content in PD in all the three slope positions. Irrespective of the slope position, P was in the order of PD (26.3 mg kg^{-1}) > PG (22.3) > PB (21.9) > PS (17.4), and they were 53, 23, 27 and 1% higher, respectively relative to the baseline values. Total N increased significantly down the slope in all the treatments except PD. Based on the intercropping systems, N differed significantly between cropping systems in the order PD (3.7 g kg^{-1}) > PB (3.3) > PG (3.2) > PS (3.1), and was 44, 28, 23 and 21% higher respectively, than baseline values. The OC recorded at the lower slope position in PS was significantly ($p \leq 0.05$) higher than at the middle and upper slope positions. A similar trend was observed in PG and PB whereas, in PD, OC was not affected by slope position. Soil organic carbon increased significantly by 20% in PG, 21% in PB and 42% in PD compared to PS.

Table 6.4: Soil chemical properties as influenced by slope position under different potato-legume intercropping systems.

Variable	Slope position	Pure potato stand	Potato-dolichos	Potato-pea	Potato-bean
Soil pH	Upper	$5.4 \pm 0.1^{a*}$	5.7 ± 0.0^{a}	5.7 ± 0.3^{a}	5.8 ± 0.2^{a}
	Middle	5.6 ± 0.1^{b}	5.9 ± 0.1^{ab}	5.8 ± 0.1^{a}	5.8 ± 0.3^{a}
	Lower	6.0 ± 0.2^{c}	6.0 ± 0.1^{b}	5.9 ± 0.1^{b}	5.9 ± 0.0^{b}
	Mean	5.7 ± 0.3C$^{\#}$	5.9 ± 0.4A	5.8 ± 0.2B	5.8 ± 0.2B
Available P (mg kg^{-1})	Upper	13.6 ± 1.5^{a}	24.9 ± 1.0^{a}	19.6 ± 0.4^{a}	19.6 ± 0.5^{a}
	Middle	14.9 ± 2.0^{a}	26.3 ± 1.5^{a}	20.7 ± 1.4^{ab}	21.5 ± 3.3^{ab}
	Lower	23.5 ± 1.6^{b}	27.8 ± 1.2^{a}	23.2 ± 1.9^{b}	24.5 ± 0.8^{b}
	Mean	17.4 ± 4.8C	26.3 ± 1.7A	21.2 ± 2.0B	21.9 ± 2.8B
Total N (g kg^{-1})	Upper	2.8 ± 0.4^{a}	3.7 ± 0.3^{a}	3.1 ± 0.6^{a}	3.2 ± 0.0^{a}
	Middle	3.0 ± 0.0^{b}	3.7 ± 0.3^{a}	3.2 ± 0.0^{a}	3.3 ± 0.7^{b}
	Lower	3.6 ± 0.1^{c}	3.8 ± 0.1^{a}	3.3 ± 0.2^{b}	3.5 ± 0.1^{c}
	Mean	3.1 ± 0.0D	3.7 ± 0.3A	3.2 ± 0.2C	3.3 ± 0.3B
Organic C (g kg^{-1})	Upper	23.2 ± 3.1^{a}	36.4 ± 3.8^{a}	30.2 ± 3.3^{a}	27.6 ± 4.6^{a}
	Middle	24.6 ± 5.9^{a}	36.2 ± 3.8^{a}	31.6 ± 2.0^{ab}	32.5 ± 4.2^{b}
	Lower	31.8 ± 1.3^{b}	37.9 ± 1.6^{a}	33.4 ± 0.8^{b}	36.0 ± 2.5^{c}
	Mean	26.5 ± 4.1C	37.5 ± 2.6A	31.7 ± 2.3B	32.0 ± 5.0B
CEC ($cmol_c$ kg^{-1})	Upper	25.4 ± 1.6^{a}	32.4 ± 0.5^{a}	30.6 ± 1.3^{a}	30.9 ± 0.5^{a}
	Middle	27.3 ± 1.5^{a}	32.8 ± 0.9^{a}	30.8 ± 0.7^{a}	31.3 ± 0.4^{a}
	Lower	31.0 ± 1.0^{b}	34.0 ± 0.6^{b}	32.2 ± 0.5^{b}	32.4 ± 0.4^{a}
	Mean	27.9 ± 0.3C	33.0 ± 0.1A	31.2 ± 0.1B	31.6 ± 0.1B

Analyses of variance (*p* values)

Variable	Slope position	Intercropping system	Slope × System
pH	< 0.001	< 0.001	0.007
Available P	< 0.001	< 0.001	< 0.001
Total N	< 0.001	< 0.001	< 0.001
Organic C	< 0.001	< 0.001	0.196
CEC	< 0.001	< 0.001	< 0.001

[*, #] Upper and lowercase letters indicate comparisons for means (± standard deviation) among the slope positions and intercropping systems, respectively at $p \leq 0.05$ by Tukey's HSD test.

6.3.7 Relationship between the assessed variables of yield and soil physical and chemical properties

Potato equivalent yield (PEY) was correlated directly (r = 0.39–0.75; $p \leq 0.05$) to pH, OC, P, SMC, CEC and N, and inversely (r = 0.89; $p \leq 0.05$) to BD (Table 6.5). However, no significant correlations were observed between PEY and other soil physical properties namely sand, silt and clay. SMC had significant correlations (r = 0.36–0.83; $p \leq 0.05$) with all variables except silt. Whereas, sand depicted no significant correlation with BD, it had significant and negative relationship (r = 0.33–0.49; $p \leq 0.05$) with all the soil chemical properties namely pH, P, N, OC and CEC. A similar relationship was observed between BD and these chemical properties. Nonetheless, all the soil chemical properties except pH had no significant correlations with silt. Clay, pH, P, N, OC and CEC had significant and positive correlations with each other with coefficients ranging from 0.38 to 0.84.

Table 6.5: Correlation (Pearson) between the assessed variables: potato equivalent yield (PEY), soil moisture content (SMC), sand, silt, clay, bulk density (BD), soil pH, phosphorous (P) total nitrogen (N), organic carbon (OC) and cation exchange capacity (CEC).

	PEY	SMC	Sand	Silt	Clay	BD	pH	P	N	OC
SMC	0.75^{***}									
Sand	-0.15^{ns}	-0.36^{*}								
Silt	-0.08^{ns}	0.17^{ns}	-0.89^{***}							
Clay	0.25^{ns}	0.42^{**}	-0.97^{***}	0.76^{***}						
BD	-0.89^{***}	-0.83^{***}	0.20^{***}	0.03^{ns}	-0.30^{*}					
pH	0.39^{**}	0.68^{***}	-0.49^{*}	0.40^{*}	0.49^{***}	-0.45^{**}				
P	0.75^{***}	0.83^{***}	-0.34^{ns}	0.16^{ns}	0.40^{**}	-0.76^{***}	0.54^{***}			
N	0.81^{***}	0.80^{***}	-0.38^{ns}	0.18^{ns}	0.44^{**}	-0.84^{***}	0.59^{***}	0.84^{***}		
OC	0.61^{***}	0.71^{***}	-0.39^{ns}	0.25^{ns}	0.42^{**}	-0.62^{***}	0.56^{***}	0.78^{***}	0.77^{***}	
CEC	0.80^{***}	0.70^{***}	-0.33^{ns}	0.17^{ns}	0.38^{**}	-0.81^{***}	0.49^{***}	0.66^{***}	0.72^{***}	0.60^{***}

Significant at $p < 0.001$ (***), $p < 0.01$ (**) and $p < 0.05$. Ns denote not significant ($p > 0.5$).

6.4 Discussion

Spatial variability of soil physical and chemical properties is a common occurrence under potato-legume production systems. The high sand content recorded at the upper slope position in all treatments except potato-dolichos (PD) (Fig. 6.5) could suggest that the soil was prone to erosion hence detaching the finer particles from the surface and depositing them at the lower slope position. This is in agreement with the findings that report that clay, which is of finer and light materials, is more susceptible to erosion than sand particles (Sadeghi and Sasanfar, 2013; Nyawade, 2015; Elias, 2017). These results also concur with findings by Selassie et al. (2015) who reported significant sedimentation of clay particles at lower slope position compared to the upper part of the slope.

The non-significant variation in physical properties down the slope in potato-dolichos treatments could have been due to higher biomass production, which protected the soil particles from raindrop impact and being washed away by run-off. For instance, Gachene and Wortmann (2004) and Nyawade (2015) and Gitari et al. (2018a) observed that during crop growth, potato-dolichos has a dense canopy that covers the soil, hence shielding it from the raindrop impact, which could result in detachment of fine clay particles. Secondly, as reported earlier by Blanco-Canqui et al. (2013), Nyawade (2015) and Gitari et al. (2018a), under intercropping systems there is high root density, which binds soil particles, hence reducing the susceptibility of the soil to erosion (mainly rain-impacted flow). This also supports the findings by Aranyos et al. (2016) that organic matter is vital in aggregating soil particles resulting in reduced compaction, hence promoting water infiltration and safeguarding the soil physical properties.

The low soil bulk density (BD) that was reported under intercropping systems especially in PD than in pure potato stand (Fig. 6.4) could be explained in different ways. First, it is assumed that due to high canopy cover raindrops impact on the soil was reduced, which may have reduced compaction of the soil hence the observed low BD compared to monocropping systems, which had less ground cover. Blanco-Canqui et al. (2013) and De Moraesa et al. (2016) observed that compaction tends to force soil particles together resulting in increased BD of the soil. In this study, there was high crop residue production under intercropping relative to monocropping systems, which after incorporation may have decomposed creating channels of biopores that could have reduced soil compaction, hence the low BD. Calonego and Rosolem (2010) and De Moraesa et al. (2016) observed that biopores increase friability of the soil, therefore, creating key pathways for water and air flow, and root growth. The low bulk density (BD) observed under intercrops relative to sole potato treatments is beneficial as it probably suggests greater porosity of the soil, which could facilitate water percolation and retention and movement of air and solutes. This reflects the ability of the soil to support plants growth, especially in sub-Saharan countries with erratic rainfall. The BD values reported in this study agrees with the 1.1 and 1.4 g cm^{-3} range given by Arshad et al. (1996) for clayey soils as the ideal threshold for plant growth beyond which root growth is restricted. This was further reinforced by the significant correlations that were observed between textural and BD, and soil chemical properties such as CEC and pH (Table 6.5). The negative correlations observed between BD and chemical properties, particularly OC agrees with earlier findings (Sakin, 2012; Aranyos et al., 2016; Annabi et al., 2017; Elias 2017).

In this study, the significantly higher levels of chemical properties (pH, P, N, CEC and OC) in potato-legume intercropping systems (Table 6.4) support the importance of legume residues in improving soil fertility. For instance, the high N content in potato-legume treatments especially those involving dolichos could be attributed to the high-quality biomass that contains high levels of N and P (Table 6.3). This is supported by findings reported by Cheruiyot et al. (2007) and Ojiem et al. (2007) who observed that when legume residues such as that of dolichos are ploughed into the soil as green manure, they decompose rapidly to release N that is bound in them to the soil. This can explain the significantly high chemical property values observed under intercropping systems, especially in PD, which was also reflected in tuber yield. Increase in P levels in intercrops above the potato pure stand agrees with Nuruzzaman et al. (2005), Maltais-Landry and Frossard (2015) and Soltangheisi et al. (2018) who reported that legumes have the ability to mobilize P from the soil through solubilizing exudates such as carboxylates. This may explain the high P contents recorded in potato-legume plots compared to pure potato stand. The ability of legumes, particularly dolichos to take up nutrients and retaining them within their system, which later is released after decomposition could explain the observed uniformity in chemical properties under PD down the slope, which is in line with earlier findings (Gitari et al., 2018b; Soltangheisi et al., 2018). Therefore, inclusion of such a legume into potato production system in Kenyan Nitisols could mask the reduction of crop yield due to erosion; hence enhancing productivity (Gachene et al., 1997).

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Indirectly, the significant increase that was observed in N and OC especially in potato-legume treatments (Table 6.4) could be linked to a microclimatic condition created by higher canopy during the crop growth period with low temperature (Gitari et al., 2018a; Nyawade et al., 2018). Such conditions might have decreased soil N mineralisation resulting in less loss of N through leaching and erosion and could explain the high element levels after potato harvest in line with Neumann et al. (2012) finding that N mineralisation is slow when temperature decreases. Nonetheless, the ability of such green manures to release nutrients is dependent on factors such as their chemical composition, soil moisture and temperature (N'Dayegamiye et al. 2017). For instance, in accordance with Finney et al. (2016) and White et al. (2017) C:N ratio is the primary driver of N supply with legume crops with a low C:N ratio being able to assimilates high N content in their biomass, which will results in a high N supply when their residues decompose compared to potato residues.

Conventionally, potato farmers apply di-ammonium phosphate fertilizer at planting and calcium ammonium nitrate for topdressing (Muthoni et al., 2013). Given that this study was carried out on a sloppy terrain, some chemical elements from the applied fertilizers, especially in pure potato stand treatments, could have been washed away by runoff through soil erosion from the upper and middle slope positions to the lower slope position. These results agree with Nyawade (2015) who observed high losses of basic cations in pure potato stand compared to potato-legume intercropping systems. Such deposition of cations and other humic materials at the lower slope position could also explain the observed high CEC, N and OC, especially in pure stand treatment (Table 6.4) and reflect similar findings by Selassie et al. (2015) and Elias (2017).

Although P is less vulnerable to other losses pathways such as leaching, lateral flow of soluble P through erosion results in environmentally significant losses as attested by Burkitt et al. (2004) and Nyawade (2015). With carrying away of basic cation, it is expected that soil pH would decrease as it was observed especially at the upper slope position in pure potato stand treatment (Table 6.4). These results highlight the need for soil improving strategies to make Nitisols and other related tropical soils more productive under intensive potato-based cropping systems. In a similar study, Bekunda et al. (1997) reported that Nitisols tends to acidify with continuous cultivation without application of organic matter. Similar acidic conditions in Nitisols have been reported by Nyawade (2015) who observed lower pH value under pure potato stand compared with potato-legume intercropping systems, which was attributed to the transportation of cations through runoff. Moreover, as observed by Mallory and Porter (2007), prolonged uptake of the basic cations by potato with the minimal turnover of crop residues could also be responsible for decreased pH in pure potato stand.

The significant correlations that were observed between soil particle size indices and other soil properties such as CEC and pH (Table 6.5) was an indication that availability of soil nutrients is governed by texture, which is a key factor in improving soil quality. The observed positive correlation between clay and silt, and negative correlation with sand content and OC are consistent with past observations (Annabi et al., 2017; Elias, 2017; Rosemary et al., 2017). For instance, Elias (2017) observed a positive correlation between clay and silt, and negative correlation with sand content and OC. The calcium ammonium nitrate fertilizer that was applied to all treatments might have supplied Ca^{2+} (a key constituent of CEC), which could have resulted in the formation of strong Ca^{2+}-clay-OC bonds (Walia and Dick, 2018). This could explain the observed strong correlations between CEC and OC. According to Fassil and Charles (2009) and Rosemary et al. (2017), clay minerals and organic matter, which are negatively charged, are responsible factors for CEC as they act as anions to adsorb and hold the positively charged cations. However, CEC is dependent on the nature of the clay minerals and the level of negative charges they contain (Fassil and Charles, 2009). Given that the major clay mineral in tropical Nitisols is kaolinite that has high negative charges then this could explain the high correlation between clay and CEC (IUSS Working Group WRB, 2015; Elias, 2017). The positive correlation among clay, P and OC also could be due to the adsorption of P onto organic matter and clay that is common on soils low in pH (Hopkins et al., 2014; Gitari et al., 2015).

The above results give an insight into soil improving that could make Nitisols and other related tropical soils more productive under potato production systems. Ploughing back of crop residues could result in the greatest benefits in the long term by building up soil fertility, hence enhancing their productivity (Ortiz-Escobar and Hue, 2008; Maltais-Landry and Frossard, 2015; Nyiraneza et al., 2015). Considering the high soil C and N observed in intercropping systems relative to potato pure stand, there is need to encourage farmers especially in sub-Saharan Africa to embrace intercropping systems that yield higher organic biomass such as potato-dolichos.

6.5 Conclusions and recommendations

The results obtained in this study have indicated that potato-legume intercropping systems and slope significantly influences potato equivalent yield (PEY) and, important soil physical (bulk density) and chemical (pH, N, P, CEC and OC) properties. Although PEY was highest under all intercropping systems than sole cropping, its variability with slope was minimal under PD. Soil texture was affected by the slope position with silt and clay increasing down the slope whereas sand recorded contrasting results. Higher N, P, CEC and OC were observed at lower slope position than at middle and upper slope positions. These variables were significantly highest in PD than in other treatments, an indication that dolichos residues were more superior in not only improving soil fertility but also in reducing variability in soil physical and chemical properties at different slope positions. This is worthwhile information for soil management that could not only enhance soil fertility of potato-based intercropping systems but also reduce variability of soil physical and chemical properties due to soil erosion. Therefore, potato-legume intercropping systems, especially those involving dolichos are sustainable, and they contribute to the restoration of soil fertility over time, hence there is a need to upscale such intercropping systems to potato growing farmers in sub-Saharan Africa.

CHAPTER SEVEN

General Conclusions and Recommendations

7.1 Ground cover, soil moisture content, yield and economic returns as affected by potato legume intercropping systems

Legumes are known as important intercrops enhancing the productivity of intercropping systems in both developed and developing countries. Nevertheless, there is limited information on the effect of such crops when used as intercrops on water conservation, nutrient use efficiency and overall nutrient status of the soil particularly in sub-Saharan Africa. Chapter 4 has demonstrated the feasibility of intercropping potato with legume. Of interest was the potato-dolichos intercropping system, whose tuber yield did not differ significantly with those recorded in potato pure stand. This intercropping system had the highest ground cover that created a microclimate under the canopy, which probably resulted in reduced water loss. Moreover, dolichos could have accessed water from deep soil strata owing to its deep rooting system. The additional yield obtained from legumes under intercropping systems resulted in higher economic returns than under potato pure stand. This was attributed to better utilization of water under intercropping systems compared to monocropping.

7.2 Nutrients (N and P) uptake and use efficiency as influenced by potato legume intercropping systems

Integration of legumes into potato-based cropping systems without a proper audit of whether they compete with the main crop for the nutrient is a futile innovation. Chapter 5 has presented results on N and P uptake and use efficiency. As discussed in section 7.2, dolichos with its deep rooting system was able to extract these resources from the subsoil and probably pump some at the surface horizon for uptake by the shallow-rooted potato. Dolichos might have also released P solubilizing chemicals that could have mobilized bound P in organic matter hence increasing its availability for potato uptake. With higher nutrient uptake under intercropping systems, higher potato equivalent yield were achieved, which resulted in higher N and P use efficiency than in potato pure stand.

7.3 Soil physical and chemical properties as influenced by potato legume intercropping systems

The status of soil physical and chemical properties after a crop harvest is a key indicator of soil fertility, which can help determine sustainable intercropping systems. Integration of legumes into potato-based cropping systems coupled with the incorporation of crop residues after harvest could be vital in revitalizing degraded soils due to the continuous cultivation of crops. As demonstrated in Chapter 6, in potato-dolichos intercropping system, soil physical properties did not differ significantly down the slope. This was an indication that there was less transportation of clay and silt particles down the slope. In addition, this intercropping system recorded significantly the highest values of chemical properties such as pH, N and organic carbon that did not differ significantly down the slope. This was an indication of the great role played by such intercropping systems in checking nutrient loss down the slope.

7.4 Conclusions

- The study has established that integration of legumes, particularly dolichos into potato-based cropping systems results in higher economic returns than in pure potato stand. Such positive results are beneficial, especially for resource-constrained smallholder farmers in sub-Saharan African who are reliant on rain-fed agriculture.
- Potato-legume intercropping also resulted in increased N and P use efficiency when compared to cultivating potato as a pure stand. Specifically, dolichos stood out as the legume of choice given that it did not have a negative impact on potato tuber yield.
- Integration of legume into potato-based cropping systems coupled with incorporation of crop residues can play a key role in regulating the spatial variability of soil physical and chemical

properties. Among the intercrops, potato-dolichos showed minimal variation of the soil physical and chemical properties down the slope. This is a remarkable observation that can counter the loss of soil fertility, particularly in highlands with steep slopes, which are vulnerable to soil erosion.

7.5 Recommendations

- The study recommends that farmers, especially smallholder ones to integrate legumes, particularly dolichos into potato-based cropping systems for improved productivity and returns.
- However, since this study was carried out at an altitude of 1860 m, further research is needed to explore alternative legumes for higher potato growing altitudes.
- A more focused study geared towards assessing the extent to which such legume intercrops are affected by the companion potato crop is important and on the trade-off under potato-legume intercropping systems.
- The findings of the current study further evidence the significance of continuous research with a focus on the spatial and temporal arrangement of the said legumes in potato-based cropping systems to evaluate their competition effects on the available resources.
- Future studies should also focus on assessing soil and canopy temperature, and light use efficiency under such intercropping systems for a more informed decision.
- Notwithstanding the alternative uses of crop residues, as fuel and fodder, there is need to encourage farmers to be ploughing back the crop residues into the soil.
- Given that this study was carried over for only four seasons, it would be worthwhile adopting long-term trial to ascertain the effects of these intercropping systems on the observed variables such as water conservation, nutrient use efficiency, yield, economic returns and changes in the soil chemical properties.

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