DIVERSIFICATION OF POTATO FARMING SYSTEMS THROUGH LEGUME INTERCROPPING FOR IMPROVED RESOURCE USE EFFICIENCY

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DECLARATION

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

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DEDICATION

To my parents Charles Ochuodho, Teresa Akong'o and Consolata Auma for their love, care and passion for education

and

To my brother Dr. Benson Okinyi for his inspirational phylosophy '*Chak achaka'*
(Whatever *looks like a mountain soon becomes an anthill only if you begin*)

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LIST OF ACRONYMS AND ABBREVIATIONS

AEZ	Agro-Ecological Zone
ANOVA	Analysis of Variance
CAN	Calcium Ammonium Nitrate
CGIAR	Consultative Group for International Agricultural Research
CIP	International Potato Center
CWP	Crop Water Productivity
DAP	Days After Planting
DHA	Dehydrogenase Activity
DM	Dry Matter
DOM	Dissolved Organic Matter
Dp	Deep percolation
Ep	Evaporation
Es	Saturation vapor pressure
ETo	Reference Evapotranspiration
FAO	Food and Agricultural Organization
FDA	Fluorescein Diacetate
fPOM	Free Particulate Organic Matter
GPS	Global Position System
HFOM	Heavy Fraction Organic Matter
HSD	Honest Significant Difference
INTF	Iodo Nitro Tetrazolium Formazan
Kc	Crop coefficient factor
Ks	Saturated hydraulic conductivity
LAI	Leaf Area Index
LFOM	Light Fraction Organic Matter
LH	Lower Highland
Masl	Meters above sea level
MBC	Microbial Carbon

MBN	Microbial Nitrogen
MoALF	The Kenya Ministry of Agriculture, Livestock and Fisheries
NH_4^+-N	Ammonium Nitrogen
NO_3^--N	Nitrate Nitrogen
OECD	The Organization for Economic Co-operation and Development
oPOM	Occluded Particulate Organic Matter
PAR	Photosynthetically Active Radiation
PEY	Potato Equivalent Yield
qCO_2	Microbial metabolic quotient for Carbon (ii) Oxide
RD	Rooting Depth
RLD	Root Length Density
RO	Runoff
RUE	Radiation Use Efficiency
RWU	Root Water Uptake
SMR	Soil Microbial Respiration (SMR)
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SWC	Soil Water Content
Tp	Potential transpiration rate
TSP	Triple Super Phosphate
UH	Upper Highland
UM	Upper Midland
θfc	Soil water content at field capacity
θs	Soil water content at saturation
θv	Volumetric soil water content
θwp	Soil water content at permanent wilting point

GENERAL ABSTRACT

Expanding production of potato to the midlands and lowlands of Kenya will only be possible if the effect of water deficit, high temperatures and nutrient limitation on potato growth is well understood. Potato (*Solanum tuberosum* L.) was grown singly and intercropped with lima bean (*Phaseolus lunatus* L.) or dolichos (*Lablab purpureus* L.), and the respective single crop of the legumes in three agro-ecological zones (AEZs) of Kenya; upper midland (1552 meters above sea level (masl)), lower highland (1894 masl) and upper highland (2552 masl). The objectives were as follows: i) determine the interelationships between soil water balance, soil temperatures and crop nutrient (NPK) uptake under potato-legume intercropping ii) assess the short-term effect of potato-legume intercropping on dynamics of microbial activity and SOM fractions, iii) evaluate the effect of potato-legume intercropping on soil nitrogen balance and iv) quantify the radiation and crop water productivity of potato-legume intercropping system. The study was laid out in a randomized complete block design with four replications. All the potato treatments received basal fertilization at a rate of 50 kg N ha^{-1}, 90 kg P ha^{-1} and 100 kg K ha^{-1} and topdress of 40 kg N ha^{-1}. Soil temperatures and soil water contents (SWC) were quantified at different stages of potato growth. Residues from each cropping system were quantified at the end of each season and incorporated back into the soil at start of the subsequent season. Soil samples (0–120 cm depths) were taken at the interrows of each plot prior to planting, at vegetative growth, and at the end of each season. Physical and density fractionation procedure was used to separate the soil in macro-aggregates (>250 μm), micro-aggregates (250–50 μm) and silt plus clay fractions (<50 μm), while SOM was partitioned into labile (density of 1.65 to 1.85 g cm^{-3}) and stable (2.60 g cm^{-3}) fractions. Microbial biomass carbon was determined by chloroform fumigation while enzymatic activities were assessed by hydrolyses of fluorescein diacetate and dehydrogenase. Nitrogen gains from mineralization, fertilization, and outputs from biomass accumulation, leaching, and soil erosion were quantified throughout the potato growth cycle. N losses through volatilization were quantified using ventilation chambers while the amount of N leached was extracted using solusamplers located at vertical depths of 0–1.5 m and the leachetes analyzed for nitrate contents. Leaf area index (LAI) and light interception were quantified at different stages of potato growth and related with the radiation use efficiency (RUE) and crop water productivity (CWP). The data was subjected to mixed model analyses of variance using R software with Tukeys mean separation test set at 95% propability level. Intercropping increased LAI by 26–57% relative to sole potato and significantly ($p < 0.05$) lowered soil temperatures in the 0–30 cm depth by up to 7°C. This increased SWC by up to 38%, thus increasing RUE by 56–78%, CWP by 45–67% and nutrient use efficiency by 40–67%. Compared with the sole potato, intercropping increased the contents of labile fraction organic matter by 12–28%, dissolved organic matter by 7–21% and microbial biomass by 15–38%, thus stimulating enzyme activities. Trends in soil microbial respiration followed those of enzyme activity and were 20–34% higher in intercropping than in sole potato. Soil N balance was significantly influenced by legume intercropping ($p<0.05$) and ranged between -10.7 to -18.1 kg N ha^{-1} for sole potato, 4.1 to 6.6 kg N ha^{-1} for intercropping and 2.9 to 22.3 kg N ha^{-1} for sole legumes. The residue mixture of potato and legume intercrops enhanced N mineralization with peak N release of 5 to 9 kg N ha^{-1} occurring within 8 to 10 weeks of residue decomposition. This period coincided with the peak N uptake by potato (19.9 to 31.2 kg N ha^{-1}) thus showing a close synchrony of N supply and potato N demand. These results provide a possible entry point to restoring the impoverished soil productivity in the smallholder potato farming systems and offer the possibility of potato expansion to midland agro-food systems.

Keywords: Agro-ecological zone; crop residue; intercropping; legumes; microbial activity; soil nitrogen balance; nutrient uptake; resource use efficiency; soil organic matter; soil temperature.

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background information

Potato remains one of the most important staple crops with a global production area of 19,302,642 ha, of which 1,439,329 ha is in sub Saharan Africa and 754,116 ha in East Africa (FAOSTAT, 2017). Potato is ready for harvest around 90–120 days after planting, which is 30–60 days before other staple crops such as maize, wheat and barley (CIP, 2008). This makes potato a hunger breaking and food security crop with a high market demand. In Kenya, potato is ranked the second most important food crop supporting approximately 800,000 farmers and further 2 million people along the value chain (CIP, 2008). The crop is mainly grown by smallholder farmers in the highland zones where temperature range of 15–20°C is optimal for tuberization (Muthoni, 2016).

Despite being a food security crop, potato is underperforming in Kenya and is not meeting its full potential for subsistence and commercial production. The average yield per hectare has stagnated at 7–15 t ha^{-1} against attainable yield of 20–40 t ha^{-1} (Parker et al. 2019). Deteriorating soil fertility, use of unimproved potato varieties and weak seed system partly account for the low potato yields. This situation is aggravated by upsurge in harsh climatic conditions which mainly results from persistent droughts, elevated heat stress, recurrent floods, increased soil erosion rates and disruption of traditional rainfall patterns (Karanja, 2013; Murakami et al. 2016). Globally, drought is projected to decrease yield potential of potato by 18–32% in the period of 2040–2069 (Hijmans, 2003). In the regions where a 1°C increase in mean temperatures has occurred, extreme heat waves, warmer night temperatures and hotter days have been experienced resulting in more than 50% potato yield reduction (Holden et al. 2003; Obidiegwu, 2015; MoALF, 2016). Such yield decline has been accompanied by devastated processes of canopy formation, tuberization and tuber bulking (Dahal et al. 2019; Li and Zhang 2020). In the lowlands, only heat and water stress tolerant cultivars capable of setting tubers at elevated soil temperatures may successfully complete the tuberization process (Rykaczewska, 2015). Future impacts of climate change will exacerbate these effects if no adaptation and mitigation measures are ensured (Zemba et al. 2013; Parker et al. 2019).

The deteriorating soil fertility in smallholder potato farms is largely a consequence of potato cropping systems which is done mainly in pure stands (Muthoni et al. 2013; Nyawade et al. 2018a; Gitari et al. 2018b). This practice involves maximum disturbance of soil during the growth cycle which makes the soil loose and more prone to erosion (Nyawde, 2015). Potato also delays to establish protective cover after planting and does not yield sufficient surface mulch upon harvest which leaves the soil bare at critical times when rainfall intensities are high, thus exposing soil to erosion (Chow and Rees, 1994). Soil loss under potato monocropping systems in Kenya is therefore high, with up to 169 t $ha^{-1}yr^{-1}$ having been recorded (Nyawade, 2015).

Further, the major soils in potato growing areas of Kenya are acidic with low soil organic matter (SOM) and high phosphorus sorption (Kibunja et al. 2018). These soils are mainly Nitisols, Planosols and Ferralsols and require high residue returns to replenish the low SOM contents, a quantity that cannot be attained by potato monocropping (Muchena and Gachene, 1988). Additionally, attaining reasonable yields of 20 t ha^{-1} of fresh tuber removes 235 kg N, 80 kg P, 320 kg K and 15 kg S from the soil (Burton, 2018). These nutrients must be returned through fertilizer application, a strategy which resource constrained smallholder farmers may not sustain. Where farmers apply fertilizers, the quantity is often below the recommended rates and is mainly of the di-ammonium phosphate which most studies have shown to contribute to soil acidification

(Muthoni, 2016). The use of organic manure as alternative source of nutrients faces challenges due to the bulkiness of this input coupled with its limited availability and varied quality.

Innovative and sustainable strategies capable of enhancing resilience of potato production is therefore required. One such strategy is shifting from monocropping to intercropping (Nyawade, 2015; Gitari et al. 2018a, b). Intercropping systems may add 40–250 kg SOC ha^{-1} from crop residue incorporation and biologically fix 20–140 N kg ha^{-1} which benefits the companion non-legumes and crops grown in succession (Jarecki and Lal, 2003; Giller, 2015; Naresh et al. 2017). Similarly, potato-legume intercropping enhances light interception and nutrient use efficiency and stabilizes crop yield (Egbe, 2010; Giller, 2015).

1.2 Statement of the problem

The major potato growing areas of Kenya are particularly vulnerable to climate change, having already experienced increases in extreme weather conditions including persistent droughts and floods which jeopardize food security and weaken efforts to eradicate poverty (MoALF, 2016). Potato yields average 7–15 tons per ha, far below attainable yields of up to 40 tons per ha (FAOSTAT, 2017). These problems have been accelerated by lack of crop diversification and unavailability of heat and water stress tolerant potato varieties. This has resulted in intense risk of crop failure and loss of livelihood (Demo et al. 2015; Muthoni, 2016; Gitari et al. 2019; Parker et al. 2019). Where low rainfall amounts is coupled with high heat stress and yield devastation, farmers have altogether abandoned potato production (Nyawira, 2018).

In cases where the high demand for potato has continued to compel production amidst the extreme weather conditions, farmers have resorted to expand the area under potato cultivation as opposed to improving productivity per ha (Burke, 2017). Furthermore, where potato is grown, cultivation is mainly done in the highlands which are characterized by sloping terrains and up-down slope operations (Gitari et al. 2019b). This makes soil erosion by water a major challenge (Fabeiro et al. 2001; Jemison, 2019). In these areas, sediment yield and nutrient losses due to erosion occur mainly at the onset of rains and later after potato harvest, a period which is characterized by low ground cover and high-intensity rainfall events (Gachene et al. 2019). The maximum soil disturbance during cycles of potato cultivation and harvest makes the soil loose and more prone to water erosion with values as high as 169 t $ha^{-1}yr^{-1}$ having been recorded under potato monocropping (Nyawade, 2015; King, 2017; Gachene et al. 2019; Nyawade et al. 2019). The steep side slopes of the potato mounds concentrate water in the furrows, which detaches soil particles and transports them out of the field (Xing et al. 2011; Eshel et al. 2015) while harvest translocates the soil, making it more prone to both water and wind erosion (Dong et al. 2000; Auerswald et al. 2006; Tiessen et al. 2007). The nitrate remaining in the soil after the potato-growing season are lost to leaching or denitrification between crop harvest and the next planting season (Auerswald et al. 2006).

Thus, sustainable intensification capable of increasing productivity of water and land under the current climatic scenario must be ensured to support food, income and nutrition security without causing further damage to the environment. Legume intercropping is one of such intensification measures. However, intercropping integrating potato as the base crop is not commonly practiced in the subtropics and is currently not packaged in the good agricultural practice recommendations (Nyawade et al. 2020b). Mostly, the legumes are intercropped with cereals such as maize (Maitra et al. 2020; Kermaha et al. 2017), sorghum (Dereje et al. 2016; Gebremichael et al. 2020), millet (Mohammed et al. 2008), wheat (Monti et al. 2019) or cassava (Loi, 2000). Unlike legumes, cereals and cassava are competitor for water and nutrients especially nitrogen and phosphorus hence not suitable intercrop for potato. In addition, the compatibility within potato-legume intercrop systems and resource use is poorly understood by both the researchers and intended beneficiaries such that information dissemination and farmer adoption remain low (Nyawade et al. 2020b).

1.3 Justification of the study

Potato-legume intercropping exhibits enhanced capacity to control soil erosion thus making potato production more sustainable in the highlands. By optimizing soil temperatures and soil water contents through enhanced canopy overlap, legume intercropping can enable production of potato in the drier midland agro-food systems. Legumes can fix up to 400 kg N/ha/year into a form of nitrogen available for plant uptake under optimal field conditions (Giller, 2015; Sanginga et al. 2009). This nitrogen is either used by the legume itself or become available to other species in the system after decomposition of root nodules or plant material. When deep-rooted legumes are used, intercropping has capacity to diverge the nitrate leached beyond the active root zone of potato. This is because these legumes have increased capacity to explore N supplements in the subsoil thus allowing potato to take up N in the surface soil. Nitrogen released from legume biomass residues through mineralization and nitrification, can supply enough N needs of the following crop.

Due to increased diversity of crops in intercropping, this system provides insurance against total crop failure and cushions farmers against unstable market prices, and therefore averts risks to the farmer. Along with the promotion and extension of legume intercropping, potato yields per unit area is expected to increase tremendously thus increasing income and livelihood of farmers. The legumes are besides rich in proteins and provide nutritious diet to man and forage to livestock thus contributing to increased food security. Increase in water, nutrient, light and land productivity is expected under potato-legume intercropping. Where precipitation is the main source of soil moisture and is poorly distributed in time, intercropping potato into annual crops will reduce the competitive effect for soil moisture.

1.4 Research objectives

1.4.1 Overall objective

To increase productivity of soil, nutrients, light and water through systematic introduction of legumes in smallholder potato farming systems of Kenya.

1.4.2 Specific objectives

i. To determine the relationships between soil temperatures, soil water content and crop nutrient uptake (NPK) under potato-legume intercropping.
ii. To quantify the short-term effect of potato-legume intercropping on soil organic matter fractions and microbial activity.
iii. To assess the effect of potato-legume intercropping on soil nitrogen balance.
iv. To quantify the radiation use efficiency and crop water productivity of potato-legume intercropping system.

1.5 Hypotheses

i. Soil temperature, soil water content and crop nutrient uptake exhibit positive relationships under potato-legume intercropping.
ii. Potato-legume intercropping increases the contents of labile SOM fractions and microbial activity.
iii. Potato-legume intercropping has significant positive effect on soil nitrogen balance.
iv. Potato-legume intercropping increases the crop water productivity and crop radiation use efficiency.

1.6 Thesis outline

This thesis is structured in chapter format as follows: chapter one presents the general introduction, problem statement, justification, objectives and hypotheses. Chapter two gives a detailed review of literature while chapter three describes the general methods which captures detailed site description and crop husbandry, and provides the conceptual framework developed for the study. Chapter four highlights the linkages between soil temperature, soil water balance and crop nutrient uptake. Chapter five presents the changes that occur in SOM fractions and microbial activity due to incorporation of crop residues and is cognizance of agro-ecological influence on SOM build-up and transformations. Chapter six quantifies the effect of legume intercropping and residue retention on soil nitrogen dynamics while Chapter seven assesses the productivity of potato-legume intercropping as relates to water use, land use and light use. Chapter eight synthesizes the results described in different chapters and provides the general conclusions, recommendations and policy implications.

CHAPTER TWO

LITERATURE REVIEW

2.1 Potato production systems in Kenya

Potato is grown by smallholder farmers in the lower and upper highland zones of Kenya (CIP, 2008; Muthoni, 2016). Production is for both cash and subsistence and is primarily rainfed using family labor. The soil is tilled at onset of rains to loosen it prior to planting (CIP, 2008). Potato seeds are then planted and hilled at 14–21 days after emergence. Production system is mainly monocropping with only 5–12% of the producers intercropping potato with maize (*Zea mays* L.). This is despite the fact that potato has high uptake for NPK and returns little residue thus depleting the soil organic matter (Nyawade, 2015). For this reason, potato cultivation has been shown to contribute up to 60% of nutrient losses in Kenya highlands (Nyawade et al. 2019). Yields have remained low ranging from 7 to 15 t ha^{-1} despite potential of 40 t h^{-1} (Parker et al. 2019).

The major potato cultivar produced in Kenya is Shangi, with a few number of farmers slowly adopting the new varieties such as Unica, Wanjiku, Nyota, Chulu, Lenana, Konjo (NPCK, 2017; Schulte-Geldermann et al. 2012; Kaguora et al. 2015; Harahagazwe et al. 2018). Other varieties available but in limited supply include Kenya Mpya, Kenya Karibu, Kenya Sifa, Asante, Sherekea, Tigoni, Panamera, Rudolph, Markies, Mayan Gold, Taurus, Desiree, Destiny, Dutch Robijn among others (NPCK, 2017). Farmers prefer Shangi variety due to its short tuber dormancy coupled with limited knowledge about other alternative varieties.

Heat stress and low soil moisture content often occurs during early stages of growing seasons, and has resulted in huge yield losses especially with the Shangi cultivar (Karanja, 2013; Gitari et al. 2018b). As highlighted in CIP (2017) report, releases of heat and water stress tolerant potato cultivars such as Unica has shown great adaptability to erratic weather conditions with greater potential to perform well under midland agro-ecological conditions. These cultivars are however not readily available in the local seed markets. Thus, diversification of the cropping systems is necessary to cushion the farmers from the risk of total crop failure.

2.2 Relationships among soil temperature, soil water content and nutrient uptake

High ambient temperatures and increased soil moisture stress limit potato production in the lowlands and midlands despite the greater consumer demand for the crop (Burke, 2017). Appreciable decrease in tuber yield occurs if balance between soil temperature, soil moisture and crop nutrient uptake is not attained (Ferreira and Gonc alves, 2007). High soil temperatures at tuber initiation cause fluctuations in soil moisture status, resulting in tuber malformation and tuber growth cracks (Polgar et al. 2017). When the soil water content drops below the field capacity, uptake of water and nutrients by potato crop is suppressedy leading to irregular plant growth (Levy et al. 2013; Nyawade et al. 2018a).

As water moves within the soil profile, it directly affects soil temperature and movement of crop nutrients, thus influencing nutrient availability to crops (Li et al. 2017). Losses of nitrogen in deep percolating water have been reported under potato growing systems when soil moisture contents are excessive (Claudia et al. 2013) while nitrogen volatilization occurs with increasing soil temperatures (Courtney et al. 2005). High soil temperatures reduce export of nitrate to the shoots and limit allocation of assimilates to the roots (Burke, 2017). Similarly, elevated soil temperatures within the potato rhizosphere may induce moisture stress which in turn increases the total dry matter allocation to roots and stems at the expense of tubers (Thornton et al. 1996). Claudia et al. (2013) examined the nitrogen balance under potato cropping system and found that nitrogen recovery in tubers decreased as gravitational water increased which implies that nitrogen losses in potato growing fields may become the largest nitrogen sink when there is excess water.

The major effects of high soil temperatures on potato growth are through its negative impacts on photosynthesis, respiration, reproduction, water relations and hormone production (Burke, 2017). The decrease in photosynthetic rate under high soil temperature conditions has been attributed to mesophyll conductance suppression and to stomatal closure under severe heat stress (Chaves et al. 2002). Under high-temperature conditions, tuberization is significantly inhibited and photoassimilate partitioning to tubers is greatly reduced (Lafta and Lorenzen 1995; Rykaczewska, 2017). Haulm growth is fastest in temperature range of 20–25°C whereas optimal range for tuberization and tuber growth is 15–20°C (FAO, 1996; Xiaolin et al. 2016). Though potato root growth can occur at a temperature range of 10–35°C, active root development occurs at soil temperature range of 15–20°C (Vandam et al. 1996; Rykaczewska, 2017).

High ambient temperatures occurring late in potato crop development stage is detrimental to tuber yield, particularly when haulms are lodged and the soil is exposed to incoming radiation (Alva et al. 2012). Raising night temperatures over the range of 0–20°C increases potato root length while night temperature increase to 25–27°C induces sharp reduction in the number and weight of tubers (Wilkinson and Davies, 2002; Kelly et al. 2017). High night temperatures above 20°C may induce production of gibberellic acid in the stolon tip, disrupting tuber growth (Wilkinson and Davies, 2002). Onset of tuberization may delay with night temperatures above 25°C, an observation associated with accelerated metabolism due to induction of specific inhibitory effects (Burke, 2017).

Potato requires 500–700 mm of water in a growing season (Sood and Singh, 2003) which is constrained by the shallow fibrous root system of the crop. This makes potato highly vulnerable to water deficit (Nyawade et al. 2018a; Aliche et al. 2018). Generally, water deficit modifies the activity of some enzymes and affects accumulation of sugars and proteins in potato plant. At stolon initiation, water deficit restricts stolon development and the number of stolons formed, and hinders root growth, nutrient uptake and plant response to nutrients (Rykaczewska, 2015, 2017). Water limitation at tuber initiation suppresses foliage and plant development, restricts tuber initiation and limits the number of tubers. At tuber filling stage, water shortage limits plant and tuber development, restricts tuber size, promotes tuber distortion and fastens leaf senescence. At maturity, water deficit limits relative tuber density and tuber size (Aliche et al. 2018).

Therefore, there is need to design cropping systems that can optimize the soil temperatures and increase soil moisture systems in the major potato producing areas. Under sole cropping, as much as 40% of rainfall can be lost through unproductive pathways such as evaporation and runoff (Kinama et al. 2011). In the drier lowland and midland agroecological conditions, combined use of legume intercropping and improved potato cultivars might exert potential synergy on tuber yield. Root system of potato mainly distributes within 0–40 cm soil layer (El-Abedin et al. 2017), but axial root of most legumes can reach up to 1 m soil depth (Ren et al. 2018) resulting in difference in spatial water requirement if grown in intercropping. Therefore, intercropping creates a spatio-temporal niche which allows the deep root system of the legume to colonize larger volume of the soil profile and exploit soil moisture from a larger surface area.

2.3 Effect of cropping systems on soil organic matter fractions and microbial activity

Intercropping and rotation systems have great potential to increase carbon sequestration in the soil due to their ability to return larger quantity of crop residue into soil (Jarecki and Lal, 2003). Al-Kaisi et al. (2005) demonstrated that corn-soybean–alfalfa rotation could replenish soil nutrients in degraded soils due to their potential to enrich soil organic matter. Jagadamma et al. (2007) also showed that legume integration into cropping systems could sequester SOC and enhance soil organic matter build-up. Due to greater biomass production in corn than soybean, SOC concentration under continuous corn is normally higher than under corn-soybean rotation (Lal et al. 1997). West and Post (2002) showed that increasing rotation complexity increased nitrogen storage and SOC sequestration rate by 200 kg C ha^{-1} yr^{-1}. A meta-analysis result by McDaniel et al. (2014) found that cropping systems that incorporate high quality legumes have stimulatory effect on microbial community as measured by both microbial biomass carbon (MBC) and nitrogen (MBN).

The rate and extent of these benefits depend on which size fraction is affected (Kapkiyai et al. 1999; Pikul et al. 2007; Nyawade et al. 2018b). These fractions differ in their quality, quantity and turnover rates, and respond differently to soil management systems. The mineral associated organic matter is a more processed SOM characterized by higher density and includes well-decomposed microbial products forming organo-mineral complexes with the finer mineral particles (Six et al. 2002). This organic matter fraction is relatively recalcitrant (Camberdella and Elliot, 1992). Soil labile organic matter fractions such as light fraction, microbial biomass and dissolved organic matter consist mainly of recently incorporated organic materials such as microbial and plant-derived polysaccharides, fungal hyphae and roots (Six et al. 2002; Haynes, 2005; Naresh et al. 2017). These SOM fractions have rapid turnover rates and respond to soil management intervention more rapidly than the total SOM (Louise et al. 2016). The rate at which the labile SOM fractions decompose determines the release of nutrients to plants (Balesdent et al. 2000).

The microbial biomass is a living fraction of SOM consisting mainly of bacteria and fungi that decompose litter and crop residues (Naresh et al. 2017). This process releases nutrients that are made available for plant uptake (Smith and Paul, 1990). The microbial biomass is released to the soil in forms that can be taken up by plants when the soil microbes die (Louise et al. 2016).

About 50% of microbial biomass is located in the surface 10 cm of soil profile (Naresh et al. 2017), an indication that most of the nutrient release occurs at this depth. Dissolved organic matter (DOM) is mostly a product of microbial metabolism and is highly used as substrate by the soil microbes (Jones et al. 2004; Roper et al. 2010). Any activity that rapidly alters the contents of DOM, MBC and microbial activity are regarded to be sensitive early indicators of long-term changes in SOM (Kapkiyai et al. 1999). The stable SOM fractions are product of microbial decomposition (Chabbi et al. 2009) thus reflecting long-term effect of microbial activity.

Microbial biomass just like any other SOM fractions is influenced by soil particle size distributions (Gupta and Germida, 1988; Camberdella and Elliot, 1992). The aggregate size affects the storage of SOM by occluding organic residues making them less accessible to degrading organisms (Six et al. 2000). The fresh residues provide nucleation centers for aggregation when returned to cropland and therefore promote formation of macro-aggregates which are the favorable habitat for soil microbes (Ghani et al. 2003). The high microbial activity due to enhanced substrate supply induces binding of soil particles into macro-aggregates, thus increasing aggregate stability. This results into fixation of unstable organic carbon, increasing the SOM concentration and carbon sequestration (Chen et al. 2009).

Quantification of soil microbial biomass activity is based on the rate at which respiration and enzyme hydrolyses by soil microbes occurs (Naresh et al. 2017). The overall activity or energy spent by indigenous soil microbial pool is measured by the basal respiration (CO_2 evolution) of a soil (Anderson and Domsch, 1990). If the basal respiration is related to corresponding microbial biomass size, a microbial metabolic quotient for CO_2 (qCO_2) is obtained (Lupwayi et al. 1998). Just like the microbial biomass, qCO_2 also responds readily to changes in soil management and can therefore provide an effective early warning of soil quality deterioration. Perturbations such as high soil temperatures, soil water deficits and substrates depletion elevate qCO_2 as the microorganisms become less efficient at conserving carbon (Anderson and Domsch, 1993). These processes may greatly vary with cropping systems, soil management practices and agro-ecological zones (Dinesh et al. 2009; Bichel et al. 2016).

2.4 Effect of legume intercropping and crop residue on soil nitrogen content

Intercropping that includes legume cover crops can reduce soil N leaching due to their ability to take up residual nitrogen, converting it into crop biomass which is later mineralized (Constantin et al. 2012; Plaza-Bonilla et al. 2015). Velvet bean (*Mucuna pruriens*) was able to accumulate 160 kg N ha^{-1} in 12 weeks when it was intercropped with maize (Sanginga and Woomer, 2009). Similarly, Eaglesham et al. (1981) found that N_2 fixed by cowpea was about 41 kg N ha^{-1} in maize-cowpea intercropping system. Roots of the legumes can decompose and release nitrogen into the soil where it is made available to the subsequent crops (Giller, 2015). Legume cover crop integration into potato cropping systems can appreciably reduce nitrogen losses due to soil erosion thereby increasing efficiency of nitrogen use (Nyawade, 2015; Nyawade et al. 2019).

Nitrogen mineralization from crop residues is an important source of plant available N, often accounting for N taken up by a crop (Stevens et al. 2005; Osterholz, 2016). Positive net N mineralization occurs when inorganic N is produced in excess of microbial demands while negative net N mineralization occurs when microbial consumption processes exceed N mineralization in the absence of plant uptake (Schimel and Bennett, 2004). If rates of N mineralization are high and soil inorganic N pools are small, N mineralization could readily replenish the inorganic N pool. The N mineralization process varies with residue quality, particularly with respect to residue N concentrations, C, lignin and polyphenol contents (Palm and Sanchez, 1991; Tian et al. 1992; Handayamoto et al. 1994).

Soil moisture and soil temperature also determine N mineralization rates by affecting the soil microbial activity (Cassman and Munns, 1980; Vigil and Kissel 1995). The rate of N mineralization is greater in warmer and wetter ecosystems than in colder and drier ecosystems (Henriksen and Breland, 1999; Chantigny et al. 2002). Release and retention of available N in soil increases with rise in soil moisture and soil temperature up to a threshold and then declines (Baldock et al. 2018). Low temperature conditions lower microbial respiration rate thus delaying residue decomposition and subsequent release of N (Tian et al. 1997). The N mineralized can be lost through soil erosion, removal in harvested products, leaching, denitrification, and volatilization (Brye et al. 2003; Ma et al. 2015; Inselsbacher, 2010; Loecke et al. 2012). Denitrification occurs when N is lost through the conversion of nitrate to gaseous forms of N. These forms include nitric oxide, nitrous oxide and dinitrogen gas. This occurs when the soil is saturated and the bacteria use nitrate as an oxygen source (Courtney et al. 2005). Volatilization occurs when N is lost through the conversion of ammonium to ammonia gas, which is released to the atmosphere. The volatilization losses increase at higher soil pH and conditions that favor evaporation (e.g. hot and windy) (Courtney et al. 2005). Leaching occurs mainly where increased accumulation of nitrates is followed by a period of high drainage (Arregui and Quemada, 2006).

2.5 Nutrient uptake by potato under legume intercropping

Nutrient uptake in plants is a function of capacity of the soil to supply adequate nutrients and the ability of plants to translocate the nutrients from roots to shoots (Baligar et al. 2001). This process is influenced by plant-soil interactions (Fageria and Baligar, 2005). In a study conducted to assess the effect of potato-legume intercropping systems on nutrient uptake and use efficiency in central Kenya, Gitari et al. (2018a) observed a significantly lower nutrient uptake in sole potato crop compared to potato-dolichos intercropping. Legume cover crops when integrated into potato cropping systems can control soil erosion, suppress weeds, conserve soil moisture, control diseases thereby increasing nutrient uptake, and use efficiency of potato (Xing et al. 2011; Nyawade, 2015; Giller, 2015).

Legumes such as lupin (*Lupinus albus* L.), chickpea (*Cicer arietinum* L.) and faba bean (*Vicia faba* L.) induce root acidification and exudate carboxylates such as citrate, malate, malonate, citrate and oxalate which dissolve and enhance P acquisition (Hinsinger, 2001; Vance et al. 2003; Wang et al. 2010). The exuded organic acids precipitate Ca, Fe and Al ions responsible for P fixation depositing them on the root surface. The P mobilized in excess of plant requirement is utilized by the less P efficient crops grown in rotation and/or intercropping. However, the processes underlying these observations remain poorly investigated, but speculated to be due to carboxylate exudation, formation of cluster roots, secretion of organic P-hydrolyzing phosphatase and increased biomass allocation to roots (Hinsinger, 2001; Vance et al. 2003; Hinsinger et al. 2011; Schneider et al. 2019). In a greenhouse experiment, intercropping potato with either chickpea or white lupin enhanced P acquisition by intercropped potato (Nyawade et al. 2020 c, d). The legumes secreted enzyme phosphatase and exuded citrate, malonate and malate, the concentrations of which were greater in intercropping and resulted in enhanced P solubilization.

Nutrient uptake by potato crop may differ with the nutrient under consideration. Higher uptake of Cu and Fe by potato under legume intercropping systems has been attributed to the low uptake of these elements by legumes (Naresh et al. 2017). Unlike calcium, potassium is highly mobile in the phloem making its utilization more efficient as it is readily redistributed from older leaves to younger shoot. As a result, symptoms of K deficiency in potato first appear in the older leaves. Potato crop has poor uptake and use efficiency for phosphorus as the crop has poorly developed P diffusion paths (Thorup-kristensen et al. 2001, 2003; Constantin et al. 2012). Legumes with higher nitrogen fixation potential such as as soybean may increase nutrient uptake by potato compared to poor fixers such as common bean (*Phaseolus vulgaris* L.), when grown in intercropping with potato (Giller, 2015).

2.6 Crop water productivity and light use efficiency

Under optimum growing conditions, biomass productivity of different crops can be described by the amount of solar radiation intercepted by the foliage and the efficiency with which the amount of water is converted to plant dry matter (Monteith, 1977). The productivity of water by crops may vary with cropping systems. Singh et al. (2013) observed that the total water used in intercropping system was almost same as for sole crops, but yields were increased with intercropping, thus crop water productivity was higher than in the sole crops. Increased soil moisture content under legume intercropping increases the ability of soils to supply nutrients which in turn increases the plant nutrient uptake (Alva et al. 2012).

Light interception and use efficiency processes are governed by the amount of solar radiation, leaf area index (LAI), soil temperature, soil moisture contents, soil nutrient levels and crop development stage. As LAI increases, more radiation is intercepted per unit ground area resulting in increased nutrient assimilation (Ewert, 2004). Increase in LAI to optimal levels is critical for maintaining high photosynthetic rates and crop yield (Xiaolei and Zhifeng, 2002). If the index is too low, not enough light will be absorbed and if too high, lower leaves will not receive enough light and will thus be a liability (Brintha and Seran, 2009). Soil moisture and nutrient levels affect foliage expansion and radiation capture (Stone et al. 2001; Inman-Bamber, 2004; Massignamet al. 2011).

Radiation use efficiency (RUE) has been reported as a stable parameter for many crops (Hughes et al. 1987), but variability in this parameter has too been shown (Sinclair and Muchow, 1999). This is because sunlight intercepted is not utilized with similar efficiency by all crops (Haxeltine and Prentice, 1996). There are therefore, clear differences in radiation use efficiency between crop species, particularly between those with C3 and C4 photosynthetic pathways (Kinama et al. 2011). The C4 crops have been shown to have higher RUE compared to C3 plants while combining C4 and C3 in intercropping systems increases RUE due to their additive effect on soil moisture extraction (Kinama et al. 2011). Kemanian et al. (2004) demonstrated that intercropping cereals with legumes results into higher photosynthetically active radiation (PAR) interception than when produced in their pure stands. This is because of differences that exist in vertical foliage arrangement and canopy architecture of crop varieties.

The net benefit derived from enhanced radiation interception with intercropping has largely been inferred to alteration of crop architecture and geometry (Acreche et al. 2009; Baldé et al. 2011), both of which have direct relationship with the interception efficiency of direct and diffuse irradiance (Valladares and Pearcy, 2000). Reddy et al. (2003) found that intercropping millet with groundnut was 28% more efficient in conversion of light intercepted to biomass than their monocrops, an observation attributed to 30% greater leaf area index development by the intercrop. Similarly, Ong and Black (1992) observed that intercropping pearl millet with groundnuts and pigeon pea produced 15% higher radiation interception compared to sole pigeon pea and twice that intercepted by the sole groundnut. The higher PAR conversion efficiencies of intercrop systems relative to the sole crops may be due to spread of light over greater leaf area and its more efficient distribution during early stages of growth (Addo-Quaye et al. 2011). Therefore, factors related to genotype selection and populations, which remain grey to resource-poor farmers, are important in the distribution of photosynthetically active radiation within the intercrop canopy.

2.7 Considerations for a sustainable potato-legume intercropping

A sustainable intercropping system must consider the base crop and its husbandry needs, in this case potato. The legumes should exhibit minimum competition with potato crop for nutrients, solar radiation, water and space and the peak nutrient demand should not coincide with that of potato (Nyawade et al. 2020). The intercrops should be integrated as per the local need and farmer preferences. The system must improve potato tuber yield if farmers are to take it up (Nyawade et al. 2019). Preferably, the legume should be used for human food or livestock feed and should have capacity to enhance soil productivity (Nyawade et al. 2020). If potato is used as food crop, the legume can be used as a cash crop or fodder to ensure sustenance and cash income.

Complementarities and facilitation should also exist between the crop components to minimize competition, but to increase mutual benefits (Gitari et al. 2020). Generally, potato takes up nutrients from the upper soil layers while most legume intercrops develop robust tap root systems that explore the soil matrix more extensively and absorb water and nutrients from deeper soil layers (Ren et al. 2018). In the highlands, lucerne and desmodium intercrops were able to increase their rooting zone beyond 1 m thus providing mechanism for divergence of the nitrate leached beyond potato root zone (Nyawade et al. 2020).

The intercrops must be chosen based on the prevailing agro-ecological zone (AEZ). In moisture-stressed zones of semi-humid areas, the influential factors that determine the benefits of intercrops are water and to a lesser extent, nutrients (Ren et al. 2018). In contrast, in humid zones nutrient deficiency and light because of the shading effect are more profound (Burke, 2017). Soil erosion is prevalent in these zones and thus legume cover crops might be prioritized (Schulte-Geldermann, 2013). The choice of potato cultivar is very important and is related to the agro-ecological conditions (Hellmuth, 2019).

Seedbed preparation should be done as per the need of potato, taking into considerations husbandry needs of the legume intercrops (Rana and Rana, 2011). Modifying plant spacing to increase the distance between adjacent potato and the intercrops has been considered to reduce the shading of potato by bush bean varieties and to facilitate potato harvest and hilling without damage to the legumes (Nyawade et al. 2018). However, the yield consequences of these modifications have not been conclusively tested. Nyawade et al. (2018) devised a pre-hilling practice that entailed planting potato plant in pre-mounded earths with just a slight piling up of the soil at 2 weeks after potato germination and 2 weeks later after first hilling. This practice minimized soil disturbance caused by repeated hilling, optimized soil temperature, and enhanced moisture distributions within the soil.

Temporal and spatial arrangement of the intercrop components become important as the net benefit derived from enhanced light interception in intercropping is inferred to alteration of crop architecture and geometry (Acreche et al. 2009), both of which have direct relationship with the interception efficiency of direct and diffuse irradiance (Valladares and Pearcy, 2000). In most reports, planting potato and legumes in 2 rows of potato alternating with 2 rows of legume (Fig 3) resulted in a higher potato tuber yield (Ren et al. 2018; Nyawade et al. 2020). This system improves radiation interception through development of more complete ground cover. Woomer et al. (2004) related the superior crop yields with 2:2 row-intercropping arrangement to advantages in root distribution and reduced belowground competition. When potato and legumes exhibit overlap in resource use, staggering planting time may separate rooting systems in time and result in yield advantage.

CHAPTER THREE

GENERAL MATERIALS AND METHODS

3.1 Description of the study sites

Field trials were conducted during the dry season of 2016 and wet and dry seasons of 2017 and 2018 in Kirinyaga (Kianyaga), Nairobi (Kabete) and in Nyandarua (Ol Kalou) (Fig. 3.1).

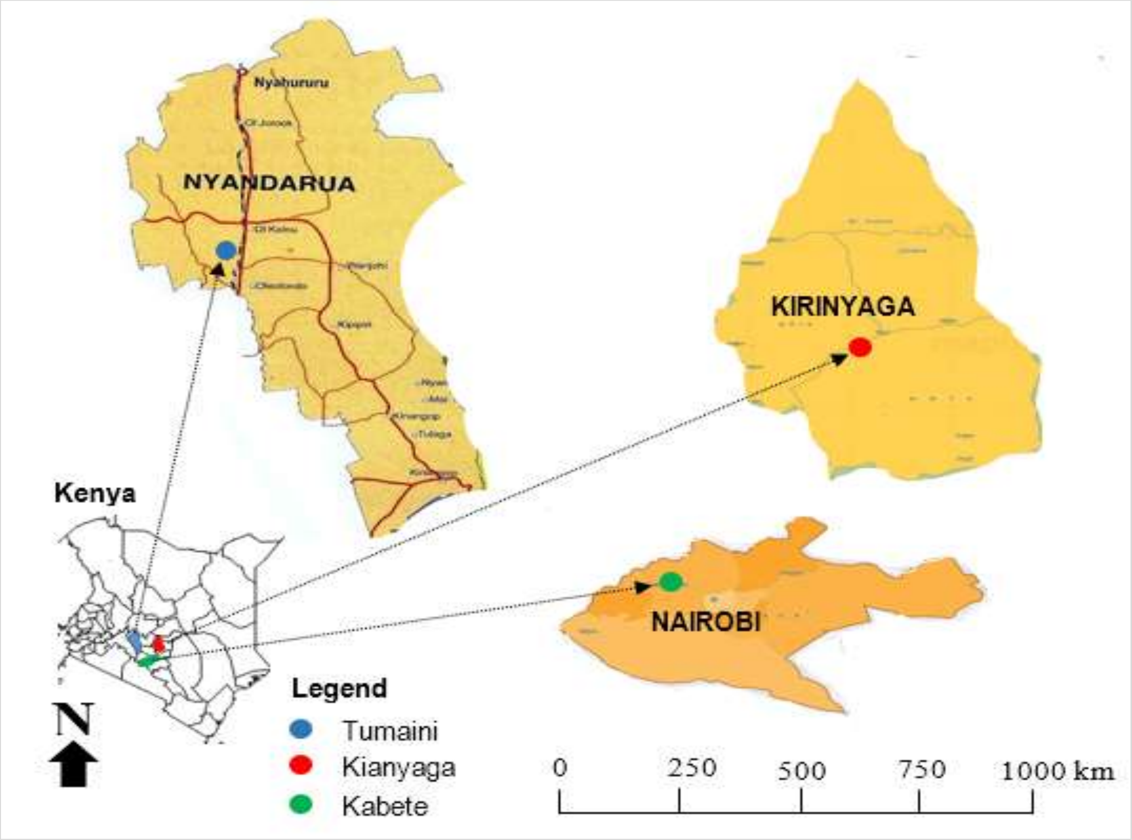


Figure 3.1: Map of study sites selected for establishment of the trials.

The region forms part of Mount Kenya's potato growing belt and borders the Great Rift Valley to the East (Muchena and Gachene, 1988; Kibunja et al. 2018). Potato production is mainly rainfed and depends primarily on family labor. The crop is grown both in the dry season that extends from October to December and in the wet season extending from March to June (Jaetzold et al. 2012; MoALF, 2016). Soil and climatic characteristics of these sites are described in Table 3.1.

Table 3.1: Climatic and soil descriptions of the experimental sites.

Parameter	Site		
	Kirinyaga	Kabete	Nyandarua
GPS coordinates	0°29'35.71"S 37°20'55.29"E	1°14'45.00"S 36°44'19.51"E	0°14'39.08"S 36°17'18.99"E
Agro-ecological zone	Upper midland	Lower highland	Upper highland
Altitude (masl)	1552	1894	2552
Mean annual rainfall (mm)	900	1000	1500
Mean annual max temp (^oC)	27.3	24.4	20.5
Evapotranspiration (mm)	1442	1152	1021
Soil type	Rhodic Ferralsol	Humic Nitisol	Ferric Luvisol
Soil description	Well drained, shallow to very deep, dark reddish brown silty loam with moderate P sorption.	Dark reddish brown clay-loam soils with low to high SOM and an acid top soil. Have a high P sorption.	Moderately to well drained, deep to very deep, dark brown to very dark red brown firm clay to silt loam. Have moderate P sorption.

Source: Jaetzold et al. (2006, 2012); Sombroek et al. (1982)

3.2 Treatments

The treatments constituted potato grown in monocropping and in intercropping with two legumes as follows:

1. Potato (*Solanum tuberosum* L.) monocrop
2. Dolichos lablab (*Lablab purpureus* L.) monocrop
3. Lima bean (*Phaseolus lunatus* L.) monocrop
4. Potato-dolichos lablab intercrop
5. Potato-lima bean intercrop

“Unica” (CIP 392797.22) potato cultivar was used in this study. This cultivar is heat and water stress tolerant making it well adapted to wide range of agro-ecological conditions (CIP, 2008; NPCK, 2017). The Rongai cultivar of *Lablab purpureus* L. (KT 003) is a species in the family *Fabacea* that produces white flowers and light brown seeds and has a high biomass production.

Lima bean cultivar was of improved bush Burpee with ability to produce high biomass under wide range of climatic conditions.

3.3 Conceptual framework

Figure 3.2 shows the conceptual framework developed for this study.

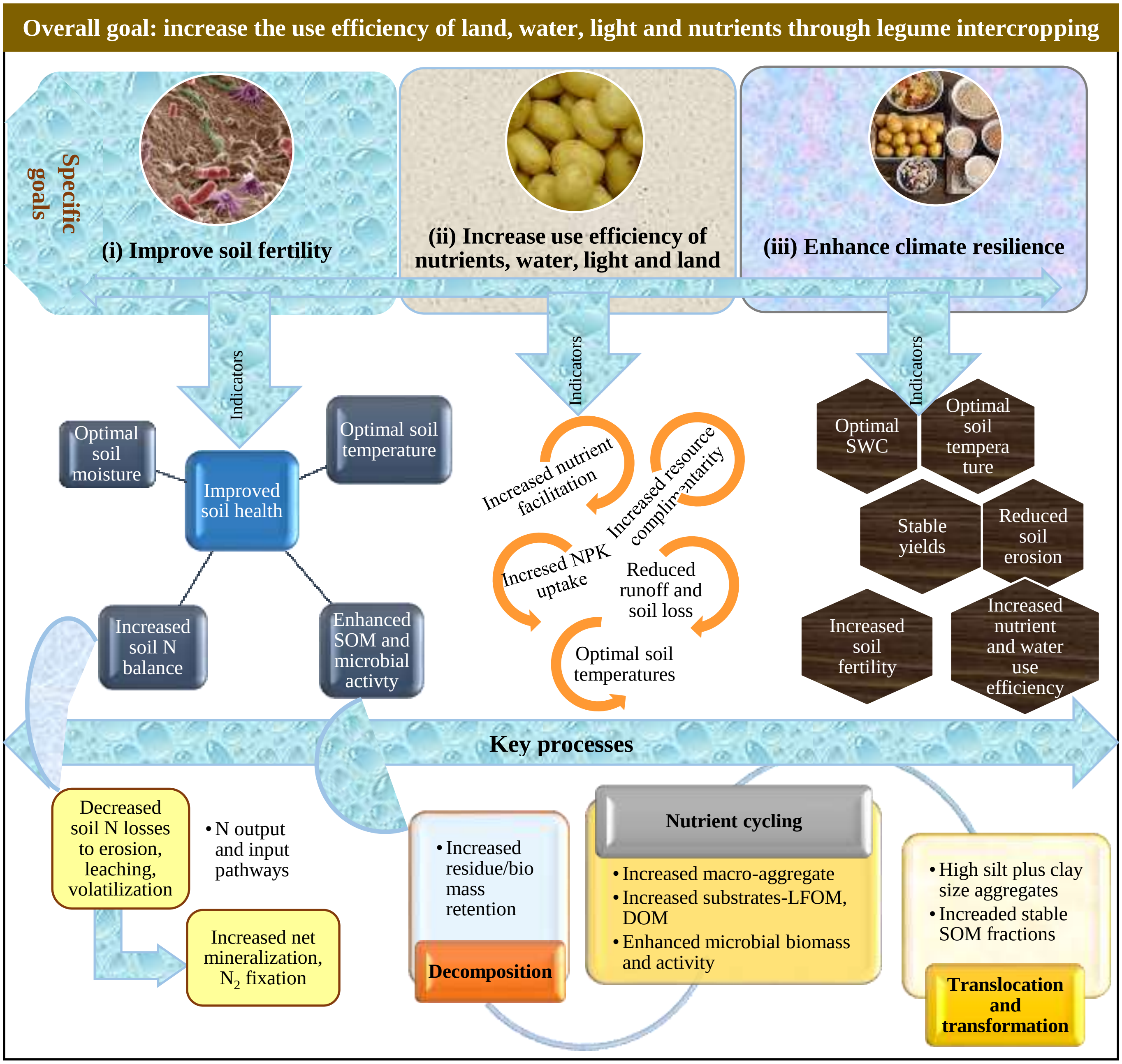


Figure 3.2: Conceptual framework developed for the study. SOM, Soil organic mater, DOM, Dissolved organic matter, LFOM, light fraction organic matter, SWC, soil water content.

Soil temperature, soil water content and cropping systems were the major independent variables explaining the changes in nutrient uptake, microbial activity, nutrient balance, soil organic matter contents, crop water productivity, radiation use efficiency and potato equivalent yields. The variables exhibited interrelationships with soil biochemical processes such as leaching, volatilization, decomposition, nutrient cycling and nutrient transformations.

3.4 Experimental design and layout

The treatments were laid out in a randomized complete block design with four replications. The plots measured 4.75 m long by 3 m wide, and were separated by 1 m path and 1.5 m distance from one block to the other.

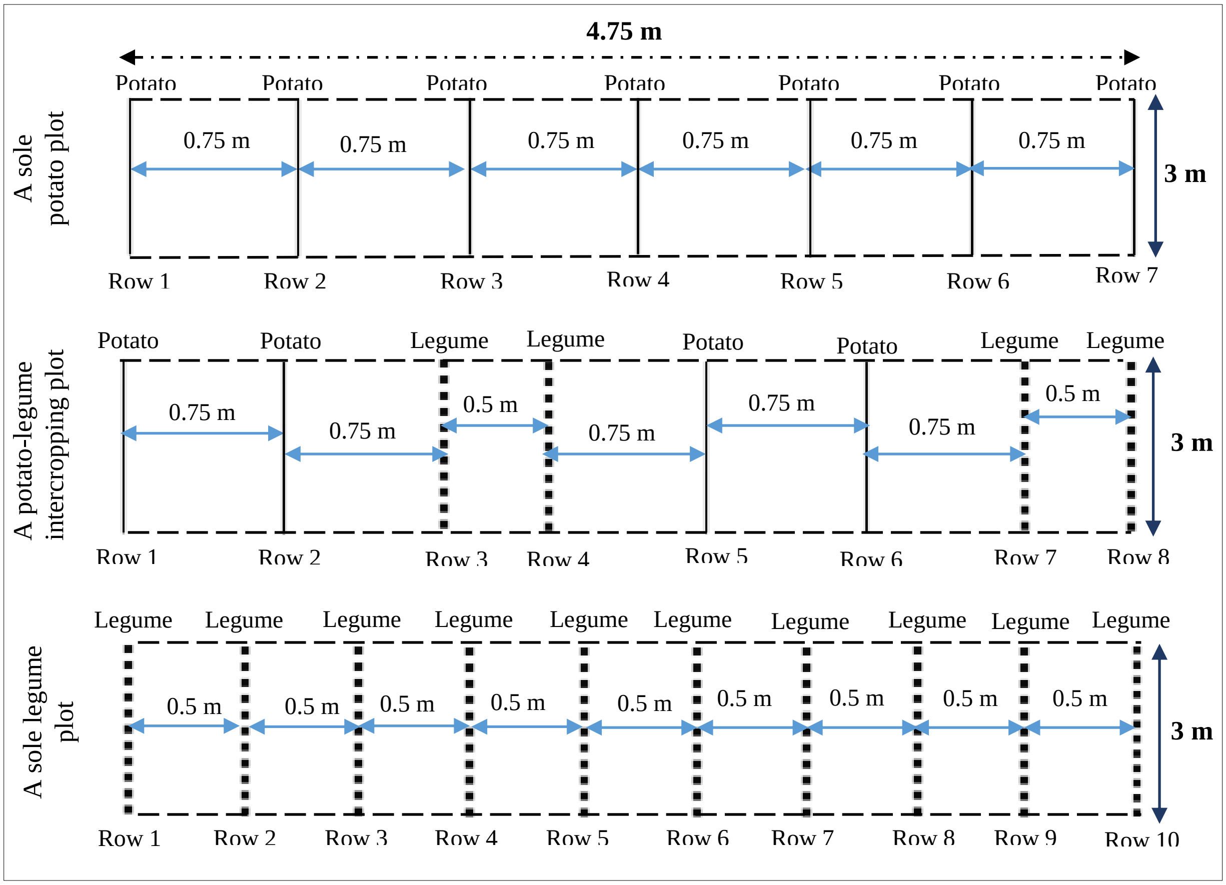


Figure 3.3: Schematic illustration of inter row spacing deployed for sole cropping and intercropping systems.

An intercrop plot accommodated 8 rows of crops (4 potato plants and 4 legume plants) planted in 2 rows of potato alternating with 2 rows of legumes (Figue 3.3). Rows were 0.75 m from potato to potato, 0.75 m from potato to legume, and 0.5 m from legume to legume. Potatoes were planted at a depth of 0.1 m on pre-hilled ridges as this practice could optimize soil temperatures and enhance soil moisture distribution (Nyawade et al. 2018a).

3.5 Agronomic practices

Fertilizer application was based on soil analysis and crop nutrient requirements (CIP, 2008). In Nyandarua, basal application of 50 kg N ha^{-1}, 90 kg P ha^{-1}, 100 kg K ha^{-1} and topdressing with 50 kg ha^{-1} calcium ammonium nitrate (CAN). In Kirinyaga, 60 kg N ha^{-1}, 80 kg P ha^{-1}, 90 kg K ha^{-1}, and 70 kg ha^{-1} CAN topdressing was applied, while in Kabete, 45 kg N ha^{-1}, 100 kg P ha^{-1}, 100 kg K ha^{-1} and 55 kg ha^{-1} CAN topdressing was applied. Topdressing was done 15–25 days after potato emergence depending on the general soil moisture conditions. The fertilizer applied at planting was NPK 15-9-20 while topdressing was done with CAN-26%. Legumes received triple superphosphate (TSP– 46%) at rate of 50 kg P ha^{-1}.

Weeding was performed by hand hoeing at 15–25 days after potato emergence when hilling the soil around the potato vines' to about 20 cm height. The legumes 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 while potato crops were sprayed with Ridomil Gold MZ 68WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) to control late blight disease. Potatoes were harvested at maturity by uprooting the tubers using hand hoes while legumes were harvested by plucking out the pods. Crop residues in each plot were incorporated into the soil at start of the subsequent seasons.

3.6 Soil sampling and soil physico-chemical analyses

Soil samples were taken from each experimental plot at 0–120 cm depths just before planting and at the end of the season using soil auger. For each plot, soil samples were drawn from the inner rows and bulked to give a composite sample. Once in the laboratory, the soils were passed through 2 mm sieve, analyzed for gravimetric moisture content, and stored at 4°C. Soil pH was measured in 1:2.5 soil to water suspensions, soil texture by hydrometer method (Gee and Bauder, 1986), total N by modified Kjeldahl method (Bremner and Mulvaney, 1982) and organic carbon by modified Walkley and Black method (Nelson and Sommers, 1996). Extraction of soil samples for analysis of available P and extractable K was done using Mehlich 1 procedures (Mylavarapu et al. 2002) and determined using UV–vis spectrophotometer (Murphy and Riley, 1962) and flame photometry (Jackson, 1967), respectively.

3.7 Data management and analyses

The statistical analyses were performed in R software, version 3.4.2 (R Core Team, 2017) using linear mixed model analysis of variance (ANOVA). The mixed-models were defined with the R-package lme4 (Bates et al. 2015) using likelihood based inference (Demidenko, 2013). Treatments and their interactions were considered as fixed factors while season and blocks (replications) were regarded as random factors. Significant interactions between fixed factors were detected using likelihood ratio tests for generalized linear mixed models. Whenever treatment effects were significant, the response variable was subjected to Tukey’s Honest Significant Difference (HSD) test ($p \leq 0.05$) for multiple means comparisons with the agricolae package. Differences between treatments are indicated by different letters. Whenever necessary, data were either log transformed or an unequal variance model used to meet assumptions of normality and equal variance.

CHAPTER FOUR

RELETION OF SOIL TEMPERATURE, SOIL WATER BALANCE AND NUTRIENT UPTAKE UNDER POTATO-LEGUME INTERCROPPING

Abstract

Expansion of potato production to the subtropical midlands will only be possible if the joint effect of water deficit and high soil temperatures is uncoupled. Potato (*Solanum tuberosum* L.) was intercropped with lima bean (*Phaseolus lunatus* L.) or dolichos (*Lablab purpureus* L.) in three agro-ecological zones of Kenya; upper midland-UM (1552 meters above sea level (masl)), lower highland-LH (1894 masl) and upper highland-UH (2552 masl). The objective was to evaluate intercropping effect on evapotranspiration, soil water balance, soil temperature and their interrelationships with crop nutrient (NPK) uptake. Crop cover, evapotranspiration, soil evaporation, soil temperatures, volumetric soil water contents and crop water balance were quantified from crop emergence to harvest. Peak crop cover was greater in intercropping (62–95%) than in sole potato (48–83%) except in the UH under potato-dolichos (74%). The amount of soil water retained under different cropping systems decreased exponentially with increasing soil temperature; the relationship was stronger with sole potato ($R^2 = 0.81$) than with the intercrops ($0.54 \leq R^2 \leq 0.68$) and weakest with sole legumes ($0.45 \leq R^2 \leq 0.58$). Soil temperatures were 3–7°C lower under intercropping compared to sole potato. Intercropped potato attained tuber yield of 0.45 to 0.86 kg tuber weight per plant compared to 0.26–0.68 for sole potato. The tap root systems by legume intercrops recaptured the water percolated below potato root-zone, converting it into crop biomass. Legume intercropping optimizes the soil temperatures and soil water balance thus enabling potato production in the drier midland agro-food systems.

Keywords: Soil moisture; intercropping; nutrient uptake; nutrient use efficiency; crop cover.

4.1 Introduction

The current climate change scenarios of decreasing precipitation and increasing temperatures point to a devastation of potato yield across the subtropical highlands. In Kenya for instance, a moderate (1°C) increase in mean temperatures over the last 37 years has caused potato yield to drop by up to 50% (MoALF, 2016). The adverse effect of increasing temperatures on potato growth and tuber yield becomes particularly important when it is coupled with water limitations (Ferreira and Gonc alves, 2007). Increase in soil temperatures to values above 15–20°C hinders tuberization process (Rykaczewska, 2015; Xiaolin et al. 2016) and causes damage to potato roots thus hindering their capacity to take up soil water and nutrients (Li et al. 2017; Onwuka and Mang, 2018). In cases where seasonal rainfall amounts fall below the range of 500–700 mm, tuber formation and filling is devastated (Sood and Singh, 2003; Pavlista, 2015).

Introduction of simple technologies capable of optimizing soil temperatures and soil water balance in Kenya and within the subtropics therefore becomes necessary. Intercropping due to its ability to achieve greater complementarity of resource utilization through use of crop mixtures having different rooting ability, canopy structure, height, and nutrient requirements has been recommended (Burke, 2017; Gitari et al. 2018a, b; Gitari et al. 2019). Intercropping that integrates legumes improves soil fertility through biological nitrogen fixation, increases soil conservation through greater groundcover, provides better lodging resistance for crops, reduces pest and disease incidence and provides insurance against crop failure or unstable market prices (Jensen, 1996, Giller, 2015; Nyawade et al. 2020a). Legume residues provide nucleation useful in formation of macro-aggregates which are the favorable habitat for soil microbes (Ghani et al. 2003; Liang, 2013). However, when the intercrops are not matched with the appropriate AEZs, and do not adjust to specific spatial arrangements, yield penalties on the main crops ranging from 2–18% has been observed (Nyawade et al. 2020).

Despite the good benefits demonstrated by legume intercropping, this practice is highly neglected among smallholder potato farmers in the tropics. In Kenya, only about 5–12% of the farmers practice potato-legume intercropping (Muthoni et al. 2013; Gitari et al. 2018a). The intercrop commonly used in potato cropping systems is maize (*Zea mays* L.), the system of which cannot fix the atmospheric nitrogen and competes with potato for water, nitrogen, phosphorus and potassium. Further, lack of scientific evidence on the role of potato-legume intercropping on yield, crop water productivity and nutrient dynamics reinforce bottlenecks that prevent effective uptake of this technology in smallholder potato farming systems.

In this regard, a number of field studies have been initiated across different agro-ecological zones of Kenya to test the effect of potato-legume intercropping on crop water productivity, light use efficiency, nutrient use efficiencies and net returns. When potato was planted at the same time with *Lablab purpureous and Phaseolus lunatus*, the system reduced soil erosion by 30–60%, increased crop water productivity by 20–56% and diverged the nitrate leached below potato root-zone (Nyawade, 2015; Gitari et al. 2018a,b; 2019; 2020; Nyawade et al. 2018a, b; 2019a, b, c; 2020a). However, proper understanding of legume intercropping on yield is only plausible if relationships among evapotranspiration, soil temperature and soil water storage is understood. This study presents the changes in soil water storage, evapotranspiration and crop water balance, and reports crop yield and nutrient uptake increase due to legume intercropping.

4.2 Materials and methods

4.2.1 Study site

Field experiments were conducted during the short and long rains of 2017 and 2018 in Kirinyaga (0°29'35.71"S and 37°20'55.29"E), Kabete (1°14'45.00"S and 36°44'19.51"E) and in Nyandarua (0°14'39.08"S and 36°17'18.99"E). Detailed description of the study sites are described in section 3.1. Measured soil properties (0–120 cm depth) before the experiment are provided in Table 4.1. According to the ratings by Gough and Wolf (1996), SOC, total N, and available P were below the optimal levels for potato growth irrespective of the study site.

Table 4.1: Initial soil physical and chemical properties.

Agro-ecological zone	Soil depth	Clay	Silt	Sand	Textural class	Pb	Θwp	θfc	Θs	Ks	pH	SOC	N	P	K
	(cm)	%				gcm^{-3}		cm cm^{-3}		mm h^{-1}		%	%	ppm	cmol /kg
Upper midland	0-30	24.5	33.3	42.2	CL	1.19	0.07	0.21	0.51	55.13	4.99	1.82	0.13	33.30	1.23
	30-60	24.2	36.9	38.9	CL	1.24	0.04	0.19	0.52	49.21	4.99	1.04	0.23	23.40	1.33
	60-90	28.9	29.8	41.3	CL	1.34	0.03	0.25	0.58	40.33	4.93	0.88	0.11	24.40	1.19
	90-120	23.8	32.4	43.8	CL	1.35	0.03	0.28	0.55	32.22	4.92	0.33	0.09	20.20	1.09
Lower highland	0-30	49.7	22.5	27.8	C	0.99	0.09	0.38	0.41	33.33	5.11	2.06	0.19	24.40	1.13
	30-60	49.2	24.2	28.9	C	1.04	0.06	0.37	0.41	27.56	5.14	1.56	0.11	18.20	1.16
	60-90	50.1	24.2	25.7	C	1.14	0.04	0.36	0.49	23.28	5.16	0.98	0.06	17.70	1.11
	90-120	51.3	24.8	23.9	C	1.19	0.05	0.38	0.48	14.98	5.20	0.42	0.02	16.60	1.00
Upper highland	0-30	38.3	56.1	5.6	SC	0.97	0.09	0.37	0.43	29.89	5.21	3.09	0.22	16.60	1.16
	30-60	36.9	58.4	4.7	SC	1.00	0.08	0.39	0.42	26.87	5.22	2.34	0.24	17.90	1.15
	60-90	34.6	59.5	5.9	SCL	1.08	0.03	0.35	0.45	18.32	5.26	1.92	0.11	15.50	1.03
	90-120	33.9	57.9	8.2	SCL	1.11	0.04	0.36	0.41	9.04	5.28	0.98	0.09	14.90	1.02

C, CL, SC, SCL denote clay, clay loam, silt clay and silt clay loam respectively. Critical levels for potato growth: SOC, 2.5%, N, 0.2%, K, 1.0 cmol/kg, and P, 30 ppm (Gough and Wolf, 1996). Soil bulk density (pb); soil water content at permanent wilting point (θwp), at field capacity (θfc) and at saturation (θs); saturated hydraulic conductivity (Ks); soil organic carbon (SOC); total nitrogen (N); available phosphorus (P) and exchangeable potassium (K).

4.2.2 Experimental layout and crop husbandry

The trials were laid out in a randomized complete block design with four replications. The treatments comprised of potato (*Solanum tuberosum* L.) grown alone or intercropped with either lima bean (*Phaseolus lunatus*, improved bush Burpee cv.) or dolichos (*Lablab purpureus* L., brown Rongai cv.) and pure stands of legumes. Detailed description of experimental design, crop husbandry and agronomic activities are described in section 3.4 and 3.5.

4.2.3 Climatic data

The daily climatic data used to compute crop evapotranspiration (air temperature, wind speed, actual vapor pressure, solar radiation and daylight hours) were obtained from agro-meteorological stations located at about 200–500 m from the study sites.

4.2.4 Soil sampling and analyses

Soil sampling was conducted at vegetative (about 45 days after planting (DAP), and tuber bulking stages (about 75 DAP) of potato development, and at the end of potato growing period. Ten (10) soil replicates were taken within and between the crop rows of each plot with a 14 mm inner-diameter soil piston auger for every 30 cm interval to a depth of 120 cm. This depth interval represented the maximum possible root penetration zone for the crops used in this study. The samples were mixed into a composite for each depth and plot and stored at 4^oC until analysis. Determination of total N content was done following the method of Keeney and Nelson (1982). Extraction of soil samples for analysis of available P and extractable K was done using Mehlich 1 method (Mylavarapu et al. 2002).

4.2.5 Determination of soil water content

Soil water content of each plot was measured for every 30 cm interval in soil profile of 0–120 cm using tensiometers (0–100 kPa). The tensiometers were located between the plant rows. Prior to their installation, the tensiometers were calibrated using gravimetric soil moisture measurements taken at soil depth 0–30 cm. The gravimetric data were plotted against tensiometer readings in a scatter plot and a regression equation between the two methods was established. The values of matric potential measured with the tensiometers were used to plot soil moisture characteristic curve from which a relationship used to compute volumetric soil water content was derived. The average soil moisture content of a given treatment and layer in each period was calculated using Eq. (4.1).

$$SM_{ij} = \frac{1}{4 * N_y} \sum_{m=1}^{4} \sum_{k=1}^{N_y} SM_{ijmk} \tag{4.1}$$

where, SM_{ij} is the soil moisture of ith treatment at jth soil layer; SM_{ijmk} is the actual value of soil moisture (m) measurement at each time; N_y is the total number of measurements of soil moisture over four seasons of the study and 4 is the number of replications.

4.2.6 Estimation of crop cover

A point frame was used to quantify the crop cover. The frame consisted of a single row of 10 pins spaced 10 mm with tripods measuring 2 m in height (Coxson and Looney, 1986). Sampling was started from 7 days after planting and continued at 2 weeks interval until harvest. Crop cover was estimated using Eq. 4.2.

$$Crop\ cover\ (\%) = \frac{Number\ of\ pins\ that\ hit\ plant\ leaves}{Total\ number\ of\ pins\ (10)} \tag{4.2}$$

4.2.7 Estimation of root water uptake

Root water uptake at a given soil depth was described by the extended Prasad model (Eq. (4.3). The model assumes that root water uptake is limited by a function of potential transpiration which decreases linearly with soil depth (Feddes et al. 1978; Hayhoe and De Jong, 1988). Estimations were made for every 30 cm interval in soil profile of 0–120 cm.

$$S_{max}(z) = \frac{RLD\ (z)}{\int_{-RD}^{0} RLD(z)dz} T_p \tag{4.3}$$

Where S_{max} (z) is the maximum root water uptake at a given soil depth (z), RLD (z) is the root length density at depth z, RD is the rooting depth (cm), and Tp is the potential transpiration rate. Rooting depth was taken as the depth at which more than 70% of the root volume was found

(Mahdian and Gallichand, 1996) i.e. 30 cm for potato, 60 cm for lima bean and 90 cm for dolichos. For intercropping, the average rooting depth for the legume and potato was taken. Soil depth here refers to soil layers in which root water uptake was measured i.e. 30 cm, 60 cm, 90 cm and 120 cm. Potential transpiration (Tp) was calculated using Eq. (4.4).

$$T_p = ET_p - E_p \tag{4.4}$$

where evaporation (Ep) was estimated using Eq. (4.5) and reference evapotranspiration (ETp) using Eq. (4.6) (Allen et al. 1998).

$$E_p = ET_p exp^{-0.6LAI} \tag{4.5}$$

$$ET_p = \left[\frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}\right] * Kc \tag{4.6}$$

LAI refers to the measured leaf area index, Rn; net radiation at the crop surface [MJ m^{-2} day^{-1}] estimated using method outlined by Allen et al. (1998), G; soil heat flux density [MJ m^{-2} day^{-1}] which due to its small magnitude beneath the reference surface was considered negligible, T; mean daily air temperature at 2 m height [°C], u_2; wind speed at 2 m height [m s^{-1}], es; saturation vapor pressure [kPa], ea; actual vapor pressure [kPa], es–ea; saturation vapor pressure deficit [kPa],Δ; slope vapor pressure curve [kPa °C^{-1}], γ; psychrometric constant [kPa °C^{-1}]. Crop coefficient (Kc) was calculated using Eq. (4.7) for sole cropping and Eq. (4.8) for intercropping.

$$\frac{ET_a}{ET_o} \tag{4.7}$$

$$K_c = \frac{f_1 h_1 kc_1 + f_2 h_2 kc_2}{f_1 h_1 + f_2 h_2} \tag{4.8}$$

where ETa is the actual evapotranspiration estimated using Eq. (4.11) and ETo is the reference evapotranspiration (Eq. (4.6) less Kc factor), *f*1 and *f*2 are fractions of the soil surface planted by potatoes and legumes in an intercropping i.e. 0.5, *h*1 and *h*2 are the height of potatoes and legumes, respectively; and *K*c1 and *K*c2 are crop coefficients for potatoes and legumes in monoculture.

4.2.8 Estimation of soil water balance

Soil water balance was estimated using Eq. (4.9) (Rosa et al. 2012).

$$D_{r,i} = D_{r,i-1} - (R - RO)_i - I + ET_i + \Delta \mathrm{SWC}_i \tag{4.9}$$

where Dr,i and Dr,i-1 are the root-zone moisture depletion at time i, Dr,i−1 is the root zone depletion at previous measurement, R is rainfall at time i, RO is runoff from the soil surface at time i, I is net irrigation depth that infiltrates into the soil at time i, ET is the actual crop evapotranspiration at time i, Dp is deep percolation beyond active root-zone at time i, ΔSWC is change in soil water content at time i (difference between final and initial SWC). All terms are expressed in mm. Surface runoff was quantified by flow meters installed at outlets of the plots. Micro-lysimeters installed to a depth of 30 cm were used to estimate soil surface evaporation. Deep percolation (Dp) was estimated as residual term of potato root-zone water balance (Eq. (4.10)) (Bethune et al. 2008).

$$DP = I + R - RO - ET_a - \Delta SWC \tag{4.10}$$

While actual evapotranspiration (Et_a) was estimated using Eq. (4.11) (Rosa et al. 2012):

$$ET_a = I + R - RO - DP - \Delta SWC \tag{4.11}$$

where all terms of soil water balance are as earlier defined. Capillary rise was not considered in this equation since the water tables across the study sites were deeper than 25 m (Gachene et al. 1989; Karuku et al. 2014).

4.2.9 Estimation of root length density

Root length density (RLD) of each cropping system was measured at vegetative and tuber bulking stages. Measurements were taken for every 30 cm interval in soil profile of 0–120 cm using 15 cm x 10 cm x 10 cm metal cores (Bohm, 1979). Roots were excavated at the inter-rows with additional sampling at stem base (about 5 cm from the stem) to take into account roots not extending to the inter-rows. Soil cores containing the roots were placed in a bucket of water and gently agitated to break down larger soil particles, and to remove debris and dead roots. This mixture was sieved through 2 mm mesh placed in a tub of water to wash away fine soil particles attached to the roots. Roots were floated on water in 40 cm × 40 cm glass tray and scanned using Epson Expression 1680 Scanner (Seiko Epson Corp., Tokyo, Japan) (Fig. 4.1). Root length density was then analyzed using WinRHIZO Root Analyzer System (Regent Instruments Inc., Quebec, Canada) (Eq. (4.12).

$$Root\ length\ density\ (cm\ cm^{-3}) = \frac{Root\ length\ (cm)}{Soil\ volume\ of\ corresponding\ depth\ (cm^3)} \tag{4.12}$$

Figure 4.1: Scanning (a) and processing (b) of roots using Epson Expression 1680 Scanner.

4.2.10 Nutrient uptake

At potato flowering stage, 6 plants were randomly sampled from 2 central rows of each plot for determination of total nitrogen, phosphorus and potassium (NPK) uptake. For potatoes, samples were separated into tubers, roots and shoot (Prasad and Hochmuth, 2016) while for legumes, only the shoot was analyzed. The samples were transferred to the laboratory, dried at 60°C to a constant mass, separately ground in a Wiley mill (0.84 mm mesh) and used for NPK determination. The total nutrient (NPK) uptake was calculated as the product between plant nutrient concentration and biomass weight.

4.2.11 Statistical analyses

The data was analyzed using R software, version 3.5.2 (R Core Team, 2017). The effects of intercropping on tuber and legume grain yield, root length density, soil water balance and NPK uptake were tested using generalized linear models (Bates et al. 2015). Tukey's honest significant difference (HSD) test was used for treatment mean separations with threshold probability level set at $p \leq 0.05$. An exponential function was fitted to give the relative change of soil moisture content as a function of root length density with an equation of the form $y = abx$, where $a = 0$. Principal component analysis (PCA) was performed using factoshiny function to examine relationships among evapotranspiration, root water uptake, soil moisture content, soil temperature and vegetal cover.

4.3 Results

4.3.1 Vegetal cover establishment by different cropping systems

Crop cover development differed among the cropping systems and between the agro-ecological zones (Fig. 4.2). In the UM and LH, peak crop cover was significantly greater in intercropping (62–95%) compared to sole potato stands (48–83%). In the UH, peak crop cover was greater in sole potato (89%) than in potato-dolichos intercropping (74%) and sole dolichos (58%). On average, plots with dolichos recorded higher crop cover in the UM (16–94%) and LH (11–95%), and those with lima bean recorded the highest crop cover (12–96%) in the UH. Crop cover percentage taken at 105 and 119 days after planting was only significant for sole dolichos and potato-dolichos intercropping.

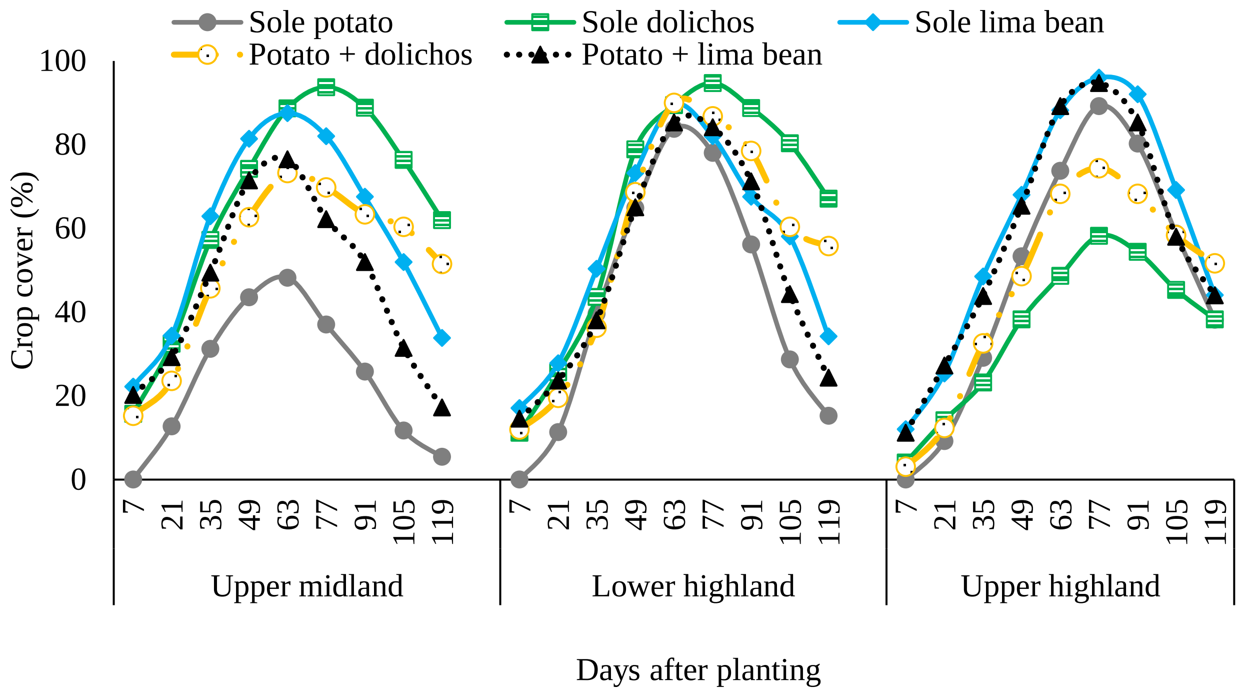


Figure 4.2: Development of vegetal cover by different treatments in upper midland, lower highland and upper highland. Values are 4 replicates expressed as averages over the four seasons.

4.3.2 Relationship between soil moisture and soil temperature

The amount of soil water retained decreased exponentially with increasing soil temperature (Fig. 4.3). However, the strength of the relationship varied among the different treatments. In the UM and LH, the relationship was stronger with sole potato ($R^2 = 0.81$) than with the intercrops ($0.54 \leq R^2 \leq 0.68$) and weakest with sole legumes ($0.45 \leq R^2 \leq 0.58$). In the UH, the relationship was stronger with sole dolichos ($R^2 = 0.68$) and potato-dolichos intercropping ($R^2 = 0.61$) than with potato + lima bean ($R^2 = 0.56$) and sole lima bean ($R^2 = 0.51$).

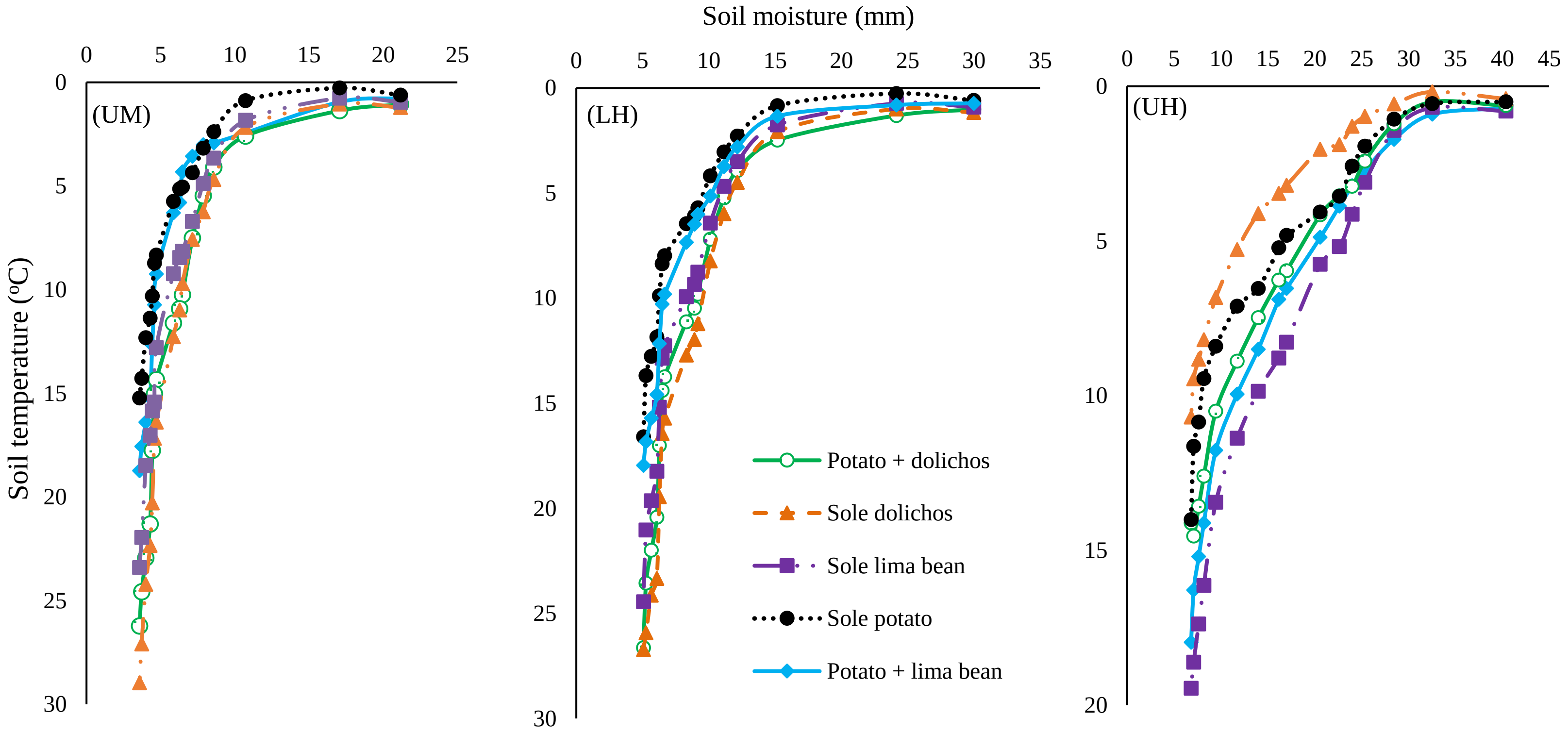


Figure 4.3: Relation of soil temperature and water content under different cropping systems. Points are values of four replicates expressed as averages over four seasons and in each agro-ecological zone; upper midland (UM), lower highland (LH) and upper highland (UH).

4.3.3 Root length density

Root length density (RLD) at 0–0.3 m depth was significantly higher in sole potato stand than in intercropping (Table 4.2). At 0.3–0.6 m depth, highest RLD (1854 to 4146 m m^{-3}) was recorded under potato-lima bean intercropping. This is compared to pure potato that showed RLD ranging between 246 and 930 m m^{-3}. At 0.6–0.9 m depth in the UM, potato-dolichos intercropping showed highest

RLD of 10326 m m^{-3}. At 90–120 cm depth, RLD ranged between 906–972 m m^{-3} for potato-lima bean intercropping compared to 2286–2460 m m^{-3} in potato-dolichos intercropping. Generally, dolichos established higher RLD in the LH and UM AEZs while lima bean showed higher RLD in the UH AEZ.

Table 4.2: Changes in crop root length density (m m^{-3}) at tuber bulking stage in depth interval 0–0.1 m under different cropping systems and agro-ecological zones.

Agro-ecological zone	Cropping system/soil depth	0–0.3 m	0.3–0.6 m	0.6–0.9 m	0.9–1.2 m
Upper Midland	Pure potato	5490_{B}^{c}	930_{A}^{a}	ǂ	ǂ
	Pure lima bean	1950_{B}^{a}	9564_{C}^{d}	846_{A}^{a}	1032_{A}^{a}
	Pure dolichos	1470_{AB}^{a}	1890_{B}^{b}	10326_{C}^{d}	1332_{A}^{b}
	Potato + lima bean	2526_{C}^{b}	4146_{D}^{c}	1566_{B}^{b}	906_{A}^{a}
	Potato + dolichos	2652_{A}^{b}	3870_{B}^{c}	5346_{C}^{c}	2460_{A}^{c}
Lower highland	Pure potato	5886_{B}^{c}	606_{A}^{a}	ǂ	ǂ
	Pure lima bean	1824_{B}^{a}	8706_{C}^{e}	$660_{A}a$	906_{A}^{a}
	Pure dolichos	1290_{A}^{a}	1206_{A}^{b}	9804_{B}^{d}	1830_{A}^{b}
	Potato + lima bean	$2886_{C}b$	3786_{D}^{d}	$1626_{B}b$	972_{A}^{a}
	Potato + dolichos	$2670_{A}b$	2892_{A}^{c}	$4206_{B}c$	2286_{A}^{b}
Upper highland	Pure potato	9270_{B}^{d}	246_{A}^{a}	ǂ	ǂ
	Pure lima bean	5646_{C}^{a}	1854_{B}^{c}	216_{A}^{a}	ǂ
	Pure dolichos	3570_{C}^{b}	1230_{B}^{b}	192_{A}^{a}	ǂ
	Potato + lima bean	6486_{C}^{c}	2412_{B}^{d}	192_{A}^{a}	ǂ
	Potato + dolichos	1950_{C}^{a}	1194_{B}^{b}	234_{A}^{a}	ǂ

Lower and uppercase letters indicate comparisons for means between the cropping systems and soil depths, respectively at $p \leq 0.05$ by Tukey's HSD test. ǂ denotes data not observed. Values are 4 replicates expressed as averages over the four seasons.

4.3.4 Root water uptake

Root water uptake (RWU) in the 0–0.3 m depth was significantly higher in sole potato (52.7–99.8 mm) than in intercropping (20.2–69.6 mm) at tuber bulking stage of potato growth (Table 4.3).

Table 4.3: Root water uptake and the corresponding soil matric potential measured in different cropping systems at tuber bulking stage of potato development.

Agro-ecological zone	Cropping system	Root water uptake (mm)				Soil matric potential (-kpa)			
		Soil depth (m)							
		0–0.3	0.3–0.6	0.6–0.9	0.9–1.2	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
Upper midland	Pure potato	52.7_{B}^{c}	9.7_{A}^{a}	ǂ	ǂ	15.7_{A}^{a}	28.9_{B}^{c}	35.7_{C}^{d}	37.9_{C}^{b}
	Pure lima bean	11.6_{B}^{a}	67.4_{C}^{d}	47.7_{D}^{b}	5.5_{A}^{a}	25.5_{B}^{b}	19.5_{A}^{a}	23.4_{B}^{c}	30.2_{C}^{a}
	Pure dolichos	10.5_{A}^{a}	29.3_{C}^{b}	75.9_{D}^{c}	21.9_{B}^{c}	32.8_{B}^{d}	18.8_{A}^{a}	12.8_{A}^{a}	26.8_{B}^{a}
	Potato + lima bean	21.8_{B}^{b}	56.7_{C}^{c}	20.6_{B}^{a}	3.2_{A}^{a}	24.7_{A}^{b}	20.7_{A}^{ab}	23.7_{A}^{c}	31.7_{B}^{a}
	Potato + dolichos	20.2_{A}^{b}	28.9_{B}^{b}	45.9_{C}^{b}	15.9_{A}^{b}	29.3_{C}^{cd}	23.3_{B}^{b}	16.3_{A}^{b}	27.3_{C}^{a}
Lower highland	Pure potato	67.7_{B}^{d}	8.9_{A}^{a}	ǂ	ǂ	18.7_{A}^{a}	34.6_{B}d	38.4_{B}^{c}	39.9_{B}^{b}
	Pure lima bean	25.8_{B}^{c}	55.9_{C}^{d}	25.1_{B}^{b}	10.5_{A}^{a}	28.6_{B}^{b}	13.2_{A}^{a}	26.4_{B}^{b}	30.5_{B}^{a}
	Pure dolichos	21.8_{A}^{b}	35.9_{B}^{c}	84.6_{C}^{d}	27.8_{A}^{b}	33.2_{B}^{b}	19.2_{A}^{bc}	14.5_{A}^{a}	26.8_{B}^{a}
	Potato + lima bean	38.6_{B}^{a}	31.8_{B}^{c}	14.9_{A}^{a}	8.3_{A}^{a}	28.9_{C}b	15.3_{A}^{ab}	23.9_{B}^{b}	25.1_{BC}^{a}
	Potato + dolichos	35.9_{C}^{a}	23.5_{A}^{b}	47.8_{D}^{c}	26.1_{B}^{b}	30.4_{C}b	24.3_{B}^{c}	12.3_{A}^{a}	28.3_{C}^{a}
Upper highland	Pure potato	99.8_{B}^{e}	14.8_{A}a	ǂ	ǂ	30.6_{A}a	48.4_{B}^{b}	50.2_{B}^{a}	52.3_{B}^{a}
	Pure lima bean	49.8_{C}^{b}	24.9_{B}^{b}	9.9_{A}^{a}	ǂ	38.4_{A}b	40.8_{B}^{a}	46.7_{BC}^{a}	51.2_{C}^{a}
	Pure dolichos	22.3_{C}^{a}	12.8_{B}^{a}	7.6_{A}^{a}	ǂ	33.2_{A}a	35.1_{A}^{a}	49.2_{B}^{a}	50.7_{B}^{a}
	Potato + lima bean	69.6_{C}^{d}	26.5_{B}^{b}	9.4_{A}^{a}	ǂ	34.8_{A}a	38.6_{A}^{a}	46.6_{B}^{a}	49.9_{B}^{a}
	Potato + dolichos	59.3_{C}^{c}	21.9_{B}^{b}	6.5_{A}^{a}	ǂ	35.4_{A}ab	41.7_{B}^{a}	46.1_{C}^{a}	48.3_{C}^{a}

Lower and uppercase letters indicate mean comparisons between cropping systems and soil depths, respectively by Tukey's HSD test. ǂ denotes data not observed. Values are 4 replicates expressed as averages over the four seasons.

The corresponding soil matric potential at this stage was significantly lower in sole potato (15.7–30.6 kpa) compared to intercropping (20.7–41.8 kpa). In the 0.3–0.6 m depth, potato-lima bean intercropping recorded highest RWU (24.9–56.7 mm). The RWU of sole potato at this depth ranged between 9.7 and 14.8 mm. The corresponding soil matric potentials were 15.3–38.6 kpa in potato-lima bean intercropping and 28.9–48.4 kpa in sole potato. In the 0.6–0.9 m depth, potato-dolichos intercropping showed the highest RWU of 75.9–84.6 mm.

4.3.5 Soil water storage as a function of evapotranspiration and soil evaporation

The cumulative soil water storage (ΔS), soil evaporation and evapotranspiration differed among the different cropping systems and sites (Fig. 4.4).

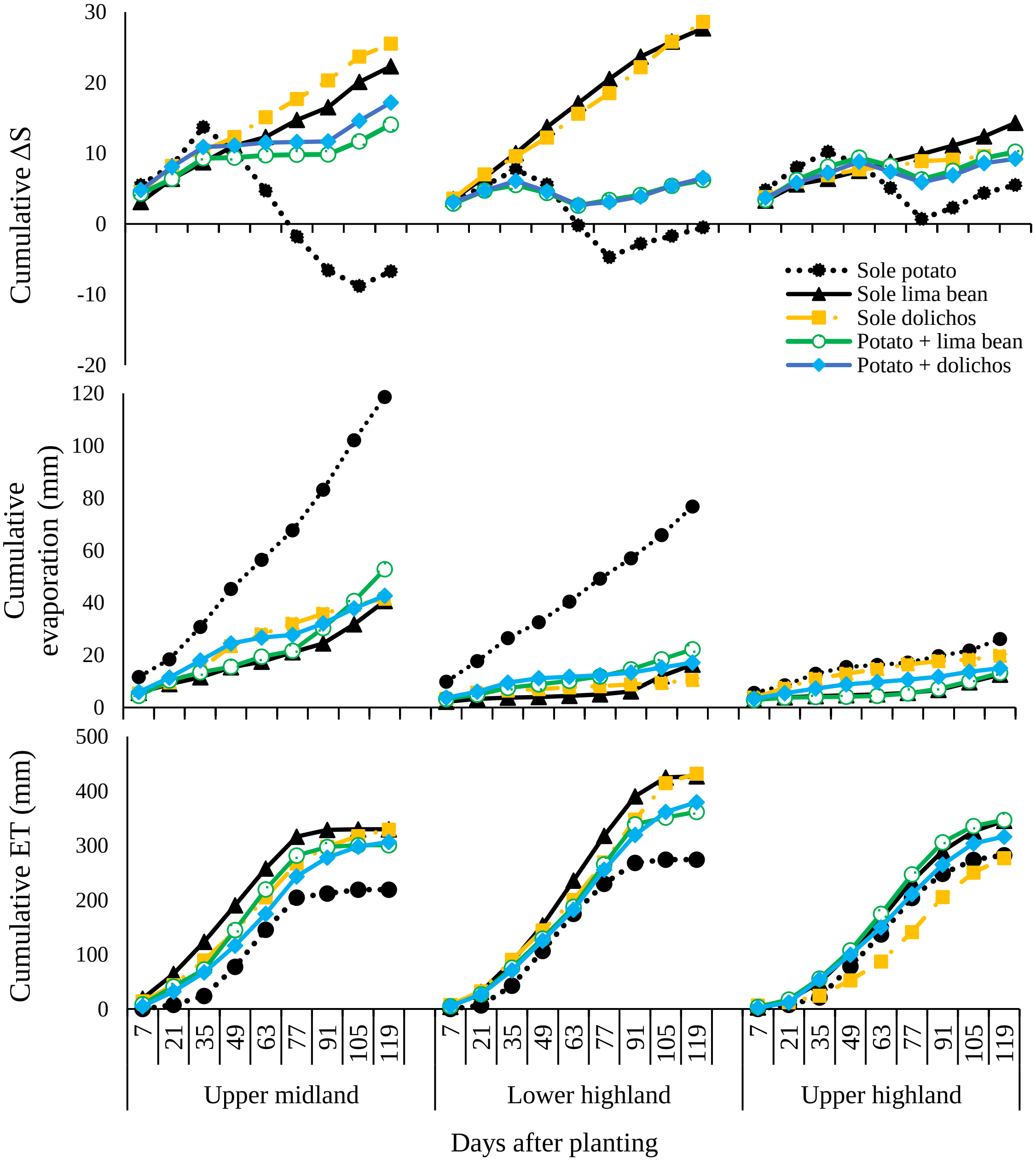
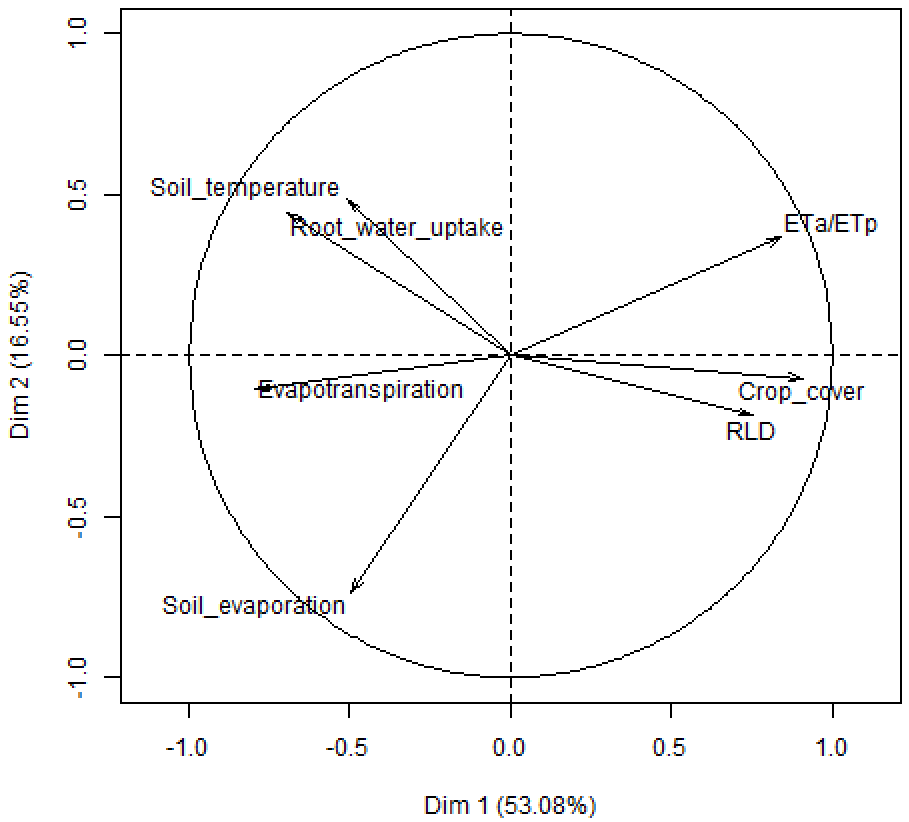


Figure 4.4: Cumulative evapotranspiration, evaporation and soil water storage (ΔS) under different treatments in the three agro-ecological zones. Values are 4 replicates expressed as averages. ΔS is shown for 0–0.3 m of soil layer. Values above and below the zero line in ΔS graph indicate soil water recharge and depletion, respectively.

The variance was greater in the UM than in the LH and lowest in the UH. In the UM and LH, the ΔS was greater under sole potato (-8.8 to 10.3 mm) compared to intercropping (4.3 to 14 mm) and lowest under sole legumes (3.1 to 9.8 mm). In these sites, soil water storage under dolichos and lima bean responded similarly to intercropping with no significant difference. In the UH, ΔS was markedly lower and ranged from 1.4 to 4.8 mm in sole potato and 3.4 to 5.8 mm in intercropping. Peak soil evaporation and ETa coincided with the peak soil-water depletion irrespective of treatments. In the UM, cumulative soil water storage for the sampling conducted between 77 and 119 days after planting were negative in sole potato (-1.6 to -8.8 mm). The corresponding cumulative ETa was at its peak ranging between 146 and 219 mm. Similarly, cumulative soil evaporation in this period was high ranging between 45 and 117 mm. The cumulative soil water storage was negative in sole potato plots in the LH (-0.2 to -4.7) for the period between 63 and 119 days after planting.

4.3.6 Principal component analyses of factors influencing soil water storage

Soil water content was explained by two principal components that accounted for 70% of the variance (Fig. 4.5). The first component explained 53% of the variance and the rest (17%) was accounted for by the second component. Crop cover had the highest factor loading in the PC1 (r = 0.91). This was followed by ETa/ETp ratio (r = 0.84), evapotranspiration (r = -0.79), root water uptake (r = -0.69), soil temperature (r = -0.51) and soil evaporation (r= 0.50). Soil evaporation was the dominance factor in PC2 (r = -0.74). All the correlations were highly significant (p = 0.00).



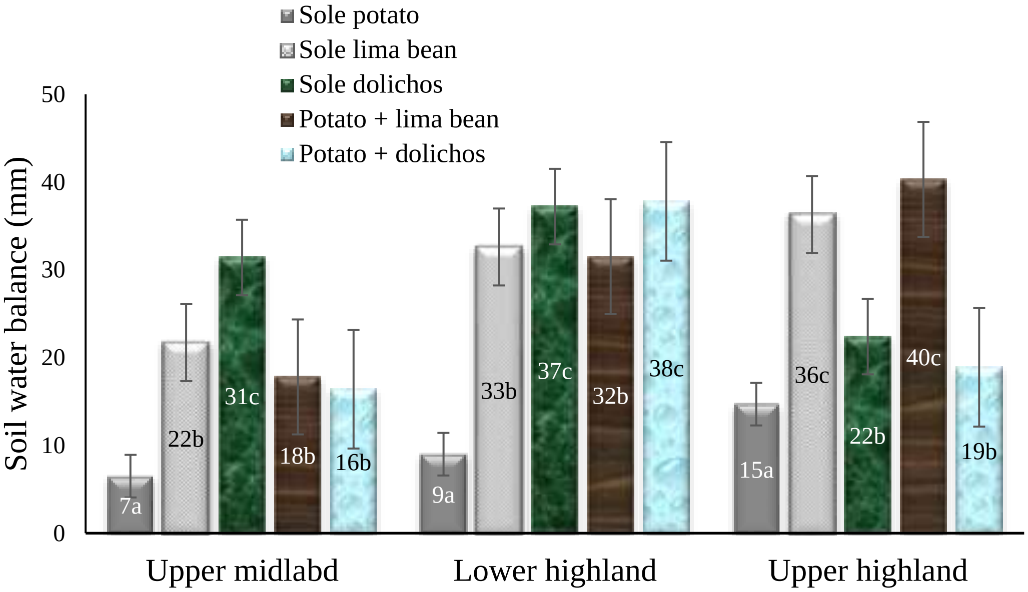
ETa/ETp is the ratio of actual evapotranspiration to potential evapotranspiration. Vectors indicate the degree of correlation between each factor and the axes.

Figure 4.5: Principal component analyses of factors influencing soil water storage in a potato-legume intercropping.

4.3.7 Soil water balance

Across the AEZs, lowest soil water balance (0–0.3 m depth) occurred in sole potato (6.5–14.7 mm), were intermediate in intercropping (16.4–40.3 mm) and highest in sole legumes (21.7–36.3 mm) (Fig 4.6). Potato-dolichos intercropping exhibited significantly higher soil water balance compared to potato-lima bean intercropping in the UM and LH AEZs. Evapotranspiration was the main component of soil water balance across the cropping systems and AEZs and varied between 218 mm and 282 mm in pure potato stands and 301–379 mm in intercropping (Appendix 1). Runoff contributed significantly to soil water balance in the LH (9.8–55.5 mm) and in the UH AEZs (38.6–

60.2 mm). Similarly deep percolation contributed significantly to soil water balance in the UH and was significantly greater in sole potato than in potato-lima bean intercropping.



Letters indicate comparisons for means between sole cropping and intercropping systems at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons. Error bars are standard error of means.

Figure 4.6: Total water balance measured under different cropping systems and sites at the topsoil depth (0–0.3 m).

4.3.8 Intercropping effect on tuber yield

In the UM, sole potato (100% potato plants per ha) attained potato tuber yields of 11.4 t ha^{-1}, an equivalent of 0.26 kg tuber weight per plant (Fig. 4.7). Potato intercropped with dolichos and lima bean (50% potato plants per ha) attained potato tuber yield of 10.8 and 10.1 t ha^{-1} (equivalent of 0.49 and 0.45 kg tuber weight per plant). This was an increase of 88% in tuber weight per plant.

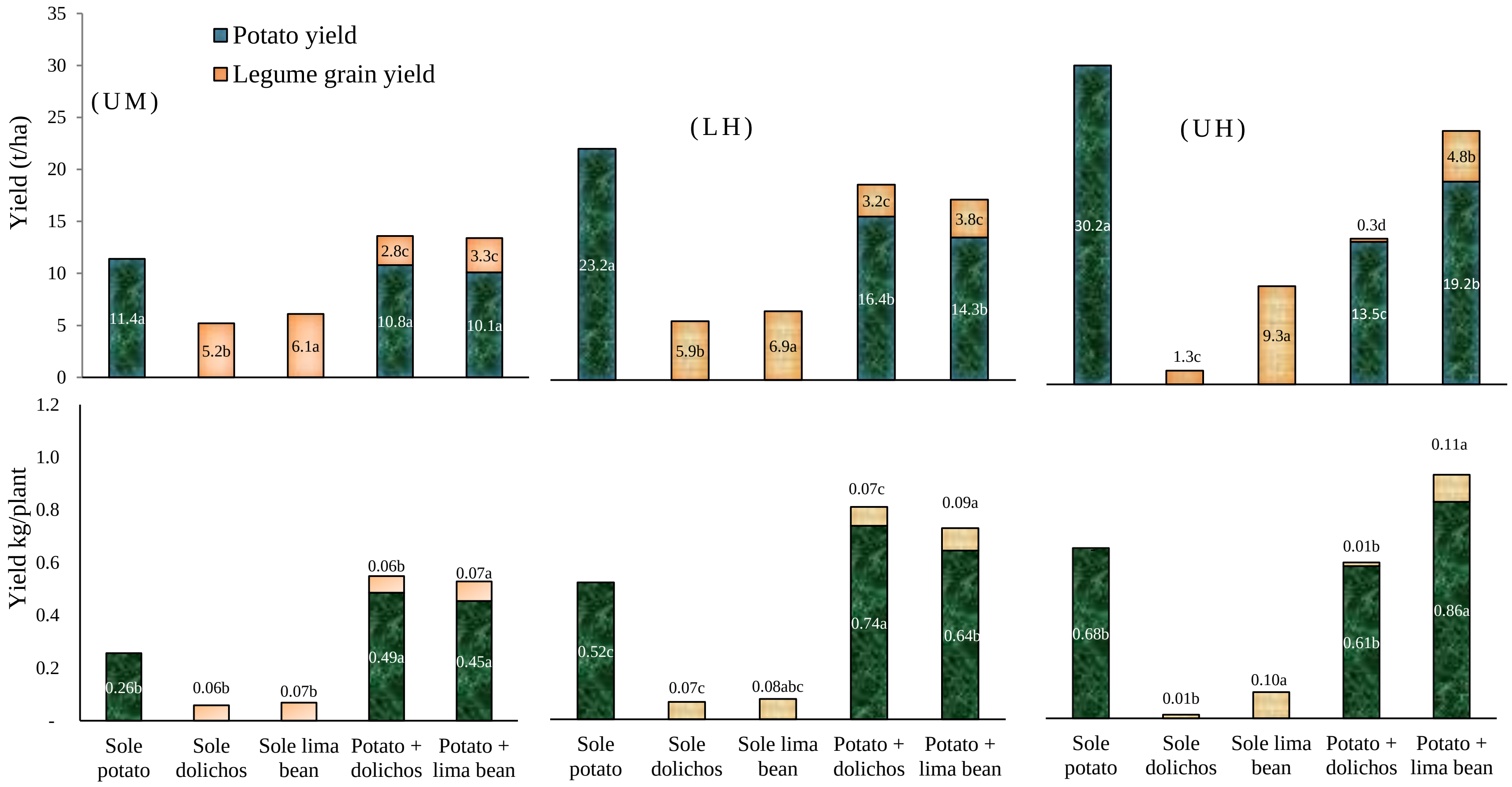


Figure 4.7: Potato and legume yields expressed in tonnes per ha and kg per plant in sole cropping and intercropping systems in the upper midland (UM), lower highland (LH) and upper highland (UH). Letters indicate comparisons for means between sole cropping and intercropping systems at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons.

Similarly, in the LH, sole potato (100% potato plants per ha) attained potato tuber yields of 23.2 t ha^{-1}, an equivalent of 0.52 kg tuber weight per plant. This is compared to potato intercropped with dolichos and lima bean (50% potato plants per ha) that attained potato tuber yield of 16.4 and 14.3 t ha^{-1} (0.74 and 0.64 kg tuber weight per plant) respectively. In the UH, tuber yields were significantly greater for potato-lima bean intercropping (19.2 t ha^{-1}; 0.86 kg tuber weight per plant) than for potato-dolichos intercropping (13.5 t ha^{-1}, an equivalent of 0.61 kg tuber yield per plant). Potato recorded significantly higher tuber weight per plant in sole potato (0.68 kg/plant) than in potato-dolichos intercropping (0.61 kg/plant).

Legume grain yields per area basis were lower in intercropping (0.3–4.8 t ha^{-1}) compared to sole legumes (1.3–9.3 t ha^{-1}) (as sole legumes occupied 100% land *vs* 50% in intercropping). However, when yields were computed per plant basis, legume intercrops had markedly higher grain yields (0.06–0.11 kg grain weight per plant) than the sole legumes (0.01–0.07 kg grain weight per plant). In the upper highland, lima bean grown in sole recorded 9.3 t ha^{-1} grain yield, an equivalent of 0.1 kg grain weight per plant compared to 4.8 t ha^{-1} in legume intercrops (an equivalent of 0.11 kg grain weight per plant). Dolichos yield was markedly lower in the UH, both in sole and intercrop.

4.3.9 Nutrient (NPK) uptake and use efficiency

Nitrogen, phosphorus and potassium uptake differed significantly among the treatments (Table 4.4). Generally, highest NPK uptake occurred in intercropping compared to potato monocropping. The uptake of NPK were highest in the upper highland AEZ and lowest in the upper midland AEZ. Intercropping recorded significantly higher NPK use efficiency ranging from 62–413 kg PEY kg^{-1} vs 45–143 kg PEY kg^{-1} in sole potato in the UM, 80–387 kg PEY kg^{-1} vs 46–

133 kg PEY kg^{-1}in the LH and 62–367 kg PEY kg^{-1} vs 80–198 kg PEY kg^{-1}in the UH (Table 4.4). P use eeficiency was about 2 fold greater in intercropping compared to sole potato across the sites.

Table 4.4: Nutrient uptake (NPK) and use efficiency by different cropping systems in the three agro-ecological zones.

Parameter	Cropping system	Upper midland			Lower highland			Upper highland		
		N	P	K	N	P	K	N	P	K
Nutrient uptake (kg ha^{-1})	Sole potato	90a	45c	143c	133b	46c	167b	197ab	80b	198b
	Sole lima bean	75b	40c	58d	59d	47c	62c	75c	60c	68c
	Sole dolichos	79b	51b	68d	83c	85b	77c	67c	83ab	40d
	Potato + lima bean	98a	61a	176b	157a	98a	196ab	223a	96a	238a
	Potato + dolichos	96a	53b	203a	148a	70b	216a	188b	34d	201b
Nutrient use efficiency (kg PEY kg^{-1} nutrient)	Sole potato	79c	195c	62e	104d	297b	80d	82d	202b	82c
	Sole lima bean	147b	305b	210b	316a	395a	302a	294a	367a	323a
	Sole dolichos	248a	382a	286a	301a	294b	325a	196b	153c	324a
	Potato + lima bean	254a	413a	142c	242b	387a	194b	151c	349a	142b
	Potato + dolichos	246a	322b	85d	167c	352a	114c	68e	375a	63c

Letters indicate mean comparisons between cropping systems by Tukey’s HSD test. ǂ denotes data not observed. Values are 4 replicates expressed as averages over the four seasons.

4.3.10 Relationship among soil water content, nutrient uptake and soil temperature

Soil water balance decreased with increasing soil temperature (r= -0.89), root water uptake (r= -0.75) and increasing uptake of N (r = -0.88), P (r = -0.67) and K (r = -0.85) (Table 4.5), but increased with increase in soil water content (r = 0.98).

Table 4.5: Pearson's correlation of soil temperature, nutrients (NPK) uptake and crop water balance.

Parameter	Soil temperature	Soil water balance	RWU	SWC	N uptake	P uptake
Soil water balance	-0.89***					
RWU	-0.75**	-0.59*				
SWC	-0.83**	0.98***	0.79**			
N uptake	-0.68*	-0.88**	0.88***	0.83***		
P uptake	-0.56*	-0.67*	0.61*	0.51*	0.53*	
K uptake	0.52*	-0.85**	0.71**	0.56*	0.59*	0.41

Corelation significant at $p < 0.001$ (***), $p < 0.01$ (**) and $p < 0.05$ (*). RWU; root water uptake, SWC; soil water content.

Soil temperatures related negatively with uptake of N (r = -0.68), P (r = -0.56) and K (r = -0.52). Root water uptake related significantly with N uptake (r = 0.88), P uptake (r = 0.61) and K uptake (r = 0.71). Nutrient uptake increased with increase in SWC (R =0.83, 0.51and 0.56 for NPK, respectively).

4.4 Discussions

4.4.1 Root water uptake

The variation of root water uptake (RWU) among the cropping systems was attributed to the heterogeneous root distribution in the soil profile and to the temporal and spatial variations in soil water content. While potato crop was characterized by roots that rarely exceeded a vertical depth of 0.3 m across the sites, lima bean and dolichos roots were traced up to 0.9 and 1.1 m respectively. These legumes could therefore access soil water to deeper layers than the potato crop. In this way, intercropping enhanced deep root water extraction and eliminated resource overlap. This is in agreement with the studies which have established that potato has shallow fibrous root systems which are concentrated in the upper soil layer (0–0.3 m) making the crop highly sensitive to fluctuating soil moisture (Aliche et al. 2018). The lack of active roots beyond 0.3 m depth in sole potato is therefore the reason why soil matric potential remained high in deeper soil layers.

At vegetative growth of potato, the soil water recharge by rainfall maintained the soil matric potential high (above the field capacity). Root water uptake at this stage was thus not limited by the soil water availability, but rather by the undeveloped root systems across the treatments. At tuber bulking stage, cessation of rains in the UM and LH caused the soil matric potential to significantly drop in sole potato plots. At this stage in the UM, the potato in sole stands generally showed signs of wilting as soil water was strongly held restricting its movement and uptake by the roots. Intercropping however ensured high canopy integrity and deeper rooting systems which kept both evapotranspiration and soil water extraction high.

4.4.2 Evapotranspiration, soil evaporation and soil water storage

Intercropping potato with the legumes promoted leaf area expansion leading to rapid ground cover development. This cover created shade that buffered the soil against direct solar and considerably reduced evaporation losses. Sole potato however left bare spaces between crop rows through which solar penetration occurred. Crop cover mediates soil water fluctuations by lowering evaporative losses through shading and holding horizontal and vertical water flow in the soil (Daly and Porporato, 2005; Asbjornsen et al. 2011). Across the sites, evaporation of surface water occurred mainly at the onset and end of the season, a period when the soil was bare and the solar intensity was high.

The cumulative ETa during the growing season was lower under sole potato due to two main reasons. First, the shallow root system by potato limited its capacity to extract the readily available water in the deeper soil layer. Second, potato attained maturity relatively fast compared to legumes. While the crop growth duration was about 90 days in potato, lima bean was characterized by slightly longer duration averaging 110 days while dolichos exhibited indeterminate growth. The extensive canopy with longer duration increased the plant demand for water and therefore evapotranspiration. Cumulatively, the amount of water consumed by legume intercrops after potato harvest averaged 30–60 mm across the seasons. This variability could be explained by changes in the timing of leaf senescence in response to ambient temperatures and soil water availability.

The topsoil changes in soil water storage (ΔS) occurred mainly after rainfall events and only after topsoil saturation occurred did the deeper soil layers respond to additional soil water.

This was most clearly shown in the UM under sole potato crop at a time the rainfall events continued to a period of about 30 days. Thereafter, the topsoil dried up rapidly following higher evaporation that exceeded recharge from rainfall. The high crop cover under intercropping at this time insulated the soil from direct solar and minimized the evaporation rates. The rainfall occurring at full vegetative growth (35–77 DAP) contributed mainly to ETa irrespective of treatments. This resulted in significant changes in soil water storage. As the soil dried up later in the season, deeper soil layers contributed an increasing fraction of water to ETa under intercropping. This was shown by the increased root water uptake in the deeper soil layers. Additionally, the high canopy cover extended by legume intercrops after potato senesces insulated the soil against evaporation and led to more water storage (total rainfall > ETa).

The differences in soil water storage (ΔS) between the sites and seasons were in part a function of rainfall. The more the rainfall, the greater the soil water content. Consequently, the larger rainfall amounts that recharged the soil after an extended period of dryness caused significant changes in soil water storage. The soil water storage in the topsoil under sole legumes was almost balanced in the UM and LH indicating that the legumes extracted water at depths beyond 0.3 m. Water fluxes below root-zone has been shown to increase the amassing of soil moisture in higher depths thus making it available for plant uptake by deep roots (Sakai et al. 2009). The coincidence of peak ETa, soil evaporation and soil water depletion in sole potato was an indication that ETa and evaporation were major contributor to changes in soil water storage.

In the UH, the contribution of runoff and deep percolation largely accounted for the changes in soil water storage. Generally, when the rainfall exceeded infiltration rates, a higher proportion of rainfall was routed to surface runoff or recharged to the ground water reservoir. This process was greater in sole potato. In the UH, lima bean achieved a dense canopy that intercepted and reduced raindrop-hitting force and slowed down the velocity of runoff. Dolichos growth was however, hindered by cold in the highlands, and thus did not establish sufficient cover to intercept the raindrop.

The more stable changes in soil water storage at start of the seasons was because of the large rainfall at a period when demand for transpiration remained low, and so the soil water recharge was rapid. At this time, the lower ETa was due to the undeveloped plants with limited capacity to transpire while the lower ETa at the end of the seasons was a consequence of plant maturity resulting in senesces of shoot. In the UH, the ETa was not primarily limited by soil water availability as there were an average of 3 days when ETa to ETp ratio was above unity; see appendix 2). These days followed relatively large rainfall events that occurred when the plants had developed full foliage.

The lower crop cover and soil moisture under sole potato were a major contributor to the lower ETa/ETp relative to potato-legume intercropping. Potatoes are much less tolerant to water stress than the legumes and prospered only when the soil water content was sufficient to meet the crop water requirement. In intercropping, the better rooting system increased the capacity of crops to extract water thus keeping evapotranspiration high with little impact on topsoil water reservoir. Increased canopy under intercropping also increased the transpiration component of evapotranspiration and enhanced the crop water use. Bachand et al. (2013) reported that transpiration accounts for 50–90% of total ETa during a growing season in intercropping systems.

The high soil evaporation, runoff and evapotranspiration were the main reasons for the low soil water balance under sole potato. Runoff occurred mainly at the onset of rains when crop cover was low and soon after harvest when the soil was bare. The high soil water balance in the UH compared to LH and UM was due to the high rainfall amounts that raised the soil water tables.

Besides, the UH exhibited lower ambient temperatures which lowered soil evaporation, thus increasing soil water storage.

4.4.3 Principal factors explaining changes in soil water storage

Soil water storage was influenced by crop cover, evapotranspiration, soil evaporation, root water uptake, and the ratio of ETa/ETp. Crop cover was the main determinant of soil water storage as shown by the highest correlation. Crop cover mediated the soil water fluctuations by lowering the evaporative losses through shading. Vegetation cover lowers the amount of direct solar radiation reaching the ground surface and subsequently buffers the soil temperatures (Salisbury and Spomer, 1964; Pielke, 2001; Blok et al. 2010; Graham et al. 2012). The stronger relationships between ΔS and ETa compared to ΔS and ETa/ETp showed that ETa was mainly constrained by soil water content (Brutsaert and Chen 1995; Yamanaka et al. 2007).

The decrease in soil water storage with both soil temperature and soil evaporation was because of the warming up of soil, the energy of which converted water into vapor thus minimizing the liquid phase of soil water. The exponential decrease in soil moisture with increase in soil temperature was an indication that the migration of soil moisture was accompanied by heat conduction thus affecting the variations in soil temperature. This is consistent with soil water-heat system relation studies that have shown that changes in soil temperature affect the phase changes of soil water content (Lu et al. 2011; Li et al. 2018). When only the wet season data was considered in this relation, the effect was weaker and not significant. This was because of the rainwater recharge that moistened the soil, lowered the soil temperature, and increased the soil water storage. Further, the crop cover weakened this association by restraining the influence of direct solar on soil-water-heat relation. Nyawade et al. (2019) reported that crop cover maintains the stability of soil moisture and temperature and therefore maintains a strong interaction between the two variables.

Root water uptake by legume intercrops occurred mainly in the deep soil layers while that by potato occurred in the topsoil layers thus guaranteeing resource complimentarity. When the soil was moist, water moved freely towards the roots making root water uptake high. Scanlon et al. (2005) showed that the high evapotranspiration rates under elevated soil temperatures reduced soil water storage and lowered RWU. This behavior was also reflected in numerical modeling studies by Walvoord et al. (2004) and Scanlon et al. (2003) who observed that high soil temperatures lowered the soil water potential and thus restricted the RWU.

The contribution of intensive root system by intercropping on moderation of soil temperature could not be overruled in this study as soil water storage related significantly with the root length density (RLD). Vegetation that supports a dense rooting system absorbs moisture stored in the soil and reduces soil evaporation and water loss (Lu et al. 2011). As soil temperatures increased, the soil dried out and water mobility declined, making increased RLD more important for lateral water extraction. This is consistent with findings reported by related studies which unraveled that high soil temperatures and water deficit within the root-zone create a mechanism that forces plants to develop deeper root systems so as to access the subsoil water reserves (Kirkegaard and Ryan, 2014; Thorup-Kristensen et al. 2016).

No significant variation occurred in soil temperature at soil layer greater than 0.30 m indicating that heat could be barely transported beyond this depth. We partly attributed this to the reduced heat flux contributed by high soil water content (Nyawade et al. 2019). The enhanced soil water infiltration under intercropping enhanced the soil water recharge but weakened the stability of soil temperature. As the thermal capacity of water is larger than that of soil (Garcia et al. 2011), the greater the soil water content, the less varied the range in soil temperature. Therefore, the soil under intercropping that was characterized by higher soil moisture content released more heat than that under sole potato, especially during the dry conditions when heat flux was greater.

4.4.4 Intercropping effect on crop yield

Intercropping had 50% fewer potato plants per ha compared to sole potato (100%), thus potato tuber yields per area unit were generally lower. However, when the yields were expressed in tubers per plant, intercropping showed a marked increase in yield over sole potato. Due to their deep taproot systems, legume intercrops were capable of recapturing the percolated water, absorbing it more efficiently and converting it into crop biomass. This reduced resource overlap allowing intercropped potato to consume topsoil water.

The high soil temperatures and low moisture contents under sole potato had devastating effects on tuber yields, especially in the UM. This is because high temperatures promoted haulm growth at the expense of tuber growth and therefore much pool of starch available for tuber growth was directed to shoot. As soil and air temperature increase, the rate of respiration increases, while the rate of photosynthesis decreases (Chaves et al. 2002). This suggests higher respiration of starch to sustain plant growth rather than it being stored in tubers. The high soil temperatures under sole potato were extended to stolon development phase of potato growth. This greatly reduced stolon numbers thus affecting tuber size distribution and subsequently the biomass accumulation. Accordingly, when heat stress coincided with tuber maturation in the UM, this hastened leaf senescence and interrupted new leaf formation, thus resulting in tuber yield reduction.

4.4.5 Nutrient uptake and use efficiency

The higher nutrient uptake due to legume intercropping was a reflection of enhanced nutrient use complementarity and facilitation contributed by legume integration. The deep root systems by the legumes enhanced nutrient acquisition in the deep soil layers. This offered complementarity that allowed potato to take up nutrients in the surface stratum. In the UM and LH zones, dolichos exhibited deep rooting system with a large surface area that grew up to a depth exceeding 1 m. Whitbread et al. (2011) showed the ability of dolichos to capture N from the subsoil and pump it to the topsoil strata thus making it available for the shallow rooted cereals. The facilitation mechanisms that could have enhanced nutrient availability and uptake include the organic acid production and enhanced mycorrhizal colonization (Hinsinger et al. 2011). Dolichos secrets organic substances such as phosphatases which promote release of P from organic materials (Hinsinger et al. 2011; Schneider et al. 2019). The greater nutrient uptake by dolichos than lima bean in the UM and LH AEZs may be related to the ability of dolichos to develop greater RLD under high soil temperature conditions. The converse was observed in the UH AEZ that was characterized by cold intolerable by this crop (dolichos).

The increase in uptake of nitrogen, phosphorus and potassium with increasing soil moisture contents was not only due to the improved root growth leading to enhanced nutrient acquisition, but also to the increased nutrient mobility caused by soil water dissolution. Enhanced LAI development in intercropping raised the plant nutrient demand thus driving NPK uptake from the soil with subsequent translocation to the shoots. As soil water content increased under potato-legume intercropping, a greater continuity of the liquid phase occurred. This likely lowered the tortuosity of nutrient diffusion path thus allowing nutrient from larger soil volume to be absorbed by plant roots. Zeng and Brown (2000) developed a relation which showed that soil nutrient mobility increases with soil water content suggesting that more nutrients can diffuse to plant roots at sufficient soil water content. Nutrient acquisition by diffusion and mass flow become faster where the soil water available in the root-zone is optimal for plant growth (Barber, 1995).

The high phosphorus use efficiency reported in this study agrees with those reported by Gitari et al. (2020) and indicates that potato is a more efficient crop in translocation of nutrients to the tubers. The use efficiency of P was high in the UM where temperatures and rainfall were the main limitation to crop production. Sandana (2016) observed that potato utilizes P well even when it is in inadequate supply despite the low uptake of the nutrient. Such findings are in line with those obtained by Wang et al. (2015) who reported high P uptake efficiency even when the nutrient supply was limited. The higher nutrient use efficiency due to legume intercropping was largely due to the higher tuber dry matter yield and enhanced legume biomass production. Further, the decrease in NPK losses in eroded sediments, leaching and volatilization under the intercrop plots (see chapter six) enhanced nutrients available for crop uptake, thus increasing the use efficiency.

4.5 Conclusions

The results from this study suggest that potato-legume intercropping has the capacity to keep root zone soil water and soil temperature optimal thus increasing nutrient uptake and potato yield. The changes in soli water storage in the topsoil reflected the net results of rainfall recharge, water consumption by ETa, output from runoff, soil evaporation and inputs from soil water redistribution. The greater root biomass contributed by legume intercrops in deeper soil layers enhanced interception of soil water. Reduction of surface temperatures was a result of increased crop cover which insulated the soil from direct solar radiation thus reducing soil evaporation. This in turn increased the soil water content and nutrient uptake. Modification of microclimatic conditions in this manner could be an effective measure to adapt potato to midland elevation agro-food systems.

CHAPTER FIVE

SHORT-TERM DYNAMICS OF SOIL ORGANIC MATTER FRACTIONS AND MICROBIAL ACTIVITY IN SMALLHOLDER POTATO-LEGUME INTERCROPPING SYSTEMS

Abstract

Continuous cultivation of potato (*Solanum tuberosum* L.) in monoculture systems represents the greatest factor deteriorating soil organic matter (SOM) in smallholder farms. With an aim to breaking this norm, a 2-year field trial intercropping potato with two legumes: lima bean (*Phaseolus lunatus* L.) and dolichos (*Lablab purpureus* L.), was conducted in the upper midland (1552 meters above sea level (masl.)), lower highland (1854 masl.) and upper highland (2552 masl.) agro-ecological zones of Kenya. The study was laid out in a randomized complete block design with four replications. Residues from each cropping system were quantified at the end of each season and incorporated back into the soil at start of the subsequent season. A combined physical and density fractionation was used to separate the soil in macro-aggregates (>250 μm), micro-aggregates (250–50 μm) and silt plus clay fractions (<50 μm), while SOM was partitioned into labile (density of 1.65 to 1.85 g cm^{-3}) and stable (2.60 g cm^{-3}) fractions. Microbial biomass contents were determined by chloroform fumigation while enzymatic activities were assessed by hydrolyses of fluorescein diacetate and dehydrogenase. Compared to sole potato, intercropping increased the contents of light fraction organic matter by 12–28%, dissolved organic matter by 7–21% and microbial biomass by 15–38%, thus stimulating enzyme activities. Trends in soil microbial respiration followed those of enzyme activity and were 20–34% higher in intercropping than in sole potato. These results affirm legume intercropping as a possible entry point to restoring the impoverished soil organic matter in smallholder potato farming systems.

Keywords: Intercropping; microbial activity; microbial biomass; soil organic matter fractions.

5.1 Introduction

Potato production in subtropical highlands is done mainly in monoculture systems yet the crop retains very little residues and therefore has limited capacity to return organic matter into the soil (Angers and Carter, 1996; Gitari et al. 2018a; Nyawade et al. 2019). Even with this little residue retained, most of it is used to feed livestock or burned during land preparation. This problem is particularly important among the smallholder farmers who lack the capacity to apply fertilizer or put in place adequate soil conservation measures to control soil erosion (Nyawade et al. 2018b; Gitari et al. 2019). As potato takes 40–45 days to establish full groundcover, and maintains this cover only for 20 days before senesces sets in, the crop leaves the soil exposed to high surface temperatures that accelerates oxidation of soil organic matter (SOM) making its supply to be imbalanced (Reicosky et al. 1995). An imbalanced SOM lacks the capacity to supply nutrients to the microbial population and therefore restricts their growth and activity (Haynes and Tregurtha, 1999). Consequently, the average potato yields in subtropical highlands range between 3 and 15 t ha^{-1}, an observation that has been related to the low content of SOM. This factor if not checked, may compel farmers to abandon potato production.

The extent of the adverse effect of poor potato cropping systems on SOM depends largely on which size fraction is affected (Nyawade et al. 2018b). These fractions differ in their quality, quantity and turnover rates, and respond differently to soil management (Kapkiyai et al. 1999). The stable SOM includes well-decomposed microbial products that form mineral complexes with organic compounds and is relatively recalcitrant to microbial attack (Camberdella and Elliot, 1992; Six et al. 2002). The labile SOM fractions are derived from the newly incorporated organic materials and include the light fraction organic matter, microbial biomass and dissolved SOM

(Haynes, 2005). This component of SOM has rapid turnover rate and responds fast to soil management intervention compared to the total and stable SOM (Haynes, 2005; Louis et al. 2016).

The soil microbial biomass is a living fraction of SOM consisting mainly of bacteria and fungi that decompose litter and crop residues (Naresh et al. 2017). This process releases nutrients that are made available for plant uptake (Smith and Paul, 1990). Generally, the microbial biomass makes up 5–10% of the total SOM, part of which is released to the soil in plant available forms upon death of soil microbes (Louis et al. 2016). The dissolved organic matter (DOM) results from microbial degradation of SOM and is used as substrate by the soil microbes (Roper et al. 2010). The rate at which labile fractions of SOM decompose determines the release of nutrients to plants (Kapkiyai et al. 1999). Therefore, any activity that rapidly alters the contents of soil labile organic matter are regarded to be early signals of changes in soil productivity that may occur over an extended period.

Quantification of soil microbial biomass activity is based on the rate at which respiration and enzyme hydrolyses by soil microbes occur (Naresh et al. 2017). If the rate of respiration is related to the corresponding microbial biomass size, it is defined as microbial metabolic quotient (qCO_2) (Lupwayi et al. 1998). The qCO_2 is sensitive to short-term changes in SOM and therefore provides early warning to a degrading soil quality. The qCO_2 gets elevated when perturbations such as high soil temperatures and soil water deficits exacerbate SOM depletion, thus negating the functions of soil microbes (Anderson and Domsch, 1990). These processes may greatly vary with cropping systems, soil management and agro-ecological zones (Lupwayi et al. 1998; Naresh et al. 2017). This is because the microbial biomass just like any other organic matter fraction, is influenced by soil particle size distributions which has great relation with the soil management and cropping systems (Camberdella and Elliot, 1992).

The macro-aggregate provides conducive micro-environment for microbial growth and also confers physical protection to the micro-aggregates thus occluding the associated SOM from physical perturbations (Six et al. 2002). It is in this regard that simple and sustainable strategies capable of increasing aggregate formation have been proposed in smallholder potato cropping systems (Nyawade, 2015; Burke, 2017; Nyawade et al. 2018b). The proposed measures highly regard technologies that retain at least 22.4 $\mathrm{Mg\,ha^{-1}}$ residue dry matter *in situ*, a value that corresponds to 1% increase in SOM (MacMillan and Buchanan, 1988). This large biomass can hardly be attained by pure potato crops (Angers and Carter, 1996). Thus, addition of materials with high lignin contents as mulch has been considered appropriate (Franchini et al. 2002). These materials are however characterized by nitrogen immobilization resulting in low nutrient release (Hassink, 1995). Legume intercropping due to its ability to integrate crop components with high nitrogen contents, offers an alternative that can reduce nitrogen immobilizations (Naresh et al. 2017). When returned to cropland, the fresh legume residues provide nucleation useful in formation of macro-aggregates which are the favorable habitat for soil microbes (Ghani et al. 2003; Liang, 2013.).

It is in view of this background that this study was conducted to assess the short-term effect of potato-legume intercropping on dynamics of SOM fractions (microbial biomass, dissolved SOM, light fraction SOM and heavy fraction SOM) in three agro-ecological zones of Kenya (upper midland, lower highland and upper highland). Early detection of changes in SOM is important for designing sound management practices that can restore soil quality, soil health and soil productivity. Identification of intercropping systems capable of increasing SOM contents to optimal levels under different agro-ecological conditions offers the possibility of potato integration into wide range of agro-food systems.

5.2 Materials and methods

5.2.1 Study sites

The trials were installed in the wet season of 2016 and were continued till 2018 dry season in three agro-ecological zones of Kenya; upper midland (1552 m above sea level (masl), lower highland (1894 masl) and upper highland (2552 masl) agro-ecological zones of Kenya. The region is representative of agricultural farming systems of Kenya where inherent low soil organic matter content greatly limits potato production. Detailed descriptions of the study sites are given in section 3.1. Measured soil properties (0–40 cm depth) before the experiment are provided in Table 5.1.

Table 5.1: Initial soil properties.

Agroecological zone	Soil depth (cm)	Clay	Silt	Sand	Textural class[§]	pH	HFOM	LFOM	DOM	MBC
			%					mg C kg^{-1}		
Upper midland	0–10	24.5	33.3	42.2	CL	5.0	453	337	271	111
	10–20	24.2	36.9	38.9	CL	5.0	451	190	208	36
	20–30	28.9	29.8	41.3	CL	4.9	414	120	111	21
	30–40	23.8	32.4	43.8	CL	4.9	388	98	108	20
Lower highland	0–10	49.7	22.5	27.8	C	5.1	610	544	418	128
	10–20	49.2	24.2	28.9	C	5.1	549	324	306	79
	20–30	50.1	24.2	25.7	C	5.2	503	203	135	64
	30–40	51.3	24.8	23.9	C	5.2	500	179	126	61
Upper highland	0–10	38.3	56.1	5.6	SC	5.2	560	575	425	216
	10–20	36.9	58.4	4.7	SC	5.2	454	324	325	110
	20–30	34.6	59.5	5.9	SCL	5.3	426	205	103	41
	30–40	33.9	57.9	8.2	SCL	5.3	421	168	104	43

[§] clay (C), clay loam (CL), silt clay (SC) and silt clay loam (SCL). : Heavy fraction organic matter (HFOM), light fraction organic matter (LFOM), dissolved organic matter (DOM) and microbial biomass carbon (MBC).

5.2.2 Trial design and crop husbandry

The trials were arranged in a randomized complete block design in plots measuring 4.75 m long by 3 m wide. The treatments comprised of sole stands of potato (*Solanum tuberosum* L., Unica cv-CIP 392797.22), sole lima bean (*Phaseolus lunatus* L.), sole dolichos (*Lablab purpureus* L.) and intercropping of potato with the two legumes. Each treatment was replicated 4 times. Detailed descriptions of crop husbandry and trial management is outlined in section 3.4 and 3.5.

5.2.3 Soil sampling and analyses

Sampling of soils was done at inter-rows of ech plot using soil piston augers for every 10 cm interval along soil profile of 0–40 cm. Sampling was conducted at vegetative growth of potato (about 60 days after planting). The depth interval 0–40 cm was considered appropriate as it represented the rooting depth for potato crop (the depth at which >70% of the root volume was found) (Mahdian and Gallichand, 1996). In each plot, 80 soil samples were taken (5 cropping systems × 4 replicates × 4 sampling depths). The samples for each treatment were composited for each depth and frozen until analysis for soil pH (by water), soil texture (hydrometric) (Gee and Bauder, 1986), total N (Keeney and Nelson, 1982) and total organic carbon (Nelson and Sommers, 1996).

5.2.4 Soil moisture and soil temperature

Quantification of soil moisture and soil temperature was done between sowing and harvesting using Onset HOBO probes (UX120-006 M) installed at every 10 cm interval along soil profile of 0–120 cm. The soil moisture and soil temperature data at depth 0–30 cm was related with different SOM fractions and microbial activity.

5.2.5 Estimation of shoot and root biomass

Root and shoot biomass were measured at vegetative growth of potato (60 days after planting) by sampling four inner rows of each treatment (2 strips of legumes and 2 strips of potato for intercropping, and 4 strips of either legume or potato for the sole crops). Roots of each cropping system were measured for every 10 cm interval in soil profile of 0–40 cm using metal cores of 0.0015 m^3 by volume (Bohm, 1979). For the monoculture system of potato and legumes, root sampling was done between two strips of potato (at approximately 37.5 cm from the strips) and two strips of legumes (at approximately 25 cm from the strips) respectively. For intercropping, the cores were driven between two potato rows in potato strips (at approximately 37.5 cm from the strips), between two legume rows in legume strips (at approximately 25 cm from the strips) and between potato and legumes in potato-legume strips (at approximately 37.5 cm from the strips). Additional root sampling was done directly at legume and potato stem base (about 5 cm from the stem) to take into account roots not extending to the inter-row space.

Samples for a given plot and sampling depth were pooled and analyzed as one. The extracted soil cores were whirled in running water to remove the embedded soil particles and dead roots, and the mixture sieved through 2 mm mesh. For shoot biomass estimations, the plants were cut at about 2 cm from the soil surface using machetes. Fresh weight of the biomass was quantified using a weighing balance. The dry mass of roots and shoots were separately determined by oven drying about 500 g samples at 65°C to a constant mass then extrapolating to kg ha^{-1}. The rest of biomass was incorporated in respective plots at start of the subsequent season using hand hoes.

5.2.6 Estimations of crop biomass lignin, polyphenols, C and N contents

Dry matter subsamples of roots and shoots were analyzed for C, N, lignin and polyphenol contents. For plant lignin content, about 20 g sample of the dry matter was ground and passed through 30 mm mesh (Van Soest and Wine, 1968). The sample was placed in a crucible and an acid detergent fiber prepared on 1 g sample added. This was followed by addition of saturated potassium permanganate (5 mL) and the content stirred with a glass rod. The crucibles were allowed to stand at 25 °C for about 90 min and the content dried overnight at 100 °C and weighed. The loss in weight of the acid-detergent fiber was taken to represent the lignin content. Polyphenols were extracted according to modified Anderson and Ingram (1993) method using methanol (70%), ascorbic acid (0.05%) and formic acid (0.5%). The dry matter samples of each plant parts were digested and used for determination of total N concentrations (Bremner and Mulvaney, 1982), while a part of it was oxidized for determination of total organic carbon content (Nelson and Sommers, 1996).

5.2.7 Particle size separation and sequential density partitioning of soil organic matter

A combined particle and density size fractionation was used to partition the soil organic matter (SOM) into size fractions (Camberdella and Elliot, 1992; Sohi et al. 2001) (Fig. 5.1). Fifty (50)g of the composite soil was dispersed in 50 mL of 5% sodium hexametaphosphate and subjected to overnight shaking. The content was passed through series of sieves of sizes 250–50 μm on a mechanical sieve shaker. Sand fractions were retained on sieves >50 μm while silt and clay fractions (<50 μm) were repeatedly siphoned off. Density separates were recovered by sodium polytungstate (SPT) following a procedure modified from Sohi et al. (2001). A deionized water was used to suspend 50 g of the soil which was then decanted to retain the organic material. The content was transferred into a centrifuge bottle (250 mL) followed by addition of 125 mL SPT solution adjusted to a density of 1.65 g cm^{-3}. The mixture was gently shaken and allowed a period of 30 min for settling and centrifuged at 2000 rpm for another 30 min. The supernatant was sieved (0.50 μm) and the residue rinsed with deionized water and referred to as light fraction organic matter (LFOM). Forty (40) ml of SPT solution of 1.85 g cm^{-3} density plus 10 glass beads were added into the settled residue and centrifuged at 175 rpm for about 18 h. The supernatant was filtered, and the retained residue rinsed to obtain occluded particulate organic matter. The material which settled was placed in SPT of density adjusted to 2.60 g cm^{-3} and shaken for 10 min before being centrifuged at 3000 rpm for about 30 min.

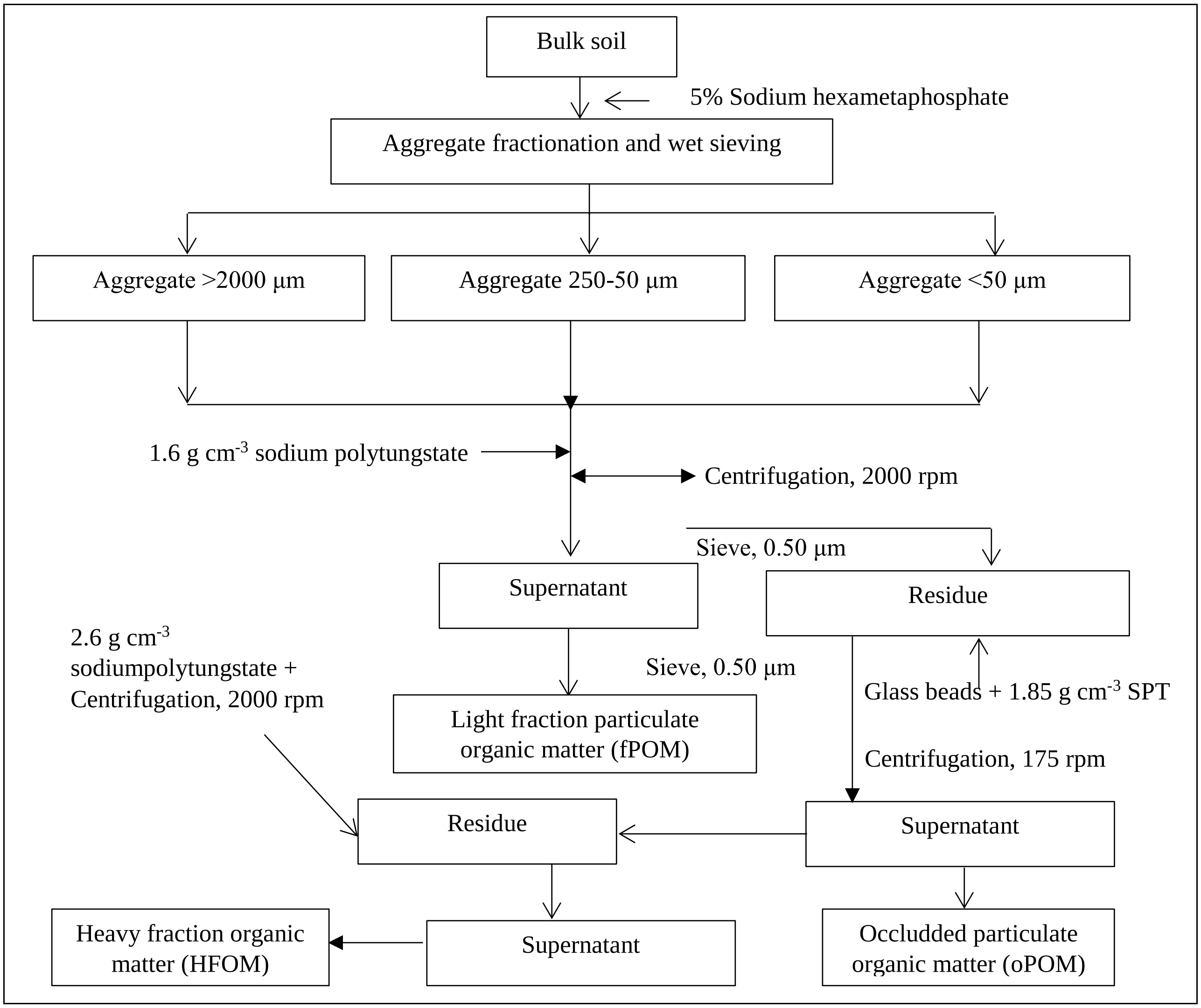


Figure 5.1: Schematic diagram of the combined aggregate size and density fractionation.

The supernatant was decanted, the residue retained and repeatedly washed with deionized water to remove the leftover SPT. This fraction was referred to as the heavy fraction organic matter (HFOM) (stable SOM). Soil samples obtained from the aggregate sizes and density size fractions were ground and used for determinations of total SOC and total N contents. Contents of dissolved organic matter (DOM) were estimated by incubating (at 20°C for 3 weeks) about 10 g soil maintained at 55% water-holding capacity (Smolander and Kitunen, 2002).

5.2.8 Soil microbial biomass

The microbial biomass C (MBC) content of each aggregate size and density fractions were fumigated using chloroform (Vance et al. 1987). About 20 g of the samples was subjected to ethanol-free chloroform for 48 h and kept in the dark at 25 °C for 16 h. A non-fumigated sample of the same weight was subjected to similar conditions. About 50 mL of K_2SO_4 (0.5 M) was added to the two sets of samples and shaken for 30 min to obtain extracts. Carbon content of the extracts (MBC) was oxidized with Mn^{3+} and analyzed spectrophotometrically at 600 nm (Bartlett and Ross, 1988). The MBC contents were estimated using Eq. (5.1).

$$Microbial\ biomass - carbon\ (MBC) = \frac{SOC_{fumigated} - SOC_{non-fumigated}}{0.33} \tag{5.1}$$

5.2.9 Microbial respiration

About 10 g moist soil sample obtained from each plot at depth interval of 10 cm to soil profile 40 cm were separately measured in a vessel placed in a corked glass jar. A parafilm pricked with holes was used to cover the jars to allow for aeration during 7 days pre-incubation. After this period, the content was incubated for 7 days in the dark at 20°C. The evolved CO_2 was trapped in 15 mL sodium hydroxide (0.2 N) placed into an airtight glass jar. Precipitation of carbonate ions was done by adding excess barium chloride (1.5 M) to the sodium hydroxide solution and the excess sodium hydroxide titrated with hydrochloric acid (0.2 N) using phenolphthalein indicator. The CO_2 absorbed during handling and titration was corrected by the blank readings (Alef, 1995). The metabolic quotient (qCO_2) was calculated using Eq. (5.2):

$$qCO_2 (g\ biomass\ C)^{-1} d^{-1} = \frac{\mu g CO_2 C\ evolved\ in\ 7\ days\ (g\ soil^{-1})}{\mu g\ biomass\ C\ after\ 7\ days\ (g\ soil^{-1})} x\ 1000 \tag{5.2}$$

5.2.10 Estimation of enzyme activities

5.2.10.1 Fluorescein diacetate hydrolysis

Hydrolysis of fluorescein diacetate (FDA) was performed according to procedures outlined by Adam and Duncan (2001). About 2 g fresh soil (sieved, 2 mm) obtained from each experimental plot was separately transferred into a conical flask (50 mL) followed by 20 mL of K_3PO_4 buffered at pH 7.4. Addition of stock solution (FDA, 1000 µg/mL) was ensured to trigger the reaction. The flasks were stoppered, transferred to an orbital incubator subjected to temperature of 30°C and shaken at 120 rpm for 15 min. After their removal from the incubator, about 15 mL chloroform (2:1 v/v) was added to the samples to end the reaction. The content was centrifuged at 1000 rpm for 10 min, the overlying liquid filtered through Whatman paper No 2 and measured on a spectrophotometer at 490 nm. A calibration graph was used to extrapolate the concentration of fluorescein released during the assay.

5.2.10.2 Dehydrogenase activity

Dehydrogenase activity (DHA) was determined following procedures outlined by García et al. (1997). Briefly, air-dry soil sample of about 1 g maintained at 60% water holding capacity (WHC) was subjected to 0.2 mL of 0.4% INT (2-p iodophenyl-3-pnitrophenyl-5-phenyltetrazolium chloride). The content was placed in distilled water maintained at 20°C and kept off from light for about 20 h. The content was shaken vigorously for 1 min in 10 mL of methanol and filtered. The extract (iodo nitro tetrazolium formazan (INTF)) was spectrophotometrically measured at 490 nm.

5.2.11 Data analysis

The data was analyzed using version 3.5.2 of R software (R Core Team, 2017). Mixed model analysis of variance was used to test the treatment effects on soil organic matter fractions and microbial activity. Cropping system and agro-ecological zones were considered as fixed factors while the variables assessed (MBC, DOM, LFOM, HFOM, DHA, FDA, SMR, and qCO_2) were considered random factors. Tukey's honest significant difference (HSD) test was used for treatment mean separations with threshold probability level set at $p \leq 0.05$. Principal component analyses (PCA) were calculated to examine relationships between the SOM fractions (MBC, DOM, LFOM, and HFOM), microbial activity (DHA, FDA, SMR, and qCO_2), soil properties (soil temperature, soil moisture, soil texture and aggregate size), cropping systems and agro-ecological zones (UM, LH and UH).

5.3 Results

5.3.1 Distributions of rainfall and air temperature

The amount and distribution of rainfall and air temperature measured during this study period is shown in Fig. 5.2. In the short rains of 2016, total rainfall amount of 266, 312 and 416 mm was received respectively in the upper midland (UM), lower highland (LH) and upper highland (UH) agro-ecological zones. This is compared to 355, 575 and 581 mm recorded respectively during the 2017 long rains. The 2017 short rains totaled to 318, 355 and 412 mm respectively in the UM, LH and UH agro-ecological zones. These rains occurred mainly during the vegetative growth stage irrespective of the seasons and agro-ecological zones. Across the seasons, the air temperatures were higher in the UM (18.9–31.2°C), intermediate in the LH (13.6–28.1°C) and lowest in the UH agro-ecologiecal zones (11.7–21.3°C).

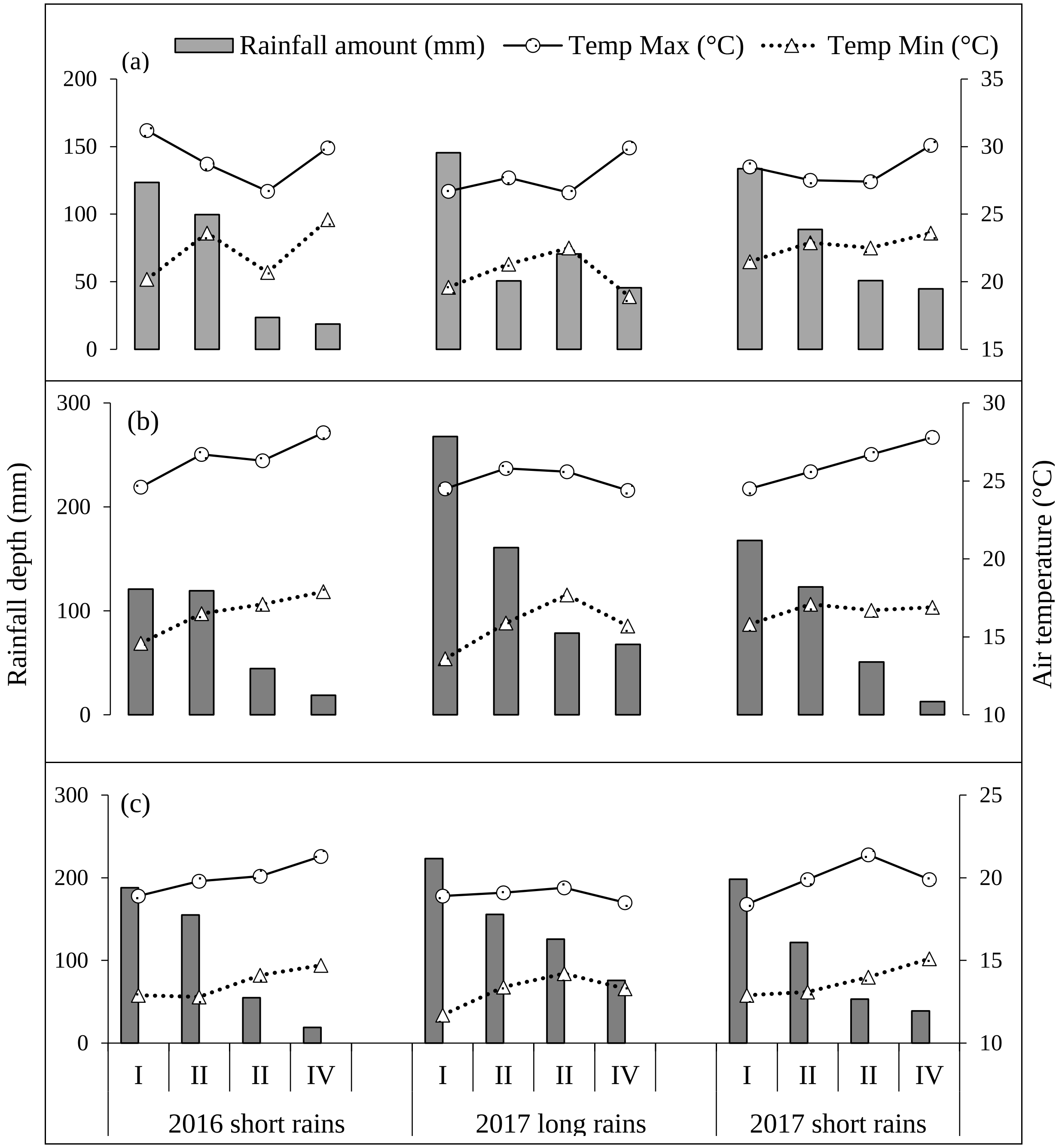


Figure 5.2: Rainfall and air temperature recorded for upper midland (a), lower highland (b) and upper highland agro-ecological zones at different potato development stages: sprout development (I), tuber initiation (II), tuber bulking (III) and tuber tuber maturation (IV).

5.3.2. Biomass accumulation and residue composition

Significant differences between the treatments were observed for cumulative shoot biomass which were greater in intercropping (3433–6640 kg ha^{-1}) and lowest in sole potato (1808–5250 kg ha^{-1}) across the agro-ecological zones (Table 5.2).

Table 5.2: Accumulative residue biomass, carbon and nitrogen supply, residue chemical composition and carbon to nitrogen ratio by different cropping systems.

Agro-ecological zone	Cropping system	Shoot DM	Root DM	Root C	Shoot C	Root N	Shoot N	Lignin	Polyphenol	Root C/N	Shoot C/N
						kg ha^{-1}					
Upper midland	Potato + dolichos	1811c	5271d	880c	699c	38.2b	38.2bc	69.4ab	19.4a	23.8a	18.9a
	Potato + lima bean	1573b	3433b	571b	592b	32.6b	26.3b	75.0bc	25.7a	24.4a	19.9a
	Sole dolichos	2432e	7502e	1125e	989e	64.1c	44.7c	52.9a	18.3a	26.3a	16.2a
	Sole lima bean	2312d	4852c	989d	769d	46.9b	38.6bc	66.2ab	23.6a	26.6a	16.9a
	Sole potato	389a	1808a	120a	311a	10.5a	2.4a	91.2c	29.1a	28.5a	25.0b
Lower highland	Potato + dolichos	2980b	6611d	1282c	933c	48.8b	52.5c	62.4b	21.3a	24.4a	19.1a
	Potato + lima bean	2880b	4840b	799b	795b	42.4b	31.3b	70.0c	24.8a	25.5a	19.7a
	Sole dolichos	3731c	8941e	1511e	1347e	80.8d	52.5c	45.4a	19.9a	28.8a	16.9a
	Sole lima bean	3611c	6290c	1339d	1065d	60.1c	49.8c	61.5b	23.6a	26.9a	17.7a
	Sole potato	746a	2850a	164a	423a	15.9a	5.5a	86.2d	27.1a	29.8a	26.5b
Upper highland	Potato + dolichos	3730c	5830c	1683c	799b	38.4b	67.3c	64.6b	21.4a	25.1a	20.1a
	Potato + lima bean	4681d	6640d	1121b	1113c	57.9c	63.3c	65.3b	23.2a	26.6a	19.2a
	Sole dolichos	1811a	4441a	2108e	678ab	35.9b	41.2b	51.4a	19.9a	26.6a	18.9a
	Sole lima bean	5411e	8091e	1947d	1491d	89.2d	75.7d	62.2b	20.6a	25.7a	16.7a
	Sole potato	2520b	5250b	228a	592a	21.4a	7.9a	83.6c	25.1a	28.8a	27.5b

Means followed by different letters within a column indicate significant differences by Tukey's $p \leq 0.05$.

Similar trend was observed for root biomass which ranged between 1573 and 4681 kg ha^{-1} in intercropping and 389 to 2520 kg ha^{-1} in sole potato. Lima bean exhibited significantly higher root and shoot biomass in the UH zone compared to dolichos. The reverse was observed in the UM and LH agro-ecological zones. The shoot and root carbon and nitrogen supplied were greatest in sole legumes, intermediate in intercropping and lowest in sole potato. Similar trend was observed for total lignin, polyphenol contents and C/N ratios.

5.3.3 Distributions of aggregate sizes and soil organic matter fractions

Aggregate distributions differed significantly between the treatments for the macro and micro-aggregates and were significantly greater in intercropping relative to sole potato stands (Fig. 5.3). For silt plus clay fractions, aggregate distributions showed statistical similarities among the treatments irrespective of the agro-ecological zones. Generally, for a given treatment, the distributions of aggregates were proportionally greater in silt plus clay size particles (43–53%) than in the micro (18–28%) and macro-aggregates (18–36%) irrespective of treatments.

The contents of light fraction organic matter (LFOM), microbial carbon (MBC) and dissolved organic matter (DOM) were significantly greater in macro-aggregate, intermediate in micro-aggregate and lowest in silt plus clay particles irrespective of the treatments (Fig. 5.4). In the UM and LH agro-ecological zones, potato-dolichos intercropping recorded significantly higher contents of LFOM, MBC and DOM in the macro and micro aggregates compared to sole potato and potato-lima bean intercropping. This trend was reversed in the UH where significantly higher contents of LFOM, MBC and DOM within the micro-and macro aggregates were found in potato-lima bean intercropping. Taken together, the LFOM within the macro-aggregates accounted for 39–55% of the total SOM, this was followed by DOM within the macro-aggregates (22–38%) and MBC which comprised 5–9.6% of the total SOM.

For the HFOM, highest contents of organic matter were recorded in silt plus clay followed by micro-aggregate and lowest in the macro-aggregates. This aggregate fraction exhibited statistically similar organic matter content between the treatments irrespective of agro-ecological zones.

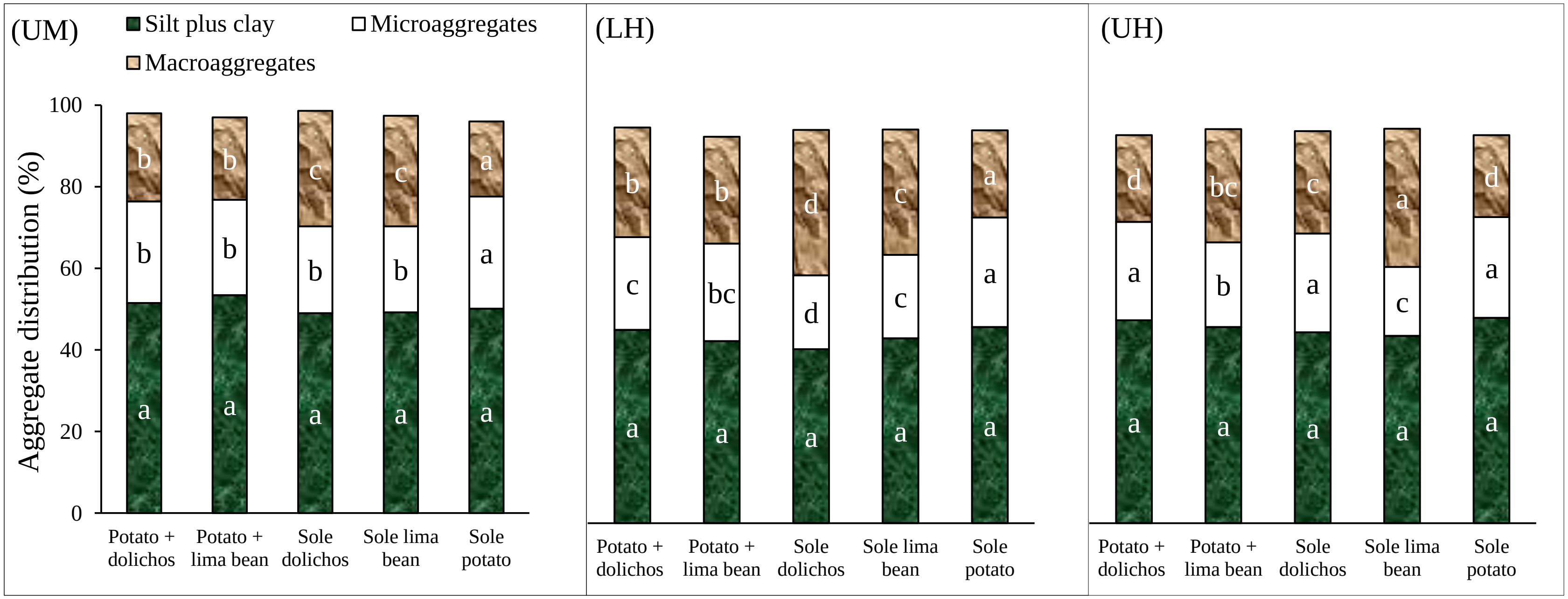


Figure 5.3: Soil aggregate distribution (0–40 cm depth) at the end of the study under different cropping systems and agro-ecological zones (upper midland (UM), lower highland (LH), upper highland (UH). Bars with different letters within an aggregate class are significantly different at Tukey's $p \leq 0.05$.

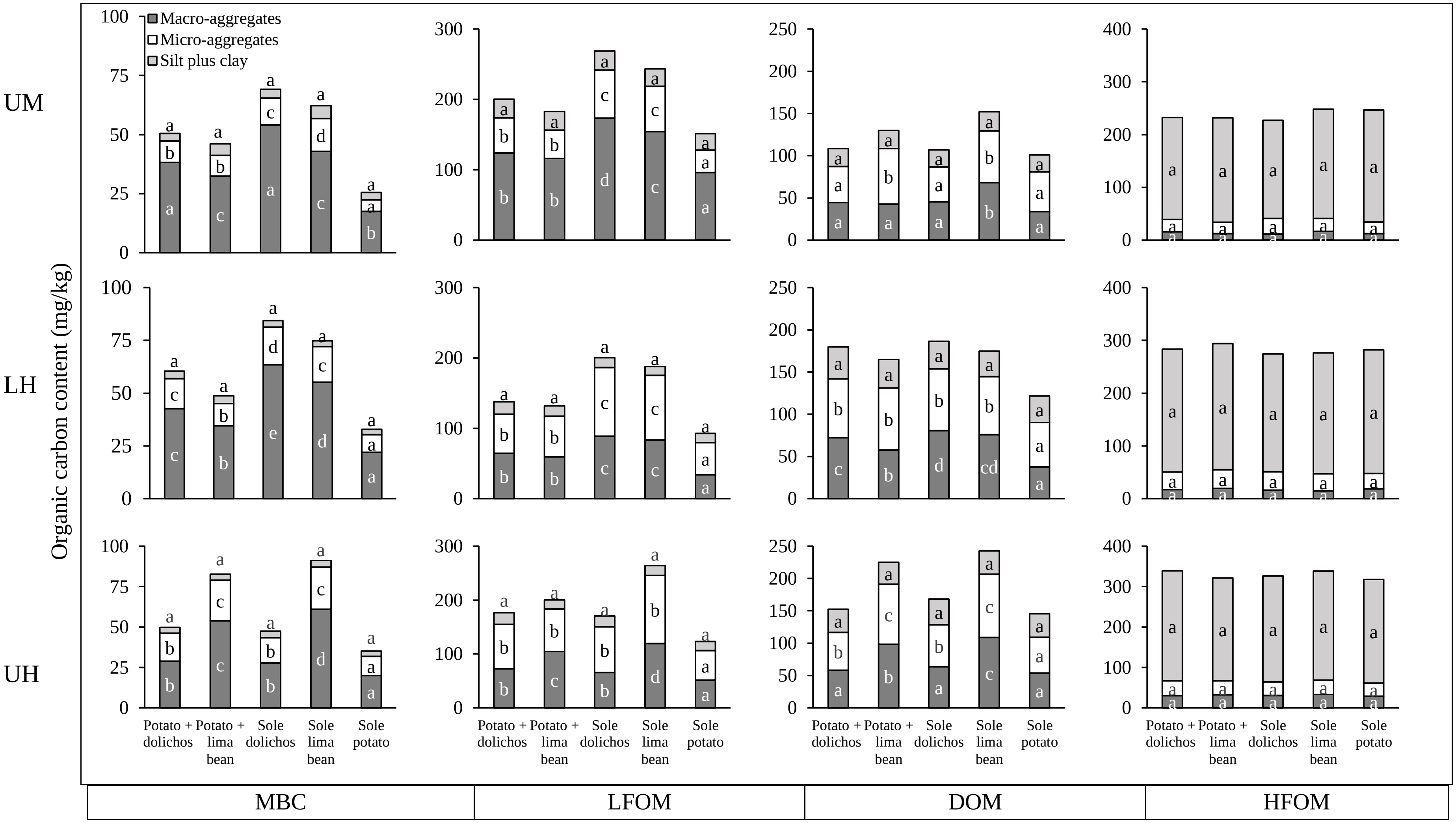


Figure 5.4: Distributions of SOM fractions (Microbial biomass carbon-MBC, light fraction organic matter-LFOM, dissolved organic matter-DOM, and heavy fraction organic matter-HFOM) within aggregate classes (μm) under different cropping systems and agro-ecological zones. Bars with different letters for a given aggregate-size differ significantly between treatments (Tukey's $p \leq 0.05$).

5.3.4 Effect of cropping systems and sampling depths on distributions of SOM fractions

Labile fractions of SOM (MBC, LFOM and DOM) varied significantly among the treatments and were consistently greatest in sole legumes, intermediate in intercropping and lowest in sole potato (Table 5.3).

Table 5.3: Soil organic matter fractions: heavy fraction organic matter (HFOM), light fraction organic matter (LFOM), dissolved organic matter (DOM) and microbial biomass carbon (MBC) measured in soil depth 0–40 cm under different agro-ecological zones.

Soil depth (cm)	Cropping system	Upper midland				Lower highland				Upper highland			
		HFOM	LFOM	DOM	MBC	HFOM	LFOM	DOM	MBC	HFOM	LFOM	DOM	MBC
		mg C kg^{-1}											
0–10	Potato + dolichos	423a	412b	335b	198c	515a	682b	501b	288b	525a	606a	635b	203a
	Potato + lima bean	409a	487b	346b	106b	508a	646b	512b	279b	546a	922c	774c	309b
	Sole dolichos	432a	584d	445c	242d	525a	806c	673c	315c	520a	729b	633b	228a
	Sole lima bean	408a	509c	432c	208c	491a	813c	605c	292b	551a	983bc	750c	402c
	Sole potato	401a	298a	240a	98a	488a	435a	334a	102a	549a	564a	417a	212a
10–20	Potato + dolichos	432a	432b	301c	167bc	514b	566b	399b	222b	508a	529b	315c	115a
	Potato + lima bean	443a	420b	246b	154b	500b	542b	388b	123b	522a	795c	444b	300b
	Sole dolichos	408a	501c	330d	208d	522b	694d	482d	301d	494a	524b	434b	134a
	Sole lima bean	431a	407b	319d	174c	443a	603c	410c	254c	501a	884c	354c	339b
	Sole potato	399a	168a	184a	32a	439a	259a	245a	63a	445a	318a	319a	108a
20–30	Potato + dolichos	389a	323b	169c	102b	465b	465b	234c	157b	434b	437c	247b	108b
	Potato + lima bean	383a	312b	145b	89b	456b	471b	208b	141b	508b	591d	295b	228c
	Sole dolichos	392a	387b	189c	167c	479b	601d	279d	240c	456a	304b	105a	98b
	Sole lima bean	387a	356b	139b	153c	462b	504c	267d	209c	525b	604d	241b	293d
	Sole potato	366a	106a	98a	19a	402a	162a	108a	51a	418a	201a	101a	40a
30–40	Potato + dolichos	376a	202b	133c	76d	436a	329b	186b	102b	411a	264b	159a	52a
	Potato + lima bean	367a	189b	121c	45b	414a	301b	169b	82b	465a	275b	210b	129bc
	Sole dolichos	387a	245c	129bc	89d	442a	378b	199b	141c	432a	301c	146a	103b
	Sole lima bean	354a	234c	116b	64c	406a	342b	187b	96b	467a	424d	207b	143c
	Sole potato	343a	87a	96a	18a	400a	143a	101a	49a	448a	165a	167a	45a

Means with different letters within a column and soil depth denote significant differences (Tukey’s $p \leq 0.05$), ns, not significant.

Heavy fraction organic matter (HFOM) however showed statistical similarities between the treatments and ranged between 343 and 551 mg C kg^{-1} across the agro-ecological zones and sampling depths. General decrease in SOM contents with increasing soil depth was observed irrespective of the treatments and agro-ecological zones. Cropping systems, soil depth and their interactions had highly significant ($p < 0.001$) effect on labile fractions of SOM. The HFOM was affected by sampling depth, but not by cropping system.

5.3.5 Microbial biomass carbon to total SOC ratio

Carbon to nitrogen ratio of microbial biomass and total SOM (MBC/SOC) were significantly influenced by cropping systems and generally decreased with increasing soil depth (Table 5.4).

Table 5.4: Microbial biomass carbon (MBC) to total soil organic matter carbon (SOMC) ratio as influenced by cropping systems in soil profile 0–40 cm under different agro-ecological zones.

	Upper midland				Lower highland				Upper highland			
Soil depth (cm)	0–10	10–20	20–30	30–40	0–10	10–20	20–30	30–40	0–10	10–20	20–30	30–40
	MBC to SOMC ratio											
Potato + dolichos	4.8cd	4.1cd	3.7b	3.5c	5.2bc	4.5c	4.3b	4.1b	4.4a	3.7b	3.5b	3.3b
Potato + lima bean	4.5bc	3.8b	3.6b	3.4bc	5.0b	4.2b	4.1b	3.9b	5.6b	5.1d	4.6c	4.2c
Sole dolichos	5.2e	4.5e	4.1c	3.3b	5.5c	4.8d	4.6c	4.4c	4.2a	3.1a	3.0a	2.9a
Sole lima bean	4.9de	4.3de	3.9bc	3.2b	5.0b	4.6cd	4.3bc	4.0b	5.8b	5.1d	4.8c	4.4c
Sole potato	3.8a	3.1a	2.9a	2.5a	4.1a	3.4a	3.2a	2.9a	4.3a	4.1c	3.2a	3.0ab

Means with different letters within a column denote significant differences (Tukey's $p \le 0.05$).

The ratios were significantly greater in intercropping relative to sole potato irrespective of the agro-ecological zones. In the UM and LH agro-ecological zones, dolichos recorded notably higher MBC/SOC ratio compared to lima bean, a trend that was reversed in the UH agro-ecological zone. The ratios generally tended to level off at 30–40 cm soil depth.

5.3.6 Microbial activities

Microbial activities measured by soil microbial respiration (SMR), metabolic quotient (qCO_2), fluorescein diacetate (FDA) and dehydrogenase (DHA) hydrolyses, differed significantly ($p < 0.01$) between the treatments (Table 5.5).

Table 5.5: Soil microbial respiration (SMR-mg kg^{-1} d^{-1}), metabolic quotient (qCO_2- mg CO_2-g biomass C^{-1} d^{-1}) and enzyme activities (fluorescein diacetate hydrolysis (FDA-g FDA/g)) and dehydrogenase (DHA-INTF/g) in response to cropping systems and soil depth under different agro-ecological zones.

Soil depth (cm)	Cropping System	Upper midland				Lower highland				Upper highland			
		FDA	DHA	SMR	qCO_2	FDA	DHA	SMR	qCO_2	FDA	DHA	SMR	qCO_2
0–10	Potato + dolichos	111.8b	50.4b	20.3c	44.5	130.8c	68.9c	25.5bc	42.2b	101.2a	50.9b	18.2a	40.1b
	Potato + lima bean	108.8b	49.2b	16.6b	44.1b	116.9b	58.6b	22.2b	41.8b	136.6b	69.9c	24.6b	38.4a
	Sole dolichos	148.9d	58.9c	22.2c	40.4a	154.8d	79.6e	28.6c	38.9a	97.2a	40.8a	17.7a	41.1bc
	Sole lima bean	133.6c	56.8c	20.3c	43.5b	137.3c	70.4d	25.8b	39.2a	148.8b	79.9d	28.9b	38.2a
	Sole potato	88.7a	35.5a	12.2a	48.9c	89.1a	42.8a	15.9a	45.6c	105.2a	53.6b	18.9a	42.2c
10–20	Potato + dolichos	98.7b	48.6c	15.5b	40.4a	120.1b	60.8b	22.3bc	40.4b	96.7a	41.1a	15.5a	39.9b
	Potato + lima bean	90.3b	44.4b	15.1b	42.4b	114.7b	55.7b	19.5b	40.1b	131.3b	65.3b	23.4b	37.7a
	Sole dolichos	133.7c	52.8d	18.9c	39.8a	144.5c	77.6d	25.2d	37.7a	93.2a	36.1a	16.6a	40.2b
	Sole lima bean	128.2c	49.7cd	17.8c	39.2a	137.8c	68.2c	23.3cd	38.7a	139.9b	73.8b	24.7b	37.4a
	Sole potato	80.5a	30.2a	9.1a	44.4c	84.8a	36.7a	10.3a	43.9c	97.8a	45.7a	16.2a	40.4b
20–30	Potato + dolichos	88.6b	44.7b	12.4c	39.1b	113.6b	52.8bc	17.4bc	37.3b	90.1a	40.5a	15.4bc	38.2b
	Potato + lima bean	82.3b	42.6b	9.4b	40.2b	99.7b	48.9b	15.5b	38.2b	128.3b	63.3b	18.8cd	38.1b
	Sole dolichos	121.5d	48.6c	13.4c	35.5a	131.9c	63.4d	20.2d	35.8a	86.7a	33.7a	13.4a	39.3bc
	Sole lima bean	110.6c	44.4b	12.1c	36.6a	108.5b	54.8c	18.8cd	35.7a	131.9b	67.9b	20.3d	35.2a
	Sole potato	70.6a	25.7a	7.2a	43.1c	73.8a	29.7a	9.9a	40.8c	88.9a	38.8a	13.9a	40.3c
30–40	Potato + dolichos	83.7c	38.8cd	11.9c	36.6b	90.3b	45.7bc	13.3b	37.1b	75.9a	37.9b	12.8a	37.7b
	Potato + lima bean	70.0b	34.6b	8.2b	37.5b	84.7b	42.4b	11.1b	37.4b	121.7c	54.7c	16.4b	37.6b
	Sole dolichos	102.8c	40.9d	11.8c	34.4a	107.7c	55.4d	16.6b	35.1a	85.8b	27.9a	12.3a	38.2b
	Sole lima bean	94.6c	36.8bc	9.1b	36.6b	103.5c	48.7c	14.4b	36.6a	127.5c	58.8c	17.9b	34.1a
	Sole potato	55.9a	22.4a	6.3a	40.4c	72.6a	25.7a	7.8b	39.4c	74.2a	28.1a	10.4a	39.5b

Means with different letters within a column and soil depth denote significant differences (Tukey's $p \leq 0.05$), ns, not significant.

Contents of FDA and DHA in the soil were significantly greater in sole legume plots than in intercropping and lowest in sole potato plots irrespective of agro-ecological zones. The enzyme activities generally decreased with increasing soil depths and were variable across agro-ecological zones. In the UH and LH agro-ecological zones, the FDA and DHA hydrolyses were greatest in sole dolichos and lowest in sole potato plots across the four soil depths. This trend was reversed in the UH agro-ecological zone where sole lima bean recorded significantly higher FDA and DHA contents relative to dolichos.

Soil microbial respiration (SMR) followed similar trend to that of FDA and DHA with sole potato plots consistently showing the lowest value across sampling depths and agro-ecological zones. Metabolic quotient (qCO_2) was significantly greatest in sole potato, intermediate in intercrops and lowest in sole legumes regardless of sampling depth. Across agro-ecological zones, both cropping systems and soil depth had significant effect on qCO_2. All the microbial activity parameters were notably higher in the UH than in the LH and were lowest in the UM agro-ecological zone.

5.3.7 Principal component analyses of factors influencing soil organic matter dynamics

Principal component analyses showing factors influencing SOM dynamics is presented in Fig. 5.5. The two principal components explained 74% of the variability in SOM fractions with the first component accounting for 56% of the variance and the rest (18%) being accounted for by the second component. The first component was strongly correlated with 10 of the original variables ($p = 0.000$) and most strongly with the microbial biomass carbon-MBC ($r = 0.98$). This component was therefore a measure of soil microbial biomass content and increased with increasing dissolved organic matter-DOM ($r = 0.80$), fluorescein diacetate-FDA ($r = 0.80$), dehydrogenase activity-DHA ($r = 0.78$), soil water content-SWC ($r = 0.70$), light fraction organic matter-LFOM (r = 0.65), metabolic quotient-qCO_2 (r = 0.61) and microbial respiration-SMR (r = 0.55), but negatively with clay content (r = −0.96), aggregate size (r = −0.94), agro-ecological zone (r = −0.80) and soil temperature (r = −0.57). The second component was majorly a reflection of cropping system (r = 0.66), which related strongly with metabolic quotient-qCO_2 (r = −0.60), soil temperature (r = −0.58), soil water content-SWC (r = 0.50) but weakly with FDA (r = −0.49), agro-ecological zone (r = −0.49), DOM (r = 0.47) and DHA (r = −0.38).

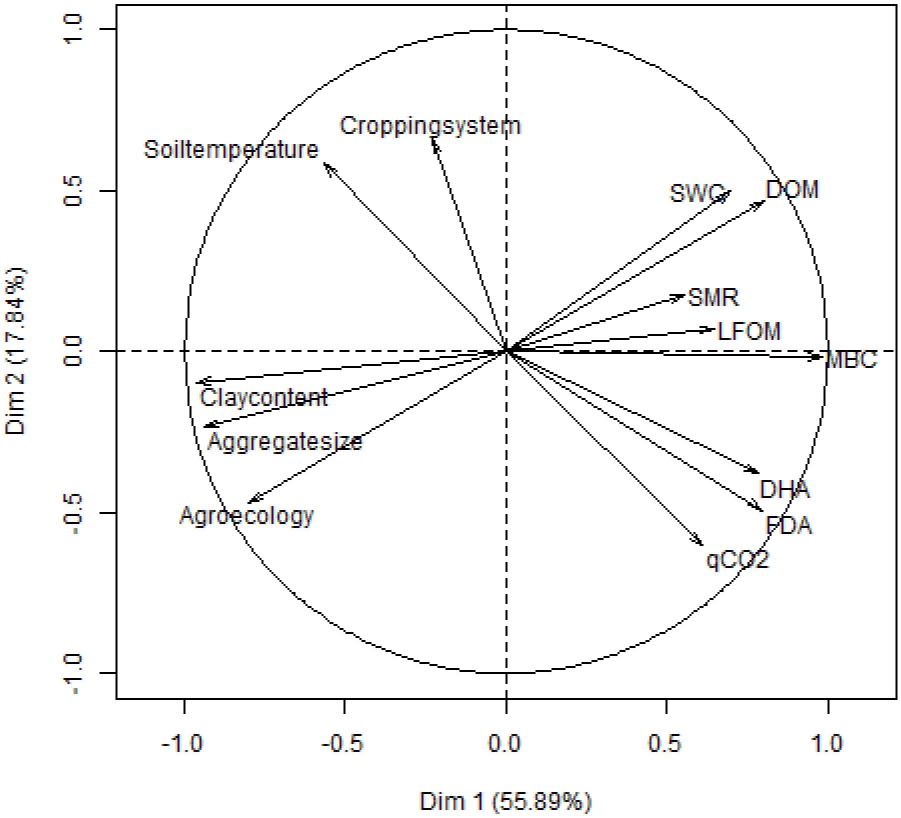


Figure 5.5: Principal component analyses of factors influencing SOM dynamics in potato-legume intercropping. SWC, soil water content, DOM, dissolved organic matter, LFOM, light fraction organic matter, MBC, microbial biomass carbon, qCO_2, metabolic quotient, FDA, fluorescein diacetate, DHA, dehydrogenase activity, SMR, microbial respiration. Vectors indicate the degree of correlation between each factor and the axes.

The interrelationship of the components revealed a direct positive association between soil FDA, DHA and MBC. Soil DHA however exhibited a weaker correlation with LFOM, MBC and DOM compared to soil FDA. There was a significant positive association between qCO_2, soil DHA and FDA hydrolysis. Further, there was a positive association between the aggregate sizes with soil labile organic matter fractions (LFOM, MBC and DOM), but a negative correlation exhibited between the clay content, microbial biomass and SMR. The activity of DHA, soil FDA hydrolysis and SMR related negatively with soil temperature, but positively with soil moisture content.

5.4. Discussions

5.4.1. Distributions of aggregate sizes and soil organic matter fractions

The high variability in sizes of macro-aggregate distributions between the treatments reflected greater effect of residue retention on sand fractions relative to micro-aggregate and silt plus clay fractions. Intercropping provided readily-degradable substrates which were decomposed by the soil microbes releasing cementing agents that glued the soil particles to form micro-aggregates. The micro-aggregates were then bound with SOM and silt plus clay particles to form macro-aggregates. This effect was influenced by residue quantity that was higher in intercropping than in sole potato. When the residue supply by legume intercropping attained a threshold level, most of it remained unprotected and was highly accessible to degrading soil microbes and their enzymes. This triggered residue degradation fostering aggregate formation. This process signified improved soil physical quality such as nutrient exchange, soil water movements and aeration (Jäger et al. 2011). These conditions were favorable for microbial growth and activities.

The content of microbial biomass differed significantly among the size fractions, a reflection that different aggregate classes provided distinct microhabitats packed with organic carbon of different qualities and quantities. The macro-aggregates had the greatest contents of MBC suggesting high population of soil microorganisms. In addition, the macro-aggregates had the highest MBC/SOC ratio irrespective of the cropping system indicating high efficiency by which the soil microbes used the carbon substrates (Anderson and Domsch, 2010). A possible reason for this observation relates to the fact that the macro-aggregate size fraction is composed primarily of partially decomposed litter that provided sources of energy to the microorganisms. Intercropping increased the contents of MBC by inputting large quantity of litter and roots thus enhancing accumulation of DOM and LFOM which provided sources of nutrition to soil microorganisms. This observation is in keeping with other studies that found high diversity, functionality and spatial distribution of fungi and bacterial populations within the macro-aggregates (Poly et al. 2001; Mummey et al. 2006). They attributed it to the fact that macro-aggregates exhibit high stability of soil water potential and are physically protected from the predators.

The microbial biomass was however significantly greater in intercropping relative to sole potato for the macro-aggregate fractions. This observation is consistent with the biomass quantity and quality which was higher in intercropping than in sole potato. The residues from legume intercrops had higher nitrogen content that increased the supply of nutrients to the soil microbes. Generally, the microbial biomass is activated by continuous addition of substrates, resulting in increased production of extra-cellular enzymes that enhance the microbial activity (Loeppmann et al. 2016). This observation was depicted in our study which showed increasing fraction of MBC which had preferential use for soil labile organic carbon as source of energy. Rasmussen and Rohde (1988) showed that low residue return to the soil results in nitrogen immobilization that adversely impacts on the microbial population density and diversity. Moreover, the soil particles obtained from intercropping had greater MBC/SOC and exhibited lower metabolic quotient (qCO_2) relative to those in the sole potato. This indicates that legume intercropping fostered the growth of soil microorganisms and enhanced the efficiency by which the substrates were used as energy sources.

The silt plus clay fractions had the least MBC/SOC regardless of the treatments indicating the lowest carbon use efficiency. This observation was ascribed to the low SOM accessibility contributed by sorption of carbon on the clay colloids.

The high contents of light fraction organic matter (LFOM) within the macro-aggregates was a reflection of high residue transformation following addition of fresh residue to the soil. This fraction resided within the macro-aggregates which remained unprotected by physical mechanisms thus allowing accessibility of degrading microorganisms and their enzymes. Due to the fact that potato had relatively higher lignin and polyphenol concentrations and exhibited higher C/N ratios, we expected to find higher contents of partially decomposed litter (LFOM) in sole potato plots. This was not the case as intercropping generally exhibited higher LFOM contents. This observation is inferred to the low residue deposition by potato that stimulated breakdown of the more resistant litter transforming it into refined dissolved organic matter (DOM). Intercropping however exhibited low quantity of polyphenols and lignin compounds and had lower C/N ratios making their residues to undergo rapid decomposition with increased partitioning of organic matter to the less protected macro-aggregates.

In contrast, the LFOM and DOM content attached to clay plus silt fractions was similar between the treatments implying that these fractions were not affected by legume intercropping. For the micro-aggregates, the SOM was encapsulated within the macro-aggregates making it more protected by physical mechanisms and was thus more stabilized and resistant to further decomposition. Similarly, no response to legume intercropping was observed for the heavy fraction organic matter (HFOM) attached to the silt plus clay fractions as these particles exhibited charged surfaces that adsorbed the SOM making it physically, chemically and biochemically protected from the microbial attack (Six et al. 2002). This fraction represented >90% of the silt plus clay fractions reiterating the importance of these particles in carbon stabilization.

The contents of labile SOM fractions (LFOM, MBC and DOM) were significantly higher in the surface soil layer (0–10 cm) irrespective of the treatments. This observation was related to the high residue concentrations within the topsoil as the hand hoes had limited capacity to incorporate the residues beyond this depth. This is consistent with other authors who argued that the more labile SOM largely depend on the tillage depth and the quantity of organic residues incorporated (Somasundaram et al. 2018). Compared to sole potato, intercropping recorded significantly higher contents of labile SOM fractions (LFOM, MBC and DOM) in the 30 to 40 cm depth, an observation we related to the high root biomass contributed by legume intercrops. Generally, up to half of the labile SOM is found in the roots (Gregory and Atwell, 1991). The fact that roots are produced directly within the microbial habitat (Merino et al. 2015), may have triggered interactions that directly affected the structure and function of decomposer organism, potentially enhancing MBC biomass. In addition, roots exude labile soil carbon compounds that promote efficiency of microbial growth resulting in increased production of MBC (Kong et al. 2011).

Despite the general decrease in HFOM with depth across the treatments, only a slight variation was observed between treatments. This was a confirmation that this organic matter fraction is bio-chemically stabilized and resistant to further decomposition, irrespective of soil depth. Nyawade (2015) postulated that HFOM generally decreases with increasing depth due to the increasing contents of Al and Fe-oxides in soils dominated by kaolin minerals such as those in this study.

5.4.2. Effect of legume intercropping on soil microbial activity

The fluorescein diacetate hydrolysis (FDA) was increased by legume intercropping suggesting enhanced microbial activities. This observation relates to the high residue deposition and transformation that occurred in these plots thus providing large energy source to the soil microbes. A similar result measured for dehydrogenase (DHA) revealed a higher microbial activity which likely was contributed by the high flux of root secretions and root exudates in the plant rhizosphere (Rakshit et al. 2012). Soil DHA and FDA hydrolysis decreased under sole potato stands suggesting a negative impact of low residue quantity on soil microbiological activity. This was probably a consequence of low energy sources for the microbial activity as reflected by the low contents measured for LFOM, DOM and MBC. Reddy et al. (2003) reported greater microbial activity as measured by FDA in soils planted with crimson legume clover for three years relative to soils subjected to non-legume rye cereal. Consistent findings were reported by Sicardi et al. (2004) who suggested that the labile SOM fractions provide readily source of energy to the soil microbes leading to enhanced microbial activity. It is for this reason that this fraction of organic matter is considered the most sensitive indicator of soil quality (Kapkiyai et al. 1999).

The high soil respiration under legume intercropping was an indication of increased rate of organic matter transformation by soil microbes. This observation was further reflected in the low metabolic quotient (qCO_2) under legume intercropping pointing to the increased microbial respiration. As soil microorganisms breakdown residues, carbon becomes incorporated into the microbial biomass, and makes integral component of MBC, a process which is slowed by high C/N ratio (Chen et al. 2014). A mixture of high and low quality residues like in this study enhances microbial activity, causing a larger carbon proportion to be incorporated into microbial biomass (Müller-Stöver et al. 2012). This enhances the efficiency by which the soil microbes convert the organic carbon into microbial biomass (Anderson and Domsch, 1990). In the UH agro-ecological zone, the unfavorable climatic conditions for dolichos growth led to lesser input of litter thus contributing to the low soil MBC content which increased the qCO_2 and lowered the microbial respiration rates.

The decrease in microbial activity with increasing soil depth was consistent with that of the substrate availability that were high in the topsoil and steeply decreased with soil depth. Topsoil represented the dynamic nexus where majority of shoot biomass was deposited. For sole potato, root biomass was found entirely in the topsoil and thus maximum plant carbon allocated to rhizodeposition was expected in this zone (Canarini and Dijkstra, 2015). In other studies, fungal evenness and richness have been shown to be high in the topsoil and drastically decrease with increasing soil depth (Jumpponen et al. 2010; Vargas-Gastelum et al. 2015). This is in line with other studies that showed that subsoils accommodate only a specific type of soil microbes that are well adapted to the low substrate conditions (Hartmann et al. 2009). Further, the content of labile SOM that readily avails the substrates to the soil microbes was high in the topsoil compared to the subsoil that was dominated by HFOM that restricted the accessibility of substrates by the soil microbes.

The significant interactive effect observed between soil depth and agro-ecological zone on FDA hydrolyses, DHA activity and SMR reflected the variability in soil microbial activity contributed by agro-ecological conditions and soil types. The soils in LH agro-ecological zone were clay dominating and generally exhibited increase in clay content with increasing depth. Thus, sorption of SOM to the Al and Fe-oxides may have restricted the substrate availability, especially in the deeper soil layers. This environment disfavored the microbial growth, restricting their activity. In the UH agro-ecological zone, the high rainfall amounts repeatedly created water-saturated conditions in the subsoils that lowered the availability of oxygen. This coupled with increase in Fe and Al oxides that formed mineral-organic associations with the SOM (Dietel et al. 2017), impaired the substrate availability for the soil microbes decreasing their activity. In the topsoil, the high biomass contents may have favored the activity of fungi contributing to increased microbial activity (Engelhardt et al. 2018).

5.4.3 Principal factors influencing dynamics of SOM fractions

The fluorescein diacetate hydrolysis (FDA) and dehydrogenase activity (DHA) were directly proportional to the microbial biomass, an observation that was related to the high residue quantity contribution by legume intercrops (Schnurer and Rosswall, 1982). This is consistent with previous studies that showed that production of DHA and FDA hydrolysis increases with increase in residue deposition thus reflecting the increase in microbial enzymatic activity (Elfstrand et al. 2007). On the other hand, soil DHA and FDA hydrolysis exhibited positive association with LFOM and DOM reflecting that the total activity of microorganisms highly depended on light SOM fractions as their source of nutrition. García-Gil et al. (2000) described DHA as an intracellular enzyme useful for microbial oxidoreductase metabolism. The activity of this enzyme highly depends on the microbial biomass metabolic state which increases with increase in residue quality and quantity. Soil DHA however provided a weaker correlation with LFOM, MBC and DOM compared to soil FDA suggesting that the contribution of crop residues to microbial biomass activity affected greater mass of fungi as DHA does not reflect the fungal population (Kumar and Tarafdar, 2003).

The significant positive association between qCO_2, soil DHA and FDA hydrolysis reflected increase in efficiency of carbon assimilation by the soil microbes per unit amount of organic residue increase. Thus, the decrease in qCO_2 observed under legume intercropping relative to sole potato plots signified a greater metabolic efficiency of the substrate contributed largely by increase in residue quality. The positive association between the aggregate sizes with soil labile organic matter fractions (LFOM, MBC and DOM), cropping systems and SMR indicated that the enhanced residue retention promoted the macro-aggregate formation thus enhancing microbial activity. The negative correlation exhibited between clay content and the microbial biomass as well as with SMR showed that the high clay content impeded the SOM mineralization by physically occluding the microbes in small pores (Rutherford and Juma, 1992), thus repressing their activity.

The activity of DHA, soil FDA hydrolysis and SMR related negatively with soil temperature but positively with soil moisture content implying inhibitory and stimulatory effects of high temperatures and increased soil moisture contents on microbial activity. Under extremely dry soil conditions, soil microbes are rapidly ‘starved’ because a dry soil does not have enough substrate supply, and is characterized by unfavorable microenvironment for microbial growth (Murphy et al. 1998). Steinweg et al. (2012) found soil temperature to be the dominant control of enzymatic activity when soil moisture was not limiting. Chavarría et al. (2016) similarly postulated that soil moisture and soil temperature are the major regulators of soil enzymatic activity at micro-plot scale.

Agro-ecological zone exhibited significant association with microbial biomass, aggregate sizes and SMR reflecting spatiotemporal variability caused by fluctuating soil temperatures and soil moisture contents. Temporal changes in soil moisture contents and soil temperature affect the amount of carbon allocated to rhizodeposits and secretions of rhizosphere products that cement soil particles into macro-aggregates (Bonde and Rosswall, 1987). The quantity of residue generation and nutrient transformation by soil microbes were besides highly dependent on the prevailing soil moisture and soil temperature conditions. Dolichos due to its inability to tolerate low temperatures in the UH agro-ecological zone (Cook et al. 2005), was characterized by reduced biomass production. This crop however, accumulated about 2 times higher biomass compared to lima bean in the UM zone and up to 5 times higher compared to sole potato. Lima bean however, tolerated both low and high soil temperatures and accumulated high biomass across the agro-ecological zones. Potato being a temperate crop performed best in the UH zone where its biomass accumulation was highest. Previous work found that agro-ecological zone influences crop selection for biomass production in such a way that crop varieties are acclimatized to the zones favoring growth conditions (Jaetzold et al. 2012). Van Gestel et al. (1993) observed a parallel course of MBC content when increase in ambient temperatures caused desiccation to the soil microbes thus interrupting their growth.

5.5 Conclusion

This study gives an insight on the potential role of legume intercropping in increasing residue return thus enhancing the formation of labile soil organic matter fractions with little impact on the stable fractions. The increase in residue retaintion due to legume intercropping increased the proportion of macro-aggregates that signified improved nutrient release, high aeration and increased soil water infiltrations, the conditions of which are favorable for microbial growth and activities. These benefits may only be of primary importance to the smallholder farmers if the system is designed in a manner guaranteeing high yield stability. In this way, the ultimate goal of enhanced soil productivity will be masked, but earned by the farmer as a bonus.

CHAPTER SIX

OPTIMIZING SOIL NITROGEN BALANCE IN A POTATO CROPPING SYSTEM THROUGH LEGUME INTERCROPPING

Abstract

Negative nitrogen balance represents a major factor causing low potato yield in potato growing areas of Kenya while its excessive surplus poses a significant environmental concern. In order to synchronize this tradeoff, a field trial integrating potato (*Solanum tuberosum* L.) with lima bean (*Phaseolus lunatus* L.) or dolichos (*Lablab purpureus* L.) in intercropping system was conducted in the upper midland (1552 m above sea level (masl), lower highland (1894 masl) and upper highland (2552 masl)) agro-ecological zones of Kenya. The study was laid out in a randomized complete block design with four replications. Soil samples (0–120 cm depths) were taken from each plot at key stages of potato growth. Nitrogen gains from mineralization, fertilization, biological fixation, and outputs from biomass accumulation, leaching, volatilization, runoff and soil erosion were quantified using standard procedures. Soil N balance ranged from -10.7 to -18.1 kg N ha^{-1} for sole potato, 4.1 to 6.6 kg N ha^{-1} for intercropping and 2.9 to 22.3 kg N ha^{-1} for sole legumes. The intermediate range of polyphenol and lignin contents in intercropping enhanced N mineralization with peak N release showing a close synchrony of N supply and potato crop N demand. Nitrate being highly mobile, was quickly leached below the active root zone in sole potato (4.2 to 46.6 kg N ha^{-1}), a process that was diverged by the deep root systems of legume intercrops (amount of N leached, 1.1 to 24.0 kg N ha^{-1}). These results suggest that legume intercropping can provide a means of balancing the nitrogen retained in the biomass and soil, thus offering a mechanism for optimizing the soil N balance in smallholder potato farming systems.

Keywords: Legume intercropping; nitrogen balance; nitrogen mineralization; nitrogen uptake.

6.1 Introduction

Nitrogen is one of the most important nutrients constraining potato production in the subtropical smallholder farming systems (Sanchez 2002; Henao and Baanante 2006; Burke 2017). The N balances in these systems are on average negative as the N outflows often exceed the N inflows. The N inflows in a potato production system are majorly from inorganic fertilizers, organic manures or additions through biological nitrogen fixation where legumes are integrated in rotation or intercropping systems (Jégo et al. 2008; Shekofteh et al. 2013). The outflow processes include N removal by soil erosion and in harvested biomass, denitrification during prolonged periods of wet soil, and volatilization of ammonia (NH_3) in high pH soils after surface granular urea application (Loomis and Connor, 1992). Leaching occurs mainly where nitrates leave the soil in drainage water (Arregui and Quemada, 2006).

Defining an appropriate fertilizer application rate that matches N supply with crop N demand is thus necessary in smallholder potato farming systems to avoid N mining. This is only possible if knowledge of the quantity of N that will be supplied by the crop residues is known. This process is defined by the soil temperature and soil water contents, residue chemical composition: lignin (L), polyphenol (P), carbon (C), nitrogen (N) and their ratios such as C-to-N, L-to-N, and L + P-to-N (Palm and Sanchez, 1991; Tian et al. 1993; Becker and Ladha, 1997; Mitchell et al. 2000). Where decomposed organic matter exhibits high C-to-N, lignin-to-N, and polyphenol-to-N ratios, N supply will not be sufficient to satisfy N requirements of soil microorganisms, resulting in net N immobilization (Lupwayi and Haque 1999; Lupwayi et al. 2006). The production and retention of available N often increases with increasing soil moisture and soil temperature to a threshold and thereafter declines (Baldock et al. 2018).

In Kenya, the low soil N content is aggravated by the poor potato cropping systems that majorly entail sole cropping with limited capacity to provide adequate soil cover and protect soil from erosion (Muthoni et al. 2013; Nyawade et al. 2018b; Gitari et al. 2018b). The nitrogen input not assimilated by potato crop accumulates in the soil as nitrate that is leached through irrigation and rainwater or lost through volatilization or denitrification (Gentile et al. 2009). To compensate for these N losses, a number of commercial farms have opted to do heavy application of inorganic N fertilizer (Kimetu et al. 2006; Muthoni et al. 2013). This strategy is too expensive for the smallholder farmers and may contribute to increased environmental pollution through eutrophication. In addition, majority of potato produced in Kenya is rainfed and grown under conditions where availability of water defines potential productivity. In such conditions, provision of an appropriate supply of N should be synchronized with temporal demand of the crop over the growing season. This is true as N makes up 1–4% of potato dry matter while too much N results in vigorous early vegetative growth leading to haying-off under water-limited conditions (van Herwaarden et al. 1998).

There is therefore a growing need to design low-cost and efficient integrated nitrogen management systems compatible with smallholder farmers' socioeconomic status. In this context, legumes or nitrogen-rich plant residues present promising alternatives to the mineral fertilizers. These crops can be simultaneously introduced into potato cropping systems. The organic residues from these plants must decompose fast enough for N to become available to potato crop. In this way, synchronization of N supply and crop N demand for a given target yield level may reduce N losses and increase N use efficiency. Intercropping that includes deep rooted crops can reduce nitrate leaching due to their ability to effectively take up residual nitrogen, converting it into crop biomass which is later mineralized for nitrogen release (Constantin et al. 2012; Plaza-Bonilla et al. 2015).

Intercropping potato with high nitrogen fixing legumes can alleviate the high cost of inorganic soil nitrogen inputs (Burke, 2017). Sanginga and Woomer (2009) reported that velvet bean (*Mucuna pruriens* L.) accumulated about 160 kg N ha^{-1} in 12 weeks when it was intercropped with maize, while Eaglesham et al. (1981) found that the nitrogen fixed by companion cowpea was about 41 kg N ha^{-1} in maize-cowpea intercropping system. Roots of legumes can decompose and release nitrogen into the soil where it is made available for subsequent crops (Giller et al. 2015). Legume cover crop integration into potato cropping systems can appreciably reduce nitrogen losses due to soil erosion thereby increasing efficiency of nitrogen use (Xing et al. 2011).

Intercropping is however practiced by only about 5–12% of the smallholder farmers in Kenya and mostly with maize (*Zea mays* L.) intercrop (Muthoni et al. 2013). We therefore conducted a two-year field experiment to compare the soil nitrogen content of sole potato and potato intercropped with lima bean (*Phaseolus lunatus* L.) or dolichos (*Labalab purpureus* L.) in three AEZs of Kenya (upper midland, lower highland and upper highland). We hypothesized that (i) legume intercropping increases the amount of dry matter available for nitrogen mineralization thus increasing the soil nitrogen content available for uptake by potato crop and (b) that legume intercropping minimizes the amount of N lost to leaching and soil erosion thus increasing the soil N balance.

6.2 Materials and methods

6.2.1 Experimental site and design

The trials were carried out during the four rainy seasons of 2017 and 2018 in three agro-ecological zones (AEZs) of Kenya; upper midland (1552 m above sea level (masl)), lower highland

(1894 masl) and upper highland (2553 masl). Detailed site descriptions are given in section 3.1. During this study period, total rainfall amount of 345, 184, 328 and 216 mm was received respectively during the 2017 long rains, 2017 short rains, 2018 long rains and 2018 short rains in the upper highland AEZs. This is compared to rainfall amount of 388, 211, 372 and 269 mm received in the lower highland AEZ, and 399, 209, 369 and 234 mm respectively in the upper highland AEZ. Across the seasons, the mean air temperatures were higher in the upper midland (15.7–27.9°C), intermediate in the lower highland (13.1–25.4°C) and lowest in the upper highland (11.1–22.3°C) AEZs. Soil chemical and physical properties measured at start of the experiment are shown in Table 6.1.

Table 6.1: Initial soil chemical properties measured at different soil depth: pH; soil organic carbon (SOC); total nitrogen (N); nitrate N (NO_3^-−N), ammonium N (NH_4^+−N).

Agro-ecological zone	Soil depth (cm)	pH	SOC	N	NO_3^-−N	NH_4^+−N
			g kg^{-1}			
Upper midland	0–30	5.0	18.2	1.3	5.8	4.7
	30–60	5.0	15.5	1.1	5.4	4.2
	60–90	4.9	12.3	1.1	3.8	2.9
	90–120	4.9	9.8	0.9	3.3	2.0
Lower highland	0–30	5.1	25.5	1.8	8.4	5.1
	30–60	5.1	15.6	1.1	7.7	4.6
	60–90	5.2	7.8	0.6	7.2	3.3
	90–120	5.2	2.4	0.2	6.6	2.0
Upper highland	0–30	5.2	36.6	2.8	9.2	5.7
	30–60	5.2	25.5	2.1	8.2	4.3
	60–90	5.3	13.1	1.1	8.3	3.1
	90–120	5.3	9.8	0.9	7.3	2.1

6.2.2 Experimental design and crop husbandry

The trials were laid out in a randomized complete block design with four replications. The treatments comprised of sole potato (*Solanum tuberosum* L.), sole lima bean (*Phaseolus lunatus* L.), sole dolichos (*Lablab purpureus* L.) and intercrop of potato with either lima bean or dolichos. Intercropping was done in 2 rows of potato alternating with 2 rows of legumes. Fertilizer application was based on soil analysis and was adjusted seasonally taking into account the amount of mineral N in the soil prior to planting. On average, this activity consisted of basal application of 50 kg ha^{-1} N, 90 kg P ha^{-1}, 100 kg K ha^{-1} and single topdressing with 50 kg N ha^{-1} in the form of calcium ammonium nitrate (26-0-0). Topdressing was done 15–25 days after potato emergence depending on the general soil moisture conditions. Legumes received only basal phosphorus applications (triple super phosphate, 0-46-0) at rates averaging 20 kg P ha^{-1}. Detailed cultural activities are described in section 3.5.

6.2.3 Soil sampling and analyses

Soil samples were taken in 10 replicates from inter-rows of each plot with a 15 mm inner-diameter soil piston auger at soil depth 0–30, 30–60, 60–90 and 90–120 cm. The soil samples were mixed into a composite for each depth, transported in cooler boxes and stored at 4^{o}C until analysis. Subsamples of 20 g fresh soil weight were extracted in 1M KCl for 1 h (1 soil: 2 solution) and centrifuged. The supernatant was analyzed for NH_4^+−N and NO_3^-−N by standard colorimetric methods using Auto Analyzer 3 (Bran + Luebbe, Germany). The N content was converted to kg ha^{-1} basis using soil bulk density values for each sampling depth.

6.2.4 Soil moisture, rainfall and ambient temperature measurements

Soil moisture content was measured every 30 cm to depth of 120 cm using HOBO soil moisture sensors installed in each plot. The soil moisture in the top 30 cm soil layer was measured gravimetrically in all replications before planting to calibrate the sensor probes and to estimate the amount of water required for irrigation. Rainfall amount of each experimental site was recorded using onsite rain gauges while air temperatures were obtained from HOBO temperature sensors installed within the experimental sites.

6.2.5 Root sampling and estimation of root length density

Root length density was estimated as outlined in section 4.2.9 and related with the amount of N leached to discern the effect of root heterogeneity on N capture.

6.2.6 Computation of nitrogen balance

Soil nitrogen balance was computed as the difference between N input and output pools within the crop root zone (0–120 cm depth) (OECD, 2001). Taking into considerations the major nitrogen input and output pathways in smallholder potato cropping systems, soil nitrogen balance was computed using Eq. (6.1):

$$N_{bal} = \left[N_{fert} + N_{initial} + N_{residual} + N_{min} + N_{fix}\right] - [N_{uptake} + N_{ero} + N_{leach} + N_{vol}] \quad (6.1)$$

where inputs: N_{fert} = N gains from fertilizer; $N_{initial}$ = Soil N available at start of the season; $N_{residual}$ = available soil N after harvest; N_{min} = N mineralization from crop residues, and the outputs; N_{uptake} = nitrogen accumulated in the plant; N_{ero} = N lost in runoff and N carried by eroded sediment; N_{leach} = N leached beyond the active root zone; N_{vol} = N lost to volatilization.

The contributions of biological nitrogen fixation to total N accumulation was estimated by the N difference method (Peoples et al. 2002) which is based on the fact that sources of N for fixing crops are soil, fertilizer and the atmosphere (Eq. 6.2).

$$\%N\ dfa = 100 - (\%N\ dfs + \%N\ dff) \quad (6.2)$$

Where, Ndff is nitrogen derived from the fertilizer; Ndfs, nitrogen derived from the soil and Ndfa nitrogen derived from the atmosphere.

The amount of N leached was analyzed from the soil solution extracted using SoluSAMPLER located at vertical depths of 0–150 cm at increasing interval of 30 cm (Biswas and Schrale, 2007). In this study, soil N beyond 120 cm depth was considered leached, as no active roots were found past this depth. Nitrogen content from the sampled soil solution was determined by UV/vis spectrophotometer and indigotic colorimetric method. The N contents were converted to kg N ha^{-1} basis using soil bulk density values measured for each sampling depth.

Nitrogen uptake by potato and legumes was computed at potato vegetative growth, tuber initiation, bulking, and maturation stages. For potatoes, samples were separated into tubers, roots and shoot while the legumes were partitioned into shoot, roots, and into grains for sampling conducted at maturity. The samples were dried in an oven at 70°C for 48 h, weighed, and subsamples analyzed for N content using Kjeldhal digestion method (Keeney and Nelson, 1982). The total N uptake per plant was calculated as the product between plant part N concentration and biomass weight.

The litterbag method (Anderson and Ingram, 1993; Verhoef, 1995) was used to measure N mineralization from crop residues. The bags measured 0.3 m by 0.3 m and were made of plastic with 1 mm mesh. At harvest of each crop, 8 bags corresponding to the number of sampling times were filled with about 250 g of crop residues from each treatment after they had been chopped into pieces 50 mm long. About 250 g soils without crop residue amendments were also added in litterbags as controls. The bags were buried at a depth of 30 cm at a distance of 30 cm between the bags along the potato-legume rows. The bags were retrieved and sampled at 2, 4, 6, 8, 10, 12, 14 and 16 weeks after residue incorporation. At each sampling time, plant materials remaining in the litter bags were oven dried at 60^{o}C to a constant weight. The oven-dried samples were weighed separately to determine dry matter (DM) losses using Eq. (6.3).

$$Weight\ loss = 100x(M0 - Mt)/M0 \tag{6.3}$$

where

M0 is the initial plant dry matter (DM) (g) in the litterbag; Mt is the plant DM mass (g) in the bag at time t when the bags were retrieved.

At each litter-sampling time, soil samples were taken at 0–30 cm on the spots where the litterbags were laid and in control plots and analyzed for mineral N. The samples were put in airtight polythene bags, stored in the laboratory at 4°C, and analyzed within 2 days of sampling. Briefly, 20 g soil samples (passed through 0.5 mm sieve) were extracted in 60 ml 1 M KCl. The mixture was shaken on an end-over-end shaker for 1 h, centrifuged and the clear supernatant transferred into 100 ml flasks. The supernatant was analyzed for total N using Kjeldahl method. The N content was converted to kg ha^{-1} basis using soil bulk density values measured with soil cores for each sampling interval. Net N mineralization was calculated as the difference between the amounts of mineral N released between the amended soil and the control soil.

The amount of N mineralized over time of sampling was calculated by the first-order model (Eq. (6.4)) (Jones, 1984).

$$N_m = N_0(1 - e^{-kt}) + N_1 \tag{6.4}$$

where

N_m (mg kg^{-1}) is the amount of N mineralized at time t (d); N_0, the initial mineralizable N content (mg kg^{-1}); k, the first-order rate constant (d^{-1}) and N_1 (mg kg^{-1}), the zero-order constant (mg kg^{-1}), i.e., N mineralized at time 0.

A subsample of 25 g soil was dried in an oven at 105°C for 24 h to determine the soil moisture content at the time of sampling. In addition, the initial materials added to the bags (0 week sampling time) were analyzed for organic C using the wet digestion procedure of Walkley and Black (Nelson and Sommers, 1996). Lignin was assessed by the acid detergent fibre method (Goering and van Soest, 1970), while the water-soluble polyphenols were quantified using procedures outlined by Folin Denis (King and Heath, 1967).

Ammonia volatilization was measured using ventilation chambers placed at inter-rows of each plot (Jantalia et al. 2012). In 2017 SR, samples were collected at 4, 11, 18, 26, 34, 50, and 64 days after planting (DAP) and at 6, 13, 23, 30, 40, 50, 59, 70 and 82 DAP in 2017 LR. In 2018 SR, the data were collected at 8, 22, 29, 36, 44, 51, 58, 71, and 86 DAP and at 6, 13, 20, 28, 40, 52, 61, 70, and 83 DAP in 2018 LR. At each sampling date, the polyfoam strips and acid solution placed in plastic cups from each chamber were collected in 125 mL of 2 M KCl solution. Fifty (50) mL of this solution was analyzed using an automated ammonia analyzer (TL 2800, Timberline Instruments). Nitrogen loss through NH_3 volatilization during consecutive sampling dates (mg NH_3–N m^{-2}) was determined using Eq. 6.5.

$$NH_3\ volatilization = \frac{NH_3 - N\ conc\ (mg\ mL^{-1}) * total\ vol\ of\ solution\ (250\ mL)}{Surface\ area\ of\ the\ soil\ covered\ by\ the\ trap\ (0.90\ m^2)} \tag{6.5}$$

Cumulative NH_3 volatilization (kg N ha^{-1}) was determined by summing up the amount of NH_3 volatilized during each sampling period throughout the growing season using Eq. 6.6.

$$Cumulative\ NH_3\ emission = \sum_i^n \frac{X_i + X_{i+1}}{2}(X_{i+1} - t_i) \tag{6.6}$$

where Xi is the NH_3–N flux measurement on day t, $Xi + 1$ is the succeeding NH_3–N flux measurement on day ti+1, and n is the final date of NH_3–N flux measurement.

Runoff and sediment samples were collected using soil sedimentation containers installed at the lowest edge of each experimental plot. The runoff water collected was overflowed into a second container with a weir. The water level in this container was monitored at 30 min intervals by a GY-type sensor (UIZ-ECH20, UIZIN, Tokyo, Japan) and converted into water discharge to determine water runoff. The runoff water samples (about 15 mL) were transferred into 20-mL vials followed by a drop of 0.5M sulfuric acid and transported in ice water (4°C) within 24 h to the laboratory and chilled at -4°C till analyses (Eq. (6.7)). The sediments were weighed after drying in an oven at 70°C. A sample of air-dried sediment from each plot (about 100 g) was collected in 100 ml can and analyzed for total N (Eq. (6.8)).

$$N_{runoff}\,(kg\,\mathrm{ha}^{-1}) = Runoff\ N(mgl^{-1}) *\ runoff\ depth(mm) * 0.253 \tag{6.7}$$

$$N_{eroded\ sediment}(kg\,\mathrm{ha}^{-1}) = \mathrm{soil\ loss}\ (kg\,\mathrm{ha}^{-1}) *\ \mathrm{sediment}\ N \tag{6.8}$$

Residual soil nitrogen was determined by collecting soil from the center of each plot at 0–30 cm m at potato harvest. The samples were transferred to the laboratory at 4°C, stored at -18°C, and analyzed for N within 1 week, following Kjedlhal method (Nelson and Sommers, 1982). Corresponding bulk density of soil was measured from an intact soil core and used to convert mg of N kg^{-1} soil to kg N ha^{-1}.

6.2.7 Data analysis

The data was analyzed using R software, version 3.5.2 (R Core Team, 2017). The treatment effects on soil water content, soil temperature and N balance were tested using general linear model analysis. Whenever interaction of cropping system and season was found significant, data were analyzed in separate seasons. Tukey's honest significant difference test was applied for multiple mean comparisons between treatments and tests with $p < 0.05$ were considered statistically significant. To derive the mineralization rate constants (k), N mineralization data was fitted to the kinetic model by data processing software KyPlot (KyensLab Inc., Tokyo, Japan) using nonlinear least-square technique. An exponential function was fitted to give the relative predictive power of N mineralization as a function of root length density with an equation of the form y = abx where a ≠ 0.

6.3 Results

6.3.1 Runoff and sediment yield

Mean seasonal soil loss and runoff differed significantly among the treatments and were highest in sole potato, intermediate in intercropping and lowest in sole legumes (Fig 6.1).

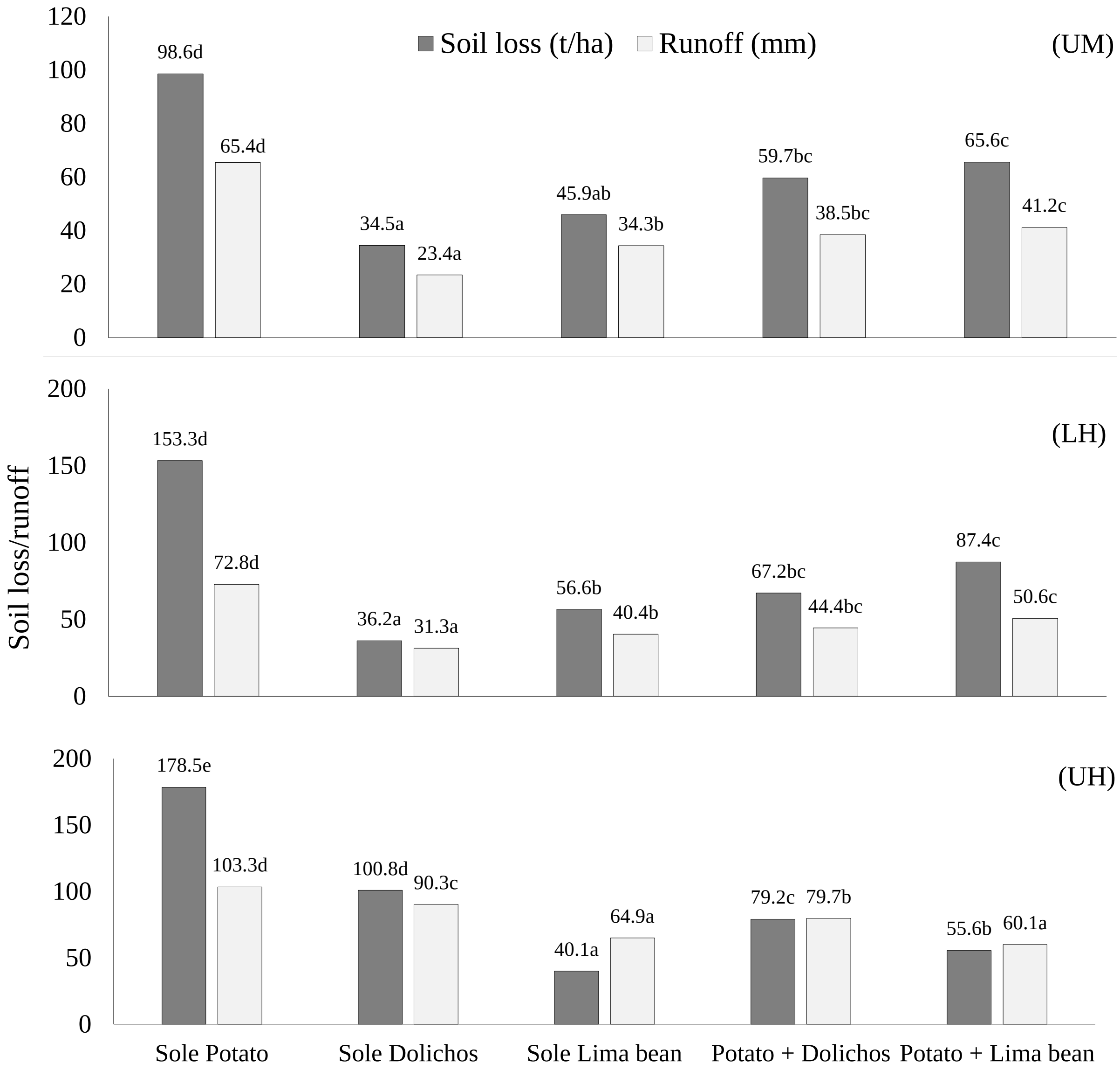


Figure 6.1: Mean seasonal soil loss and runoff measured under different cropping systems in the upper midland (UM), lower highland (LH) and upper highland agro-ecological zones. Means with different letters show significant differences between treatments at Tukey's $p \leq 0.05$. Data presented as averages of 4 replicates.

Compared to sole potato, cumulative soil loss in the UH AEZ reduced by 25–43% in potato-lima bean intercropping. Similarly, soil loss in the upper midland and lower highland AEZs reduced by 16–47% in potato-dolichos intercropping. Cumulative runoff showed a similar trend reducing by 22 to 43% respectively in potato-legume intercropping compared with the sole potato.

6.3.2 Residue yield and chemical composition

Biomass yield differed significantly among the cropping systems and was greatest in pure legumes (range of 4.4 to 7.5 t DM ha^{-1}) followed by intercropping (3.4 to 6.6 t DM ha^{-1}) and lowest in sole potato cropping (1.8 to 3.9 t DM ha^{-1}) (Table 6.2).

Table 6.2: Dry matter yield, nitrogen concentrations and chemical composition of crop residues at time of field incorporation. Values expressed as averages over four seasons.

Agro-ecological zone	Cropping system	DM (t ha^{-1})	OC (%)	Total N (%)	Lignin (L) (%)	Polyphenol (P) (%)	C:N	L:N	P:N	L+P : N
Upper midland	Potato + dolichos	5.3d	37.8b	2.0b	5.4bc	1.5a	18.9a	2.7b	0.8ab	1.7b
	Potato + lima bean	3.4b	35.8b	1.8b	5.8bc	2.0a	19.9a	3.2b	1.1b	2.4c
	Sole dolichos	7.5e	51.8c	3.2c	4.1a	1.4a	16.2a	1.2a	0.4a	0.5a
	Sole lima bean	4.9c	47.3c	2.8c	5.1ab	1.8a	16.9a	1.9a	0.7a	0.9a
	Sole potato	1.8a	27.5a	1.1a	7.1c	2.2a	25.0b	6.4c	2.1c	7.8d
Lower highland	Potato + dolichos	6.6d	49.6bc	2.6b	4.8b	1.6a	19.1a	1.9ab	0.6a	1.0b
	Potato + lima bean	4.8b	45.3b	2.3b	5.4c	1.9a	19.7a	2.4b	0.8a	1.4b
	Sole dolichos	8.9e	55.7d	3.3c	3.5a	1.5a	16.9a	1.1a	0.5a	0.5a
	Sole lima bean	6.3c	53.1cd	3.0c	4.7b	1.8a	17.7a	1.6a	0.6a	0.7a
	Sole potato	2.9a	34.4a	1.3a	6.7d	2.1a	26.5b	5.2c	1.6b	5.2c
Upper highland	Potato + dolichos	5.8b	44.2b	2.2bc	5.0b	1.6a	20.1a	2.3b	0.8a	1.4b
	Potato + lima bean	6.6c	48.0c	2.5cd	5.0b	1.8a	19.2a	2.0b	0.7a	1.1b
	Sole dolichos	4.4a	52.9d	2.8d	4.0a	1.5a	18.9a	1.4a	0.6a	0.7a
	Sole lima bean	8.1d	55.1d	3.3e	4.8b	1.6a	16.7a	1.5a	0.5a	0.6a
	Sole potato	3.9a	38.5a	1.4a	6.5c	1.9a	27.5b	4.7c	1.4b	4.3c

Means followed by the same letter down the column within an agro-ecological zone do not differ significantly by Tukey's HSD at $p \leq 0.05$.

Residue total organic carbon content varied from 27.5–38.5% in pure potato stands to 47.3–55.7% in pure legume stands. Intercropping showed intermediate range of residue OC composition ranging between 35.8–49.6% across the AEZs. The highest concentration of total N was observed in pure legumes (2.8–3.3%) followed by intercropping (1.8–2.6%) and lowest in pure potato (1.1–

1.4%). Lignin contents were significantly higher in pure potato (6.5–7.1%) relative to intercropping (4.1–5%) and lowest in pure legumes (3.5–5.1%). Similar trends were observed for the polyphenol contents that ranged between 1.4–1.8% in pure legumes, 1.5–2.0% in intercropping and 1.9–2.2% in pure potato. Compared to sole potato cropping, intercropping potato with legumes lowered the C-to-N ratio by 20–28%, lignin-to-N ratio by 50–63%, polyphenol-to-N ratio by 47–63% and lignin + polyphenol-to-N ratio by 69–80%.

6.3.3 Nitrogen mineralization and uptake

Net N mineralized ranged between 6.9–9.0 kg N ha^{-1} in sole potato, 39.3–56.0 kg N ha^{-1} in intercropping and 39.9–64.9 kg N ha^{-1} in pure legumes (Fig. 6.2a). Peak N release in intercropping system was 5–9 kg N ha^{-1} within 8–10 weeks of residue decomposition and matched with peak N uptake by potato (19.9–31.2 kg N ha^{-1}) that occurred at this time. This is in contrast to pure potato which obtained peak net mineralization of 2.6–3.6 kg N ha^{-1} at 12–14 weeks of residue decomposition. Nitrogen uptake at this period was relatively low ranging between 4.3–25.4 kg N ha^{-1}. Sole legumes exhibited peak mineralization at 6–8 weeks after residue incorporation. Nitrogen uptake by potato, though high at this period, was not at its peak. Cumulatively, intercropped potato showed significantly higher N uptake per plant compared with the sole potato and was lowest in the sole legumes irrespective of AEZs (Fig. 6.2b). This N uptake ranged from 87.5 to 171.2 kg N ha^{-1} in intercropping and 53.1–79.5 kg N ha^{-1} in sole legumes. In the upper highland AEZ, N uptake by dolichos grown either in pure stand or in intercropping was significantly lower than that of lima bean.

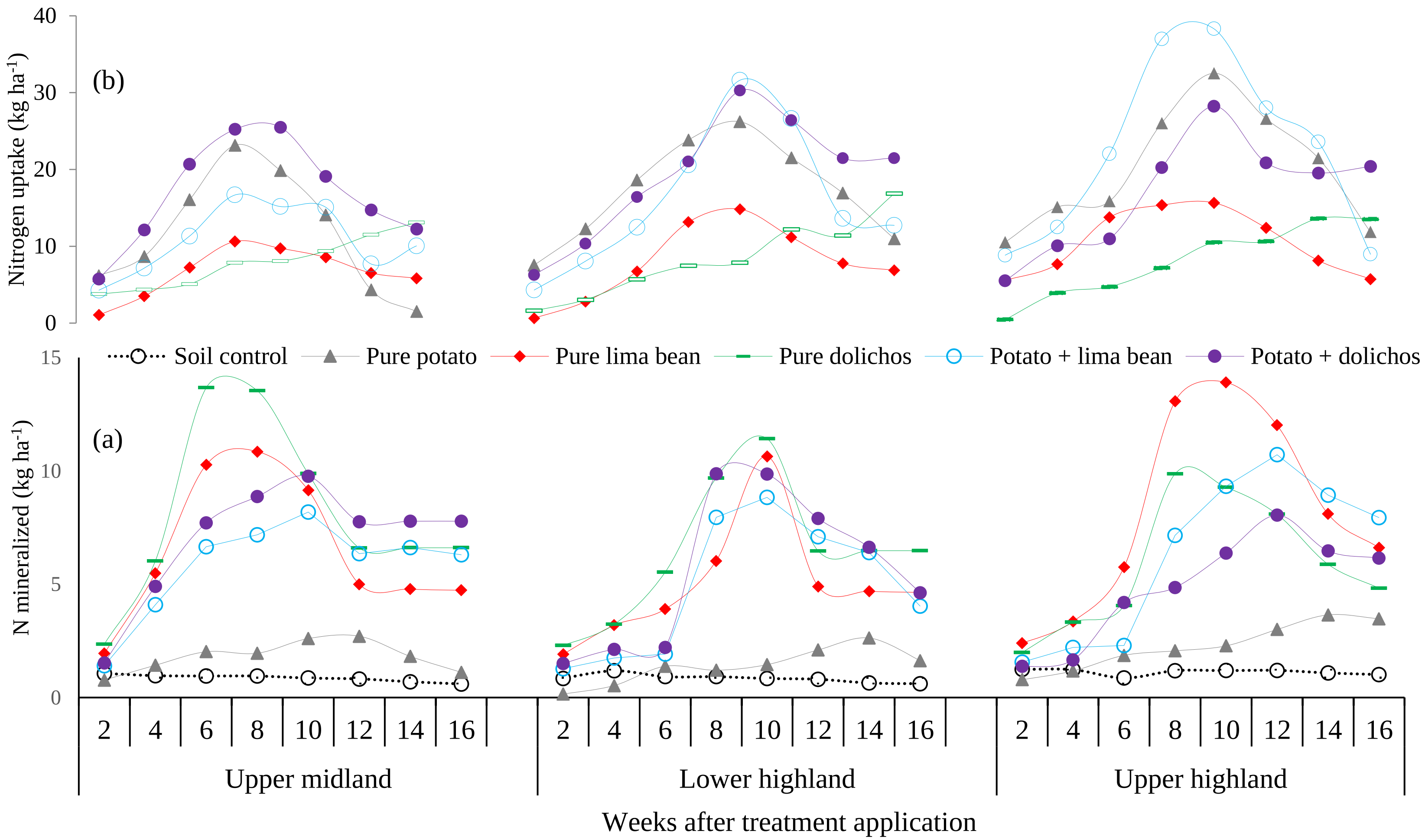


Figure 6.2: Accumulations of residue N mineralized (a) and N taken up by the crops (b) after 16 weeks of residue decomposition and potato planting respectively in the upper midland, lower highland and upper highland agro-ecological zones. Soil control treatments without residue amendments were included during decomposition for comparisons and for computation of net N mineralization.

6.3.4 Soil nitrogen balance

Soil N depletion occurred in pure potato stands (-38 to -24.5 kg N ha^{-1}) while surplus occurred in monocultures of dolichos (5.5–58.2 kg N ha^{-1}) and lima bean (19.7–55.5 kg N ha^{-1}) (Table 6.3). Intercropping showed intermediate soil N balance (3.1–9.5 kg N ha^{-1}). The main component of soil N input was mineralization followed by residual N and N_2 fixation across the cropping systems and AEZs.

Table 6.3: Nitrogen balance and its components under different cropping systems in the upper midland (UM), lower highland (LH) and upper highland (UH) agro-ecological zones.

		Nitrogen inputs					Nitrogen outputs					
	Cropping system	Fertilizer	Mineralization	N_2 fixation	Residual N	Initial N	Crop N uptake	Leaching	Runoff	Erosion	Volatilization	ΔN
		Kg N ha^{-1}										
(UM)	Pure potato	90.0c	9.3a	-	1.6a	1.0a	94.3b	6.6c	1.4d	2.2c	34.4a	-37.0a
	Pure lima bean	0.0a	34.7b	2.7a	21.5b	1.0a	36.1a	2.4b	0.5a	0.3a	0.9d	19.7c
	Pure dolichos	0.0a	39.2b	12.3c	24.5b	0.8a	40.9a	1.7ab	0.2a	0.1a	0.7d	33.2d
	Potato + lima bean	52.0b	48.7c	6.8b	19.8b	0.9a	92.4b	1.3a	1.3cd	1.2b	28.8b	3.1b
	Potato + dolichos	52.0b	51.6c	21.9d	23.7b	1.1a	116.9c	1.2a	1.0bc	0.9ab	21.7c	8.6b
(LH)	Pure potato	90.0c	25.7a	-	6.9a	1.1a	106.3b	28.8b	3.8c	2.2c	20.6a	-38.0a
	Pure lima bean	0.0a	62.0c	4.2a	29.1bc	1.1a	38.6a	6.6a	0.2a	0.3a	0.4c	50.4c
	Pure dolichos	0.0a	73.7d	14.9c	33.2c	0.9a	58.4a	5.2a	0.2a	0.2a	0.4c	58.2c
	Potato + lima bean	45.0b	55.4bc	8.9b	24.3b	0.8a	115.7bc	4.4a	1.6b	2.0c	7.7b	3.0b
	Potato + dolichos	45.0b	67.4cd	16.5c	28.2bc	0.9a	135.8c	3.9a	0.6ab	1.3b	5.7b	10.7b
(UH)	Pure potato	100.0c	26.7a	-	16.5b	2.8a	116.9d	36.9	4.0b	3.8c	8.8a	-24.5a
	Pure lima bean	0.0a	80.1c	5.2c	25.4c	2.6a	46.0b	10.9a	0.5a	0.3a	0.1d	55.5c
	Pure dolichos	0.0a	43.3b	1.8a	8.8a	2.5a	24.8a	24.3	1.0a	0.3a	0.5d	5.5b
	Potato + lima bean	50.0b	82.1c	7.9d	18.7b	2.1a	134.1e	11.7a	1.6a	1.7b	2.2c	9.5b
	Potato + dolichos	50.0b	45.1b	3.3b	9.9a	2.5a	71.0c	20.9b	4.0b	2.1b	5.5b	7.3b

Δ-N indicates the soil nitrogen balance. Values followed by different letters within a column denote significant differences at Tukey's $p \leq 0.05$. Values are 4 replicates expressed as averages over four seasons.

Leaching, erosion and runoff accounted for 14–40% of the N output in the upper highland and were highest in sole potato stands, intermediate in intercropping and lowest in sole legumes. Volatilization contributed 12–23% of N output in the upper midland AEZ and was highest in pure potato stands and lowest in sole legumes.

The amount of N leached decreased with increasing root length density ($0.53 \leq R^2 \leq 0.90$) (Fig. 6.3). The relationship was strongest in pure potato plots (R^2 = 0.90) followed by potato + lima bean (R^2 = 0.65), pure dolichos (R^2 = 0.63) and lowest in sole lima bean (R^2 = 0.53).

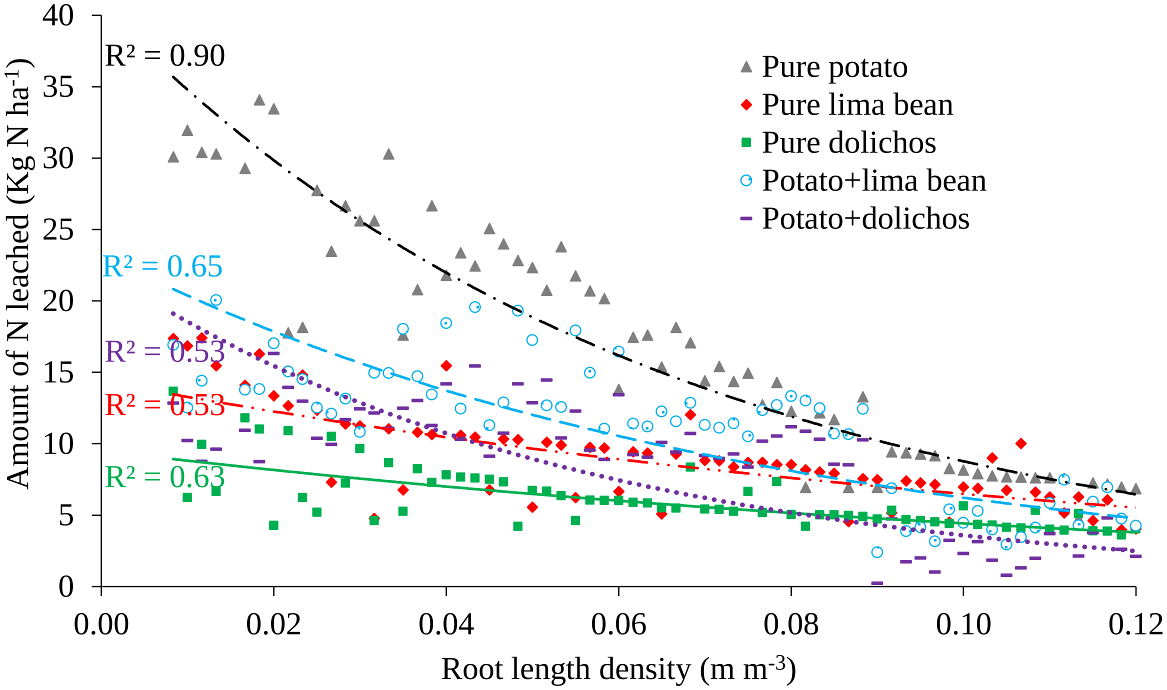


Figure 6.3: Amount of nitrogen leached below the active root zone as a function of root length density under different cropping systems. Each point is treatment average of 4 replicates across the sampling sites.

6.4 Discussion

6.4.1 Influence of potato-legume intercropping on soil erosion

Legume intercropping increased leaf area index as legumes exhibited rapid growth which enhanced canopy overlap thus covering the empty spaces in the inter-rows of potato and legumes (see Fig 4.2 and 7.3). This reduced the raindrop hitting force and slowed down the velocity of runoff. While the low canopy of dolichos reduced the raindrop falling height and minimized the raindrop hitting force, the effective canopy overlap by lima bean enhanced the capability of leaves to resist bending thus augmenting stem flow. This increased the effective rain-receiving area which eliminated erosion and runoff generation. The canopy of dolichos was extended after potato harvest to the subsequent season and was thus effective in controlling post-harvest runoff and soil erosion. The canopy closure of potato was effective only after 40 to 45 days and diminished at physiological maturity when plants began to senesce. Jego et al. (2008) noted that the shorter period of growth characterizing potato intensifies soil erosion especially after the plants begin to senesce.

The low sediment yield and runoff generation under potato-dolichos intercropping in the upper midland and lower highland AEZs resonates with the high LAI observed in this treatment. This observation suggests a greater soil stabilizing effect of dolichos which may be asserted to the continuity of groundcover throughout the year compared with the other treatments which were left bare soon after potato harvest. In the upper highland AEZ, growth of dolichos was suppressed by the low ambient temperatures (Cook et al. 2005). In similar studies, reduction of sediment yield, runoff generation and associated N loss under potato-dolichos intercropping has been adduced to the canopy heterogeneity contributed by differences in plant heights (Nyawade et al. 2019). The first raindrops that hit the canopy is intercepted and dispersed by dolichos which exhibits greater height relative to potato. Pure potato stands due to their low uniform canopy height, converge the smaller raindrops into bigger drops renewing their erosion potential.

6.4.2 Residue N mineralization and N uptake

The N mineralization process was influenced by residue biochemical composition, the effect of which was greatest under sole legumes indicating that legumes enhanced supply of N to the soil. This observation was indicated by the ratios of residue C-to-N, lignin-to-N, polyphenol-to-N and lignin + polyphenol-to-N which were low in intercropping relative to pure potato stands. This observation agrees with previous findings which showed that legumes provide high amounts of N-rich residues thus enhancing N mineralization and supply (Palm and Sanchez, 1991; Tian et. 1992; Handayamoto et al. 1994).

Generally, N mineralization was lowest within the first 2 weeks of residue decomposition under sole potato residue but increased sharply at the sixth week. During this period (sixth week), the potato tissues had less than 10 g kg^{-1} N with C-to-N ratio of approximately 30, indicating that this concentration is a reasonable critical level for initial net mineralization of potato residue. With legume intercropping, immobilization was observed within the first 2 weeks of residue incorporation probably due to the low build-up of microbial population which are involved in residue degradation (Ruijter et al. 2010).

The increase in residue N mineralization after the 4th week of residue decomposition irrespective of treatments could be due to release of soluble and readily decomposable N-containing biochemical compounds like amino sugars, nucleic acids and proteins (Paul and Clark, 1989). The peak N release at 6–10 weeks across the treatments after residue incorporation was consistent with the residue mass loss and signified intense organic matter degradation at these times. At later stages of decomposition, little extra N was released, an observation we attribute to the decrease in residue mass which was the source of microbial substrates.

The differences in N mineralization patterns between the sites was attributed to seasonal soil moisture and temperature variations. Moisture and temperature control decomposer activity and thus influence plant residue decomposition (Tian et al. 1993; Mitchell et al. 2000). The lower temperatures in the upper highland AEZ could have lowered the respiration rates thus delaying net mineralization (Tian et al. 1997). The low mineral N during the wet seasons in this study could therefore be attributed to the generally low soil temperatures which lowered the decomposition rate of crop residues.

The occurrence of peak residue N mineralization and N uptake in intercropping indicated synchrony of N supply and demand. At week 4 after potato planting, pure legumes showed higher cumulative N uptake due to their ability to grow fast and take up the N mineralized. A comparatively slow mineralization from sole potato residues resulted in low initial N supply as greater amount of N was immobilized in potato residue at this time. The increase in N uptake by intercropped potato could have also been due to root facilitative interactions such as rhizodeposition and N-transfer (Jensen, 1996). Whitbread et al. (2011) showed the ability of dolichos to capture N from the subsoil and pump it to the surface soil strata thus making it available for the shallow rooted crops.

6.4.3 Soil N balance and its components

A significantly higher N balance was recorded in intercropping relative to sole potato reflecting the effect of legumes on N dynamics. Intercropping increased groundcover across the seasons and agro-ecological zones which greatly conferred shading to the soil. This lowered the soil temperature and reduced ammonia volatilization while minimizing N losses to soil erosion and runoff. Nitrogen being highly mobile in its nitrate form was quickly leached below the potato-root zone whereas the legume intercrops developed deep root systems that enhanced the recovery of the N leached from the topsoil.

The greater N fixation by intercropped legumes was perhaps in response to increased soil N competition by potato grown in association. This, according to previous studies permits legumes' greater reliance on symbiotic N_2-fixation (Inal et al. 2007). Alonso-Ayuso et al. (2014) found that high competition with barley for soil N forced vetch to rely on N_2 fixation for its N requirement, and in return accumulated large amount of N compared to sole vetch. Therefore, in conditions that enabled the growth of both companion species, the increased uptake of N by potato caused a temporary decrease in soil N thereby increasing the proportion of N_2 fixed by the legume. Hauggaard-Nielsen et al. (2009) argued that the high N_2 fixation potential of legumes grown in intercropping is due to the high degree of complementarities arising from species interaction that enables natural regulation mechanisms between intercrop components. Such mechanisms include improved N capture in mixed crops as a result of complementarity in foraging strategies in space (soil profile) and time (growth period of the crop) (Lithourgidis et al. 2011). Snoeck et al. (2000) showed that up to 30% of N_2 fixed by legumes was transferred to the associated non-legume under field conditions. They attributed this to the interactions of roots and to the secretion of root exudates. Similarly, the legumes in this study had deeper rooting depth which enabled them to explore greater soil volume and diverge the N leached beyond the potato root zone.

The generally higher N_2 fixation by dolichos over lima bean could be ascribed to the genetic differences among the crop cultivars as interactions between legume microsymbionts are highly specific (Qiang et al. 2003). In addition, the continued accumulation of biomass by dolichos days after lima bean senesced may explain the differences in relative contribution of fixed N_2 between the two legumes. Cook et al. (2005) noted that dolichos is able to take up N from soil layers up to

1.5–2.4 m depth. Studies conducted in central Kenya indicated that the N contribution of dolichos is in the range of 8 to 25 kg N ha^{-1} while that of lima bean is in the range of 1.6 to 7 kg N ha^{-1} (Chemeningwa et al. 2007).

The greater N uptake by dolichos than lima bean in the lower highland and upper midland agro-ecological zones may be related to the enhanced N_2-fixation. This mechanism directly affects N uptake and metabolism (Wyeh and Rains, 1978). The converse was observed in the upper highland AEZ due to the low temperatures that dolichos could not tolerate. Chemeningwa et al. (2007) recorded higher nodule numbers per plant for dolichos than for lima bean under elevated temperature conditions. This was attributed to dolichos' high adaptation to water stress. The notably lower crop nitrogen uptake in the upper midland AEZ relates to the low soil moisture and high ambient temperatures.

Nitrogen volatilization was lowest in sole legumes because these treatments were not fertilized with N, and thus lacked the N emission triggered by N fertilization. The differences in cumulative ammonia volatilization between the study sites were attributed to the differences in temperature and rainfall. The lower temperatures coupled with higher rainfall amounts in the upper highland AEZ may have decreased ammonia volatilization (Whitehead et al. 1988) while the high ambient temperatures and low soil moisture in the upper midland AEZ favored net volatilization.

6.5 Conclusion

The results from this study give an insight on the potential role of potato-legume intercropping in enhancing N inputs into the soil while minimizing the output pathways, thus offering a mechanism for optimizing soil nitrogen content in smallholder farming systems. Reduction of nitrogen loss in this manner could be an effective measure to improve soil productivity and increase the efficiency of nutrient use while dampening nitrogen losses to water bodies. Even though the observed biological N_2 fixation contribution by the legumes in this study seemed insufficient to cover the total potato N need, this amount of nutrient remains important to the resource-constrained farmers. These contributions will better be understood if linkages between litter fauna and residue biochemical composition is assessed and established under different temperature and moisture regimes.

CHAPTER SEVEN

INTERCROPPING OPTIMIZES SOIL TEMPERATURE AND INCREASES CROP WATER PRODUCTIVITY AND RADIATION USE EFFICIENCY OF POTATO

Abstract

Integrating crop species with different photosynthetic pathways has a great potential to increase efficiency in the use of scarce resources. In order to tap the resource complementarity emanating from this mix, this study intercropped potato (*Solanum tuberosum* L.) with lima bean (*Phaseolus lunatas* L.) and dolichos (*Lablab purpureus* L), and related soil temperature with radiation use efficiency and crop water productivity of rainfed potato in the upper midland (1552 meters above sea level (masl), lower highland (1894 masl) and upper highland (2552 masl)) agro-ecological zones of Kenya. The study was laid out in a randomized complete block design with four replications. Soil samples (0–120 cm depths) were taken from each plot at key stages of potato growth. Leaf area index (LAI), light interception, soil temperature and soil water contents (SWC) were quantified at different stages of potato growth and related with the radiation use efficiency (RUE) and crop water productivity (CWP). Intercropping increased LAI by 26–57% relative to sole potato stands and significantly lowered the soil temperatures in the 0–30 cm depth by up to 7°C. This caused an increase in SWC by up to 38%, thus increasing RUE by 56–78% and CWP by 45–67%. Land equivalent ratios of the intercrops were generally greater than unity indicating more efficient and productive use of land resource. Intercropping potato with legumes is coupled with optimum root-zone soil temperature and soil water content, thus potentially exerting additive relations in radiation interception and subsequent conversion into crop biomass.

Keywords: Intercropping; radiation interception; radiation use efficiency; soil water content; soil temperature.

7.1. Introduction

Sustainable potato production requires careful optimization of the use of resources to improve soil fertility and crop productivity. This does not preclude the use of solar radiation and soil moisture resources. Biomass productivity of potato crops grown under optimum growth conditions has accordingly been described by the amount of soil water utilized per unit biomass production and the efficiency by which solar radiation is converted into plant biomass (Monteith, 1965, 1977). These processes are partly determined by the leaf area index (LAI), and an index of radiation interception referred to as the extinction coefficient (Lizaso et al. 2003). As LAI increases, more radiation is intercepted per unit ground area resulting in higher assimilation rates (Ewert, 2004).

The efficiency by which the intercepted radiation is converted into dry matter by potato crop has great relation with the soil temperature and soil moisture contents. Under water deficit conditions, potatoes curl their leaves to lower transpiration rates (Struik, 1989). This mechanism reduces the radiation interception and in turn negatively impacts plant water uptake. Optimal foliage growth and therefore light interception of potato occurs at soil temperature range of 15–20°C (Rykaczewska, 2015). Elevated soil temperatures within the potato rhizosphere induce moisture stress that increases total dry matter allocation to roots and stems at expense of tubers thus reducing crop water productivity (Thornton et al. 1996). Raising night temperatures over the range of 0–20°C increases potato root length while temperature increase to above 25°C induces sharp reduction in the number and weight of tubers (Wilkinson and Davies, 2002).

The adverse effects of elevated soil temperatures on potato growth can be optimized by cropping systems capable of enhancing persistence of leaf area coverage. Intercropping is one of such systems well recommended due to its multiple benefits (Muthoni et al. 2013; Nyawade et al. 2018a; Gitari et al. 2018a, 2018b, 2019). Intercropping achieves greater complementarity of light use per unit area of land with crop mixtures having different rooting ability, canopy structure, height, and nutrient requirements (Nyawade et al. 2019). This complementarity in the use of resources depends on microclimate modification created by the two crops grown in companion.

Nevertheless, little information is available on crop water productivity and radiation use efficiency of potato in relation to soil thermal regimes generated by legume intercrops. This information is needed for identification of management practices that may optimize the high soil temperature conditions prevalent in the tropical and sub-tropical potato growing areas. Therefore, the present work was designed to test the hypothesis that potato yield, crop water productivity and radiation use efficiency of potato grown in intercropping systems exhibit positive relationship with the soil temperature and soil moisture contents.

7.2 Materials and methods

7.2.1 Experimental site and trial design

The trial was carried out during the rainy seasons of 2017 and 2018 in three agro-ecological zones of Kenya; upper midland-Kirinyaga (1552 m above sea level (masl)), lower highland-Kabete (1894 masl) and upper highland-Nyanadarua (2552 masl)). Nyandarua receives mean annual temperature of 18.2°C with an annual rainfall amount of 1500 mm. Kabete receives average temperature of 21.2°C and annual rainfall of 1000 mm. Kirinyaga exhibits relatively lower annual rainfall amount ranging between 600 and 1000 mm and mean annual temperature of 24.4°C. The low rainfall couple with high ambient temperatures are the major hindrances to potato production in the UM and LH AEZs. The initial soil physical and soil chemical characteristics are presented in Chapter 4 (Table 4.1).

A heat and water stress tolerant potato (*Solanum tuberosum* L.) cultivar, Unica (CIP 392797.22) (CIP, 2018), was grown in sole stands and in intercropping with either lima bean

(*Phaseolus lunatus* L.) or dolichos (*Lablab purpureus* L.) and the respective single crop of the legumes. The treatments were laid out in a randomized complete block design with four replications. Intercropping arrangement constituted 2 rows of potato alternating with 2 rows of legumes. Pre-sprouted tubers were planted at a uniform depth of 10 cm on pre-hilled ridges spaced at 75 cm with an inter-seed spacing of 30 cm. Two legume bean seeds were planted per hole at within row space of 20 cm and inter-row space of 75 cm between potato and legume strips and 50 cm between two legume strips. The crop management and cultural practices are described in section 3.5.

7.2.2 Determination of soil water content and soil temperature

Soil water content (SWC) of each plot was measured at 0–30 cm, 30–60, 60–90 and 90–120 cm depth intervals using tensiometers (0–100 kPa) installed in the inter-row of potato and legumes as described in chapter 4, section 4.2.5. Prior to their installation, the tensiometers were calibrated using gravimetric soil moisture measurements taken at soil depth intervals similar to that of tensiometers.

The soil temperature was measured using temperature sensor probes (Onset HOBO USeries, UX120-006 M). The probes were installed at the depth of 0–30 cm in each experimental plot. Soil temperature measurements were taken between sowing and harvesting and recorded by automatic data-logging equipment at every 1 h common step.

7.2.3 Determination of leaf area index, light interception, crop yield, light extinction and radiation use efficiency

Radiation interception of photosynthetically active radiation (PAR) and leaf area index (LAI) were measured from 14 days after potato emergence and progressively at 14 days interval until physiological maturity using a Sunfleck Ceptometer-LP-80 (Decagon Devices, Pullman, WA, USA). Measurements were taken only under the sky-blue conditions with no or minimum clouds, between 1130 and 0130 h (local time), and during a period of constant incident solar radiation. This was meant to eliminate the effect of solar elevation on light interception. Data collection interval thus deviated by about 1–3 days depending on the sky conditions. Dead and brown plant materials were removed from the experimental plots before each radiation measurement. For each measurement, nine above and below canopy readings were taken perpendicularly to the crop rows to ensure that more leaf area was exposed to the light sensors. Corresponding LAI values were read upon averaging the above and below canopy readings. Plot values were computed from the average of four successive middle row readings. The PAR intercepted was calculated using Eq. (7.1–7.3) (Koocheki et al. 2016).

$$\mathrm{PAR}_{intercrop} = PAR_o\left[1 - \exp\left(\left(-\lambda_{potato} * LAI_{potato}\right) + \left(-\lambda_{legume} * LAI_{legume}\right)\right)\right] \qquad (7.1)$$

$$\mathrm{PAR}_{potato} = \frac{\lambda_{potato} * LAI_{potato}}{(\lambda_{potato} * LAI_{potato}) + (\lambda_{legume} * LAI_{legume})} \qquad (7.2)$$

$$\mathrm{PAR}_{legume} = \mathrm{PAR}_{intercrop} - \mathrm{PAR}_{potato} \qquad (7.3)$$

Where PAR is the photosynthetically active radiation (400–700 nm); LAI, the leaf area index, λ, light extinction coefficient; PAR_{o}, photosynthetically active radiation incident which equals to half the daily global radiation (Monteith and Unsworth, 1990). Daily global radiation was estimated from the daily sunny hours recorded from the adjacent meteorological station. The light extinction coefficient (λ) was determined from the slope of the linear regression between the natural logarithm of radiation transmission and leaf area index (Monteith, 1965).

The tuber and legume yields were estimated from the central 1.2 m^2 area of each plot. Tubers were dug out using fork hoe at 85–95 days after planting when the stems were completely dry, brushed and fresh weight taken. About 500 g of the samples from each plot were sliced and dried in an oven at 65°C for 72 h and reweighed to determine tuber DW. Harvesting for lima bean and dolichos was done at 100 and 120 days respectively. The shoot biomass estimations was done by cutting the plants at the soil surface using machetes. The dry mass was determined by oven-drying about 500 g samples at 65°C to a constant mass. The yields (tubers and legumes) were converted into potato equivalents (PEY) using Eq. (7.4). For dolichos, the estimations considered grain and shoot biomass separately for this legume is used both as pulse and forage.

$$PEY\ (kg\ ha^{-1}) = PY(kg\ ha^{-1}) + \frac{LY\ (kg\ ha^{-1}) * LP\ (US\$\ kg^{-1})}{PP\ (US\$\ kg^{-1})} \tag{7.4}$$

Where PEY = potato equivalent yield, PY = potato yield, LY = legume yield, PP = market price of potato (0.38 US\$ kg^{-1}) and LP = market price of legumes (0.21, 0.05 and 1.15 US\$ kg^{-1} for lima bean grain, dolichos forage and dolichos grain respectively).

Radiation use efficiency (RUE) (g MJ^{-1}) of each cropping system was estimated by fitting a linear regression (least square) to the cumulative amount of radiation absorption (MJ m^{-2}) and dry matter accumulation from successive harvests (g m^{-2}) (Monteith, 1994). The slope of each regression was taken as the RUE for each treatment. Data taken at crop physiological maturity were excluded from RUE calculations due to its negligible role in biomass accumulation (Black and Ong, 2000).

7.2.4 Estimation of crop water productivity

Crop water productivity (CWP) was computed from the soil water balance equation and potato equivalent yield (Allen et al. 1998, Eq. (7.5)), as:

$$CWP = \frac{PEY}{P + CR + \Delta SW + I - E - RO} \tag{7.5}$$

Where PEY = potato equivalent yield obtained; P = precipitation; CR = capillary rise of water; ΔSW = change in soil water storage in root zone between planting and harvesting period, I = irrigation; E = surface evaporation; R = runoff. Capillary rise was assumed negligible because the groundwater table was more than 25 m below the soil surface (Karuku et al. 2014). Micro-lysimeters installed in each plot to a depth of 30 cm below the soil surface were used to estimate the soil surface evaporation. Deep percolation was estimated by tensiometers installed to 150 cm soil depth.

7.2.5 Assessment of intercrop productivity

The Land equivalent ratio (LER) was used to evaluate the productivity of intercrops over sole cropping (Eq. (7.6) (Mead and Willey, 1980).

$$LER = \frac{Y_{il}}{Y_{sl}} + \frac{Y_{ip}}{Y_{sp}} \tag{7.6}$$

Where Yil and Yip are intercrop yields of legume and potato respectively while Ysl and Ysp are the sole yields of legume and potato. The LER values above unity indicate that intercropping is more productive and efficient in using land resource than sole cropping, and values less than unity that sole crops are more productive.

7.2.6 Statistical analyses

The data was analyzed using R software, version 3.5.2 (R Core Team, 2017). The treatment effects on soil water content, soil temperature, crop water productivity and radiation use efficiency were tested using a mixed model analysis of variance (ANOVA) with cropping system, season and agro-ecological zone considered as fixed factors and block as random factor. Whenever the interaction of cropping system and season was found significant, data were analyzed in separate seasons. The homogeneity of variances was tested by Bartlett test and where the variances were not homogeneous, data were transformed by the function y = X1/2 or y = log(x). Tukey's honest significant difference test was applied for multiple mean comparisons between treatments, and tests with $p < 0.05$ were considered statistically significant.

7.3 Results

7.3.1 Climatic variables measured during the study period

Averaged across the seasons, the mean rainfall amounts received during the study period were higher in the 2017 long rains followed by 2018 long rains, 2018 short rains and were lowest in the 2017 long rains (Table 7.1). These rains were 30–60% lower than the long-term averages and occurred mainly at tuber emergence and vegetative growth regardless of the site.

Table 7.1: Mean rainfall amount, diurnal and night temperatures, solar radiation, saturation vapor deficit and evaporation for the period between potato planting and harvesting.

	2017 LR			2017 SR			2018 LR			2018 SR		
Parameter/Agro-ecology	UM	LH	UH	UM	LH	UH	UM	LH	UH	UM	LH	UH
Rainfall amount (mm)	290	308	388	184	221	299	243	298	379	190	237	321
Diurnal temperature (°C)	28.5	25.4	22.2	29.8	25.4	21.0	27.3	24.9	21.4	27.9	25.3	22.5
Night temperature (°C)	20.3	17.8	14.5	21.3	18.5	16.0	20.8	18.1	16.5	17.3	16.5	17.3
Solar radiation (MJ m^{-2})	21.2	19.8	18.8	21.5	19.3	19.8	20.6	20.4	18.1	21.8	19.1	19.3
Vapor deficit (mbar)	8.0	6.1	5.2	7.9	6.5	5.9	8.0	6.1	5.2	7.1	6.1	5.0
Soil evaporation (mm day^{-1})	11.2	9.7	4.5	12.5	9.6	4.8	10.9	9.2	4.1	13.6	10.0	4.8

LR, long rains, SR, short rains, UM, LH, UH, upper midland, lower highland, upper highland agro ecological zones respectively. Values expressed as averages over four seasons.

The diurnal and night temperatures were highest in the UM zone and lowest in the UH zones. Mean global solar radiation were greater in the UM zone compared to the LH and UH AEzs. Soil evaporation ranged between 4.5 mm day^{-1} in the UH zone and 11.2 mm day^{-1} in the UM, and saturation water deficit between 5.2 and 8.0 mbars across the sites.

7.3.2 Leaf area index development

The leaf area index (LAI) differed significantly between treatments and was greatest in legume intercropping (1.24–3.78) relative to sole potato cropping (Fig. 7.1). Intercrop of potato and dolichos attained maximum LAI in the UM (1.25–2.68) and in the LH (1.45–3.13) irrespective of the season. This was reversed in the UH zone where intercrop of potato and lima bean recorded the greatest LAI (1.78–3.78). Leaf area index was significantly greater in the long rains (0.45–3.78) than in the short rains (0.06–2.29) irrespective of the agro-ecological zone and peaked one week earlier in the UM zone compared to the UH zone.

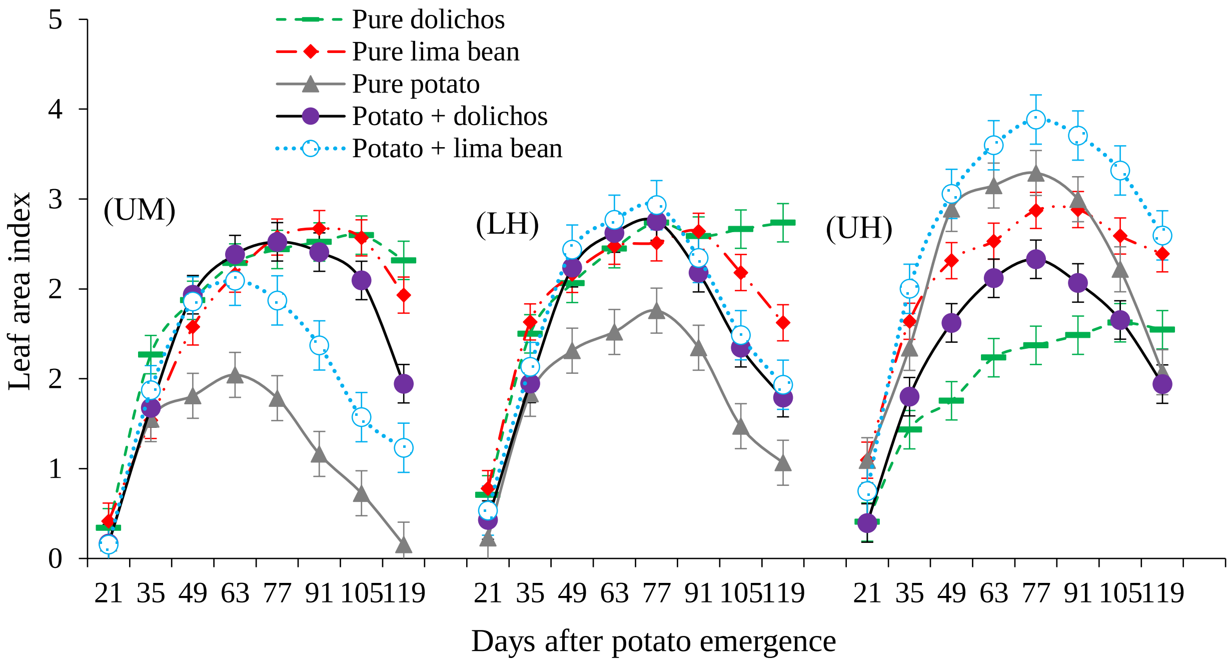


Figure 7.1: Development of leaf area index by different treatments in upper midland (UM), lower highland (LH) and upper highland (UH) agro-ecological zones. Each point is treatment average of 4 replicates. Vertical bars indicate standard error of means. LR=long rains, SR= short rains.

7.3.3 Soil water content and soil temperature

There were significant differences ($p < 0.05$) in the mean volumetric soil water contents (SWCs) measured between the different cropping systems and growing seasons (Table 7.2). Compared with the sole potato stands, highest significant SWC in the surface soil layer was measured under potato-dolichos in the UM (0.07–0.19 cm cm^{-3}) and in the LH AEZs (0.18–0.31 cm cm^{-3}), but under potato-lima bean in the UH zone (0.24–0.36 cm cm^{-3}). Generally, SWC was consistently highest in the UH AEZ (0.17–0.36 cm cm^{-3}) and lowest in the UM AEZ (0.02–0.26 cm cm^{-3}) regardless of the sampling stage. Mean soil temperature was significantly higher under sole potato (22.6–28.1°C) than under legume intercropping (18.1–23.7°C) irrespective of agro-ecological zone and seasons. Seasons, agro-ecological zones, and cropping systems had significant effect on soil temperature and soil water content.

Table 7.2: Intercropping effect on soil moisture content and soil temperatures across the four seasons of study.

Agro-ecological zone		2017 LR	2017 SR	2018 LR	2018 SR	2017 LR	2017 SR	2018 LR	2018 SR
		Volumetric water content[1] (cm^3 cm^{-3})				Soil temperature[1] (°C)			
Upper midland	Sole Potato	0.13a	0.02a	0.10a	0.08a	27.1c	28.1d	26.2d	27.5c
	Sole Dolichos	0.26d	0.10c	0.24e	0.22d	20.6a	20.9a	20.3a	21.4a
	Sole Lima bean	0.21c	0.06b	0.21de	0.18c	22.9b	21.5b	21.8ab	21.6ab
	Potato + Dolichos	0.19bc	0.07b	0.18cd	0.16bc	22.5b	22.4bc	22.2bc	21.9ab
	Potato + Lima bean	0.17b	0.09bc	0.14b	0.15b	23.1b	23.6c	23.7c	22.3b
Lower highland	Sole Potato	0.22a	0.14a	0.20a	0.15a	24.7c	25.8d	24.8d	25.4c
	Sole Dolichos	0.37e	0.22d	0.32c	0.31d	17.1a	20.4a	17.3a	21.4a
	Sole Lima bean	0.32d	0.16b	0.31c	0.28c	19.5b	21.2b	19.6b	21.3a
	Potato + Dolichos	0.28c	0.18bc	0.31c	0.24b	19.5b	21.1b	20.4bc	21.8ab
	Potato + Lima bean	0.25bc	0.19c	0.25b	0.26bc	20.7b	23.9c	21.8c	22.4b
Upper highland	Sole Potato	0.26a	0.17a	0.19a	0.18a	22.6d	23.5d	21.7d	22.3e
	Sole Dolichos	0.30b	0.27c	0.34d	0.24bc	15.3a	20.6c	19.3c	18.7bd
	Sole Lima bean	0.38c	0.24b	0.27c	0.25c	17.8b	17.4a	17.8a	15.4a
	Potato + Dolichos	0.31b	0.27c	0.27c	0.22b	17.9bc	19.8bc	17.9a	19.1cd
	Potato + Lima bean	0.36c	0.24b	0.23b	0.26d	18.1c	18.3ab	18.9bc	17.5b

Letters indicate comparisons for means between the cropping systems at $p \leq 0.05$ by Tukey's HSD test. SR, short rains season, LR, long rains season. [1]Significant interaction between cropping system, agro-ecological zone and season was found for volumetric soil moisture content and soil temperature at the 0.05 probability level. Values expressed as averages over four seasons.

7.3.4 Light interception and leaf extinction coefficient

Fractions of light intercepted were consistently greatest in intercropping of potato and dolichos (0.54–0.59) in the UM and in the LH zones (0.61–0.85), but in potato-lima bean (0.76–0.82) in the UH zone (Table 7.3). These values were consistently lowest in the sole potato stands and decreased as crop growth advanced to tuber bulking. Intercropping significantly lowered the leaf extinction coefficient of both legumes and potato with the values ranging between 0.35 and 0.65 across the sites. Cropping systems, seasons and agro-ecological zone had significant effect on fractions of light intercepted.

Table 7.3: Intercropping effect on light interception and leaf orientation.

Agro-ecological zone	Cropping system	2017 LR	2017 SR	2018 LR	2018 SR	2017 LR	2017 SR	2018 LR	2018 SR
		Fraction of light intercepted[1]				Leaf extinction coefficient			
Upper midland	Pure potato	0.29a	0.22a	0.27a	0.25a	0.61c	0.65c	0.62d	0.63d
	Pure lima bean	0.44b	0.47b	0.48b	0.48b	0.38b	0.39b	0.41bc	0.37bc
	Pure dolichos	0.58c	0.56c	0.59c	0.54c	0.39b	0.36a	0.42c	0.34a
	Potato + lima bean	0.59c	0.61c	0.65d	0.53c	0.37a	0.38ab	0.41bc	0.36a
	Potato + dolichos	0.73d	0.71d	0.75e	0.69d	0.36a	0.37ab	0.38a	0.38c
Lower highland	Pure potato	0.35a	0.42a	0.44a	0.30a	0.54c	0.5c	0.57c	0.57c
	Pure lima bean	0.65b	0.71b	0.76b	0.61b	0.42b	0.46b	0.41b	0.44b
	Pure dolichos	0.70c	0.79bc	0.74b	0.64b	0.35a	0.37a	0.42b	0.37a
	Potato + lima bean	0.71c	0.82c	0.85c	0.61b	0.38ab	0.38a	0.42b	0.38a
	Potato + dolichos	0.82d	0.87d	0.88c	0.78c	0.36a	0.37a	0.37a	0.38a
Upper highland	Pure potato	0.43a	0.45a	0.54c	0.38a	0.51c	0.54c	0.53c	0.54d
	Pure lima bean	0.72c	0.71c	0.79d	0.68c	0.36a	0.37ab	0.38a	0.39bc
	Pure dolichos	0.45a	0.41a	0.46b	0.41a	0.37a	0.36a	0.37a	0.38a
	Potato + lima bean	0.81d	0.82d	0.76d	0.79d	0.39a	0.35a	0.38a	0.37a
	Potato + dolichos	0.54b	0.52b	0.50b	0.50b	0.45b	0.40b	0.44b	0.41c

Letters indicate comparisons for means between the cropping systems at $p \leq 0.05$ by Tukey's HSD test. SR, short rains season, LR, long rains season. [1]Significant interaction between cropping system, agro-ecological zone and season was found for fraction of light intercepted at the p<0.05. Values expressed as averages over four seasons.

7.3.5 Intercropping effect on potato yield equivalent

Highest potato equivalent yield were recorded by intercropping (7.2–38.2 t ha^{-1}) relative to sole potato (1.3–16.3 t ha^{-1}) and were significantly greater in the long rains (5.4–38.2 t ha^{-1}) than in the short rains season (1.3–27.5 t ha^{-1}) (Table 7.4). Potato-dolichos intercropping attained significantly lower potato equivalent yield (12.8–21.7 t ha^{-1}) compared with potato-lima bean (19.4–33.8 t ha^{-1}) in the UH zone. Potato equivalent yield responded significantly to the effect of cropping system, seasons and agro-ecological zones.

Table 7.4: Potato yield as affected by intercropping across the four study seasons.

		2017 LR	2017 SR	2018 LR	2018 SR
Agro-ecological zone	Cropping system	Potato equivalent yield (t ha^{-1})[1]			
Upper midland	Pure potato	8.9a	1.3a	5.4a	3.2a
	Pure lima bean	12.3b	4.7b	9.9b	6.8b
	Pure dolichos	19.7c	7.3c	12.7bc	9.9c
	Potato + dolichos	25.1d	9.5d	16.9d	18.9d
	Potato + lima bean	17.3c	7.2c	13.2cd	9.8c
Lower highland	Pure potato	13.9a	2.9a	7.4a	6.5a
	Pure lima bean	18.9b	5.8b	17.1b	9.8b
	Pure dolichos	25.2c	9.6c	22.6c	13.8c
	Potato + dolichos	38.2d	14.5d	34.6d	24.7d
	Potato + lima bean	24.9c	9.4c	23.8c	13.5c
Upper highland	Pure potato	16.3b	7.9a	9.4a	6.5a
	Pure lima bean	22.2c	19.6c	22.6cd	19.8c
	Pure dolichos	13.1ab	15.8b	11.1a	14.8b
	Potato + lima bean	33.8d	19.4c	26.8d	27.5d
	Potato + dolichos	12.8a	14.5b	19.6b	21.7c

Letters indicate comparisons for means between the cropping systems at $p \leq 0.05$ by Tukey's HSD test. SR, short rains season, LR, long rains season. Values expressed as averages over four seasons. [1] Significant interaction between cropping system, agro-ecological zone and season was found for the potato equivalent yield at $p \leq 0.05$.

7.3.6 Intercropping effect on crop water productivity and radiation use efficiency of potato

Intercropping potato with legumes showed significantly higher crop water productivity ranging between 4.04 and 9.67 kg ha^{-1} m^{-3} relative to sole potato (1.02–3.23 kg ha^{-1} m^{-3}) (Table 7.5). Crop water productivity was significantly greater in potato-dolichos intercropping than in potato-lima bean intercropping in the UM and LH AEZs (4.04–9.67 kg ha^{-1} m^{-3}). This trend was reversed in the UH AEZ where potato-lima bean exhibited highest CWP (3.21–5.98 kg ha^{-1} m^{-3}). Radiation use efficiency (RUE) of potato varied significantly among the treatment and ranged between 0.18 and 0.98 g MJ PAR^{-1} in sole potato and 1.23–2.89 MJ PAR^{-1} in potato-legume intercropping.

Table 7.5: Crop water productivity and radiation use efficiency in response to intercropping.

Agro-ecological zone	Cropping system	2017 LR	2017 SR	2018 LR	2018 SR	2017 LR	2017 SR	2018 LR	2018 SR
		Crop water productivity[1]				Radiation use efficiency[1]			
		kg ha^{-1} m^{-3}				MJ PAR^{-1}			
Upper midland	Sole Potato	1.13a	1.02a	1.57a	1.32a	0.77a	0.18a	0.28a	0.30a
	Sole Dolichos	4.58b	3.21c	3.04b	4.23c	1.89b	1.09b	1.72b	1.34c
	Sole Lima bean	4.34b	2.02b	3.11b	2.13b	1.78bc	1.21b	1.56b	1.05b
	Potato + Dolichos	6.23c	4.04d	6.96d	5.88d	2.09d	1.38c	2.12c	2.01d
	Potato + Lima bean	5.99d	4.02d	4.02bc	4.01c	1.98cd	1.23b	2.08c	1.32c
Lower highland	Sole Potato	2.43a	2.12a	2.45a	2.25a	0.87a	0.98a	0.59a	0.65a
	Sole Dolichos	4.63b	4.34c	4.25b	5.33c	1.99b	1.28b	1.84b	1.67c
	Sole Lima bean	5.31c	3.21b	5.19c	3.23b	1.89b	1.27b	1.87b	1.35b
	Potato + Dolichos	5.84c	5.53c	9.67d	6.81d	2.89d	1.43d	2.87d	2.31d
	Potato + Lima bean	4.53b	5.22c	5.16c	5.12c	2.04c	1.33c	2.13c	1.56bc
Upper Highland	Sole Potato	3.23a	2.21a	3.02a	2.87a	0.98a	0.36a	0.54a	0.53a
	Sole Dolichos	3.78a	4.21b	3.23a	5.98c	2.03b	1.76cd	1.98c	1.98c
	Sole Lima bean	5.98b	3.21b	5.12b	4.56bc	1.94b	1.64c	1.84c	1.97c
	Potato + Dolichos	9.09d	6.54c	8.00d	4.55b	0.97a	1.96d	0.89b	0.98b
	Potato + Lima bean	7.38c	9.20d	7.02c	9.02d	2.56c	1.48b	2.49d	2.36d

Letters indicate comparisons for means between the cropping systems at $p \leq 0.05$ by Tukey's HSD test. SR, short rains season, LR, long rains season. Values expressed as averages over four seasons.[1] Significant interaction between cropping system, agro-ecological zone and season was found for crop water productivity and radiation use efficiency at the 0.05 probability level.

7.3.7 Intercropping effect on land productivity

Land equivalent ratios (LER) were above unity with intercropping in the UM and LH AEZs (1.09–1.29) but lower than unity with sole potato (0.42–0.74) and sole legumes (0.91–0.98) (Fig. 7.2). The highest LER in this study (1.31) was obtained in potato-dolichos system in the UM AEZ. Intercropping potato with dolichos obtained a LER value below unity in the UH AEZ (0.17), the value of which was much lower than that of the sole potato (0.98).

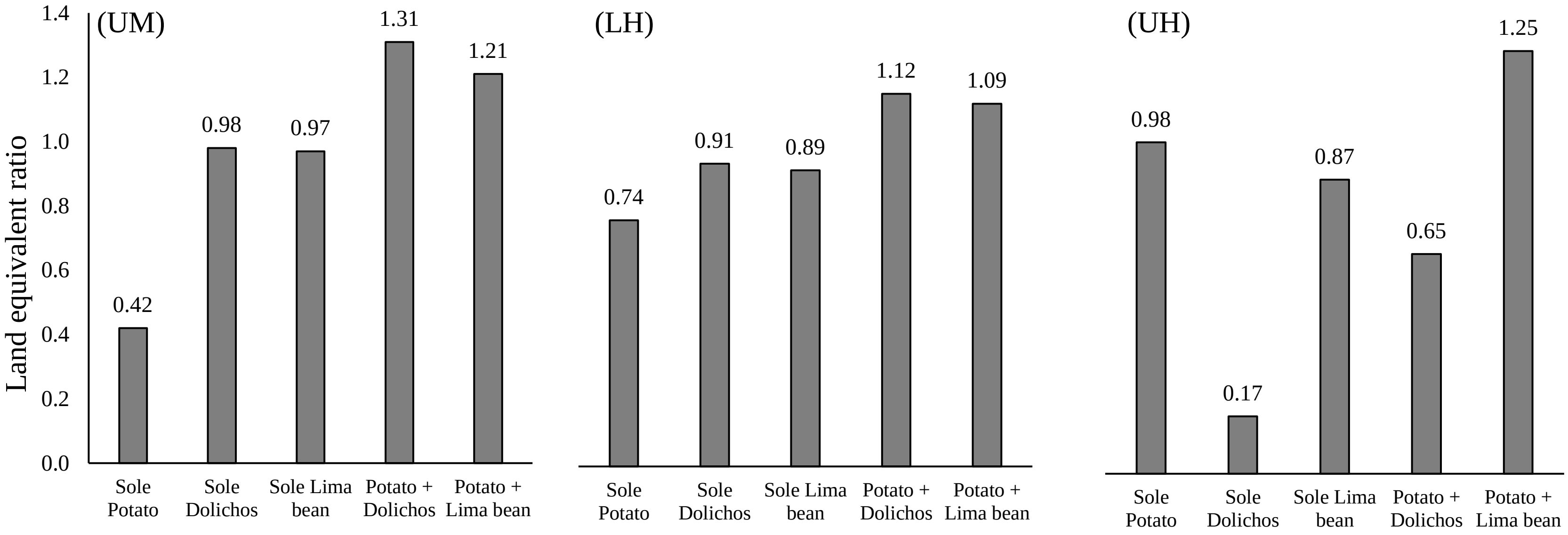


Figure 7.2: Land equivalent ratios (LER) measured in the upper midland (UM), lower highland (LH) and upper highland (UH) agro-ecological zones. Data presented as pooled averages across the four study seasons. The LER values above unity indicate that intercropping is more productive and efficient in using land resource than sole cropping, and values less than unity implies that sole crops were more productive.

7.3.8 Relationships among potato yield, soil water content, soil temperature, crop water productivity and radiation use efficiency

Potato equivalent yield, crop water productivity and radiation use efficiency responded significantly to the effect of soil water content, soil temperature, night temperatures and to the interaction of soil water content and soil temperature (Table 7.6).

Table 7.6: Response of potato yield, crop water productivity and radiation use efficiency to soil moisture and temperature.

Dependent variable	Independent variables	Coefficient	Standard error	t Stat	p
Potato equivalent yield	Soil water content (SWC)	2.340	0.936	2.500	0.002***
	Soil temperature	-6.710	3.010	-2.230	0.000**
	Night temperature	-0.642	0.274	-2.346	0.031*
	SWC*Soil temperature	2.100	2.170	0.970	0.043***
	SWC*night temperature	0.420	0.190	2.180	0.019*
	Soil temperature*night temperature	-2.360	0.440	-5.310	0.760
Crop water productivity	Soil water content (SWC)	1.360	7.570	0.180	0.000***
	Soil temperature	-0.137	0.039	-3.513	0.009**
	Night temperature	-0.080	0.044	-1.818	0.023*
	SWC*Soil temperature	7.500	0.560	13.330	0.000 ***
	SWC*night temperature	0.160	0.060	2.820	0.065
	Soil temperature*night temperature	-0.110	9.300	-0.010	0.078
Radiation use efficiency	Soil water content (SWC)	4.130	2.360	1.750	0.006**
	Soil temperature	-0.137	0.039	-3.513	0.009**
	Night temperature	-1.710	0.300	-5.690	0.042*
	SWC*Soil temperature	-7.580	2.810	-2.690	0.007**
	SWC*night temperature	2.750	5.210	0.530	0.069
	Soil temperature*night temperature	-0.140	0.080	-1.630	0.010

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1; Adjusted R square-Potato equivalent yield = 0.83; Crop water productivity = 0.78; radiation use efficiency = 0.82.

The interaction of soil temperature and soil water content had the highest significant positive effect on both the potato equivalent yield, crop water productivity and radiation use efficiency. Soil water content showed stronger effect on all the three parameters (potato equivalent yield, crop water productivity and radiation use efficiency) compared to soil temperature and night temperatures.

7.4 Discussions

7.4.1 Variability of crop leaf area index

The greater leaf area index (LAI) under intercropping could be explained by the differences that existed in the vertical foliage arrangement and canopy architecture of the different crop varieties. As indicated by the significantly lower leaf extinction coefficient, the larger and nearly vertical leaves exhibited by dolichos provided complementarity to the slender leaves of potato. Ma et al. (2015) observed that potato canopy is characterized by leaf bending, creating bare surfaces between the crop rows which greatly hamper the LAI. Dolichos provided a low dense canopy which closed these bare spaces while the effective canopy overlap by lima bean bridged the inter-row spacing thus enhancing LAI development (see Fig. 7.3). The canopy closure of potato was effective only after 40 to 45 days followed by rapid decline after physiological maturity. The legume intercrops conferred a complimentary canopy that kept LAI relatively high during these periods.


(a) (b) (c)

Figure 7.3: Canopy overlap by potato grown alone (a) and potato intercropped with lima bean (b) and dolichos at vegetative growth of potato. Photos taken in the upper midland agro-ecological zone at vegetative growth of potato.

Even though the higher soil temperature conditions early in the season favored tuber sprout and early canopy development in the UM and LH AEZs relative to the UH AEZ, the restricted peak leaf area index and limited persistence led to no advantage. While evaluating the effect of three temperature regimes (16, 22 and 27°C) on potato leaf formation, Shah et al. (2004) recorded leaf number values of 32, 20 and 14, respectively per mainstem indicating depressing effect of high soil temperatures. Potatoes grown under high soil temperature conditions often grow taller with longer internodes, reduced leaf numbers, and are characterized with leaves which are shorter and narrow (Struik et al. 1989). Elevated soil temperatures have further been shown to decrease the number of potato leaves emerging from lateral branches (Nyawade et al. 2018a). All these affect the potential of LAI development and subsequently, radiation interception and use efficiency.

Attainment of peak LAI at different times in different sites suggests that the spatial distribution of LAI was affected by agro-ecological zones. This variability could be explained by changes in the timing of leaf senescence in response to water availability and ambient temperatures. Low nutrient availability under low soil moisture levels in the UM zone may have accelerated leaf senescence to satisfy the nutrient demand of sink organs leading to earlier attainment of peak LAI. Consistent results were found by Sinclair (2000) who argued that water deficit considerably reduces the stomatal conductance leading to an interruption of biomass accumulation. Under such conditions, water reserves of the plants may be consumed which can lead to termination of LAI development. Zahoor et al. (2010) demonstrated that high ambient temperatures might cause loss of cell wall plastid integrity. This coupled with stomatal closure in response to heat stress generally lowers the photosynthetic rates. Stomatal closure occurs due to decreased leaf turgor under low atmospheric vapor pressure along with root-generated chemical signals (Chaves et al. 2002). These processes might have shortened the crop leaf longevity leading to decrease in LAI. A better LAI development in the UH AEZ than in the LH AEZ could be because of the higher and well distributed rainfall amount which led to better nutrient assimilation.

The observed values of leaf extinction coefficient are in agreement with those reported by other authors for potato in tropical Africa (Allen and Scott, 1980). The higher leaf extinction coefficient (above 0.5) observed in pure potato stand was an indication of few vertical leaves in these treatments (Sinclair and Muchow, 1999). It thus implies that monocropped potato had more bent leaves with increased its propensity to converge solar radiation.

7.4.2 Soil temperature and soil water content

The high soil moisture content in the 0–30 cm in intercropping was related to the shading conferred by the greater canopy that minimized the soil evaporation losses. In sole potato, heat from the topsoil was more easily lost to evaporation through the intervening bare soil surfaces. Gitari et al. (2018b) found that intercropping potato with dolichos increased crop water productivity by 20% due to the creation of canopy shades which lowered the soil surface evaporation. The reduced ability of dolichos to confer protective shade in the UH AEZ was attributed to its low adaptation to low temperature conditions (Cook et al. 2005). The deep root systems by the legumes further minimized soil water extraction within the topsoil as they had increased capacity to extract water from the subsoils.

7.4.3 Effect of legume intercropping on radiation interception

The increased light interception by intercrops relative to sole potato stands could be asserted to the increased canopy size. The intercrops generally attained maximum canopy above 3, a value that corresponds to full groundcover by a typical potato cropping system (Allen and Scott, 1980). This was partly attributed to the increased number of leaves forming on lateral branches of legumes. Plants in intercropping systems were thus able to occupy all the empty niches thus contributing strongly to canopy size and radiation interception.

Because dolichos and lima bean leaves have similar leaf characteristics on their adaxial surfaces, corresponding light absorption would be expected to be identical. This was not the case in this study as sole stands of dolichos intercepted more light than lima bean in the UM and LH AEZs. Dolichos put short, dense canopy with few interior leaves relative to lima bean which established tall, broad dense crown with many interior leaves which allowed very little light to penetrate through the canopy.

The reversal of radiation interception by dolichos relative to lima bean in the UH AEZ indicated that differences in radiation interception among the cropping systems were influenced by agro-ecological zones. This observation could be explained by the fact that different crops have different thermotolerance limits (Wahid et al. 2007). Unlike legumes which indicated progressive growth with little response to prevailing heat stress, potato crop responded by developing leaves showing downward curvatures, similar to finding by Romero (2017). This observation was confirmed by the consistently higher leaf extinction coefficient in the sole potato. This mechanism greatly reduced leaf area exposure to solar radiation and thus reduced radiation interception. The mechanism was probably meant to avoid water loss by potato under extreme temperature conditions. In the UM AEZ where crops suffered longer heat stress, potato leaves drooped followed by wilting that started from the lower strata leaves. Only leaves that exhibited some level of greenness recovered turgor and finalized their production cycle. These leaves however had limited capacity to absorb solar radiation, an observation affirmed by the proportional decrease of LAI with increasing soil and ambient temperatures.

7.4.4 Intercropping effect on biomass accumulation and land productivity

Intercropping accumulated higher biomass and was more light use efficient compared to potato monoculture system due to their more vertical leaves as was indicated by the relatively low leaf extinction coefficient. The invariably lower dry matter yield of potato intercropped with lima bean compared to potato intercropped with dolichos in the UM and LH AEZs is primarily due to the shading effect caused by the bushy canopy of lima bean. The quality of light in terms of the ratio of light intercepted to total solar radiation reaching the potato crop was thus compromised by the understory canopy of lima bean. Burke (2017) noted that shading prolongs the stolon elongation period and delays tuberisation. When shading reduced radiation by approximately 50%

during the period of tuber initiation, tuber numbers decreased by 20%. These results strongly suggest that the amount of solar radiation intercepted by potato was indeed causal in determining dry matter accumulation.

Land productivity measured by land equivalent ratio was greater than unity indicating more efficient and productive use of land resource by intercrops. It was therefore more productive to intercrop potato with legumes than grow each component in monocultures as legume intercrops converted the intercepted radiation more efficiently into biomass. Intercropping in addition, increased the efficiency by which the soil nutrients and soil water were converted into biomass. It may therefore be inferred that intercropping is a resilient cropping system capable of stabilizing yields while guaranteeing efficient use of land resource.

7.4.5 Relation of potato yield, crop water productivity and radiation use efficiency to temperature and soil water content

Based on our observations, canopy and tuber growth were generally slowed during the periods of heat stress and increased thereafter when the soil temperature and soil moisture conditions improved to nearly optimal levels for potato growth. A direct consequence of this effect was shortening of the tuber bulking period. Burke (2017) noted that high soil temperatures coupled with high ambient temperatures caused premature senescence in potato with yield reduction of 20–30%. In a study conducted by Radeni and Caesar (1986), heating soil to 28°C reduced the flow of assimilates to tubers. Similarly, Krauss and Marschner (1984) observed cessation of starch accumulation when developing tubers were subjected to soil temperature of 30°C. It could also be possible that allocation of assimilated carbon into non-structural and structural carbon was altered by the high soil temperatures (Arai-Sanoh, 2010).

For the legumes, the effect of high soil temperatures were mediated in part by the deep roots. While potato crop was characterized by roots that rarely exceeded a vertical depth of 30 cm, dolichos roots were traced to 120 cm depth while lima bean roots penetrated to about 90 cm depth. Legumes could therefore access cooler subsoil layers. This is in agreement with the previous studies which have established that potato has shallow fibrous root systems which are concentrated in the topsoil layer making the crop highly sensitive to fluctuating soil moisture contents and high surface soil temperatures (Aliche et al. 2018; Gitari et al. 2018b).

Moisture deficits during root initiation period induce lignification of adventitious roots and hampers potato growth (Belehu and Hammes, 2004). This process is exacerbated under high soil temperatures. It may therefore be concluded that the consequence of aiming for the highest tuber yields in potato production is a water demand in excess of that which can consistently be met by the plant from natural sources. This view was evident in the UM zone that despite it receiving great irradiance, could not attain the high biomass yield primarily due to the low and poorly distributed rainfall.

Soil temperature interacted with soil moisture to influence the potato yield, crop water productivity and radiation use efficiency. High soil temperatures have been shown to increase the soil water flow resistance through the soil-plant-atmosphere continuum and hence reducing the plant root water uptake (Schwarz et al. 1997). Therefore, keeping soil water contents high at extreme soil temperature conditions would minimize the impact of high soil temperatures and increase the efficiency by which the intercepted light is converted into plant biomass. Prolonged heat and water stress results in root clumping, root deformations and shrinkage, and causes weak root-soil contact that limits root water uptake and transport (Trebejo and Midmore, 1990). This effect is especially true if heat stress is coupled with soil water deficit and/or an increase in soil temperature (Irmak, 2016).

Night temperatures also showed a significant effect on potato yield, crop water productivity and radiation use efficiency. Intercropping lowered the night soil temperatures to an optimal range of 15–20˚C for tuber formation thus increasing tuber weight and yield. High night soil temperatures above the latter range may induce high gibberellin acid concentrations in the stolon tip with consequent disruption of tuber growth (Wilkinson and Davies, 2002). Onset of tuberization was generally delayed with night temperatures greater than 25°C, an observation associated with accelerated metabolism and growth due to induction of specific inhibitory effects. Radiation use efficiency of potato has been shown to decrease during high temperatures only if the partial stomatal closure is coupled with high night temperatures that lower net respiration (Burke, 2017). The greater specific heat capacity of a moist soil could have contributed to the yield increase observed in the UH AEZ (Hunt et al. 2010).

Radiation use efficiency was significantly lower in the UM relative to LH AEZ partly because of reduced partitioning of dry matter to tubers under heat and water stress conditions. This effect was offset to some extent in intercrops due to legumes' ability to confer shade that optimized soil temperature and soil moisture conditions. The reduced efficiency by which the solar radiation was converted into tuber dry matter in the LH AEZ appeared to be associated with the delay in the onset of tuber bulking and increased stem growth caused by the higher temperatures, an observation well explained by Bodlaender (1963). The lower soil temperatures within the optimal range for potato growth in the UH AEZ favored rapid tuber initiation resulting in greater number of tubers formed. Prolongation and greater persistence of leaf area index in the UH AEZ further contributed to extended radiation interception thus compensating for the radiation interception sacrificed earlier in the season when the low soil temperatures delayed tuber sprout.

The observed effect of season on radiation use efficiency is primarily due to variations in the amount and distribution of rainfall in relation to the potential demand for water. The larger amount and better distribution of rainfall during the long rains season increased the soil water content which in turn favored early establishment and growth of crops. On the contrary, potato suffered from severe moisture stress conditions during flowering and tuber filling stages. This greatly contributed to low vegetative growth and yield decreases during the short rains. Extremely dry soil not only restricts respiration, but also facilitates wilting due to depressed xylem and leaf tissues (Falah et al. 2010). In potatoes, this condition is generally manifest first in the newly formed leaves with consequent death if this condition continues throughout the plant.

7.5 Conclusion

This study demonstrate the potential role of legume intercropping in enhancing radiation interception and use efficiency of potato grown under heat and water stress conditions. Legume intercrops reduced soil temperature, hastened foliage development and canopy cover of the soil which in turn reduced soil temperature and favored tuber initiation. By extracting water from the deep soil layers and lifting it to the leaves via evapotranspiration, legumes enhanced leaf area index development under heat and water stress conditions. This enhanced radiation interception and subsequent conversion into biomass. These findings have implications with respect to potato production in tropical lowlands where high temperatures are amongst the major problems limiting the potato production. Farmers are likely to stabilize potato yields and accrue high returns from systematic legume integration into potato cropping system. These benefits can only be realized if crop diversification is based on agro-ecological and system compatibility.

CHAPTER EIGHT

GENERAL DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

8.1 General discussions

Potato production in the lowlands and midlands is limited mainly by erratic rainfall and high ambient and soil temperatures. As soil temperatures increase, soil dries up much faster and water movement in the soil becomes limited for the shallow rooted potato crop. Chapter four of this study revealed the capacity of potato-legume intercropping to moderate the soil temperatures and increase the soil water contents. Legume intercrops developed increased root length density at greater depths which progressively extracted the free water from deeper soil layers. The deeper root system exhibited by legume intercrops provided a mechanism for continued nutrient uptake leading to divergence of the nutrients leached below the potato root zone. Since there was lack of protective canopy cover in the bare regions between the double rows of potato stands, these portions were directly exposed to solar radiation and exhibited higher soil evaporation. The resultant high soil temperatures reduced potato root growth, potentially restricting the uptake of water and soil nutrients.

As intercropping had greater positive influence on nutrient uptake at vegetative phase and water consumption at tuber bulking phase of potato growth, it becomes evident that significant water and nutrient savings can be achieved by tailoring the timing of legume incorporation to specific stages of the potato growth cycle. In general, water and nutrient deficits during stolonization and tuber initiation and bulking, had adverse effect on tuber yield.

As evident in chapter five, the high formation of SOM under legume intercropping relative to sole potato cropping was due to the high crop residue retention. When intercropped with legumes, the total biomass accumulation increased by up to 10 fold suggesting increased source of SOM. The SOM content was particularly high in the third season of residue incorporation suggesting cumulative buildup of SOM. The fact that roots were in close proximity to soil microbes and soil mineral surfaces, induced interactions that directly affected the decomposer community structure and function, potentially enhancing microbial biomass and activity. It is thus apparent that progressive legume inclusion in consociation with potato crop would in the long-term restore the impoverished soil fertility in smallholder potato farms. Thus, improvement of SOM in smalholder farming systems not only requires the application of chemical fertilizers but also strategies that integrate legumes into cropping systems.

The greater microbial activity in plots with dolichos relative to those with lima bean in the UM and LH AEZs was attributed to the greater biomass generated by dolichos. This trend was reversed in the UH AEZ where low temperatures hindered dolichos growth and therefore biomass accumulation. This observation points the need to promote legume varieties adapted to the range of existing climatic conditions so as to ensure wide adaptability and stable supply of SOM. Further, the low soil organic matter contents under sole potato cropping indicated that this system might contribute to faster deterioration of soil health and quality. This was partly due to the low residue return and the high residue content of lignin and polyphenols. This caused nitrogen to be immobilized and become unavailable for subsequent crops thus restricting the microbial growth and activity.

Chapter six of this study demonstrated the capacity of potato-legume intercropping to optimize the amount of nitrogen retained in the biomass and soil, thus offering a mechanism for optimizing the soil N balance. The high acquisition of nitrogen in the surface soil layer by potato crop created depletion zones thus generating a heterogeneous pattern of resource distribution. This probably compelled the legume components to develop extensive root systems to enhance N acquisition from deeper soil layers. When legumes were grown in intercropping systems, the ratios of incorporated residue C-to-N, lignin-to-N, polyphenol-to-N and lignin + polyphenol-to-N decreased, creating favorable conditions for SOM decomposition thus resulting in net N mineralization. Most of N release occurred at a time when N uptake by potato crop was at its peak, an indication that synchrony of nutrient supply and demand was attained thus reducing excessive N accumulation. Reduction of nitrogen loss in this manner could be an effective measure to increase the efficiency of nutrient use. Thus, potato-legume intercropping is an option to help reduce N-fertilization as compared to sole potato production.

As demonstrated in chapter seven, intercropping increased biomass yield, an observation that was associated with either increase in numbers of tubers per hill or increase in individual tuber weight. The choice of legume was found to be very important and should be based on the AEZ. The yields expressed as potato equivalents were greatest in potato-lablab intercropping in the upper and lower highland AEZs and in potato-lima bean intercropping in the upper highland AEZ indicating that these systems may be preferred by smallholder potato farmers in these zones. Dolichos was better adapted to the midlands and lowlands because of its high tolerance to drought once established. The increased solar interception and use efficiency by intercropping relative to potato monocropping was asserted to the increased canopy size and duration. Factors related to genotype selection and populations were found important in the distribution of photosynthetically active radiation within the intercrop canopy.

Land equivalent ratios of intercrops were above unity indicating more efficient and productive use of land resource. In the upper midland zone, the high soil temperatures recorded in sole potato plots adversely affected potato root development making much of starch to be directed to stems and leaves at the expense of tuber expansion. It could also be possible that allocation of assimilated carbon into non-structural and structural carbon was altered by the high soil temperatures. For the legumes, the effects of high soil temperatures were mediated in part by their deep roots coupled with their good adaptations to high temperatures. In addition, the legume intercrops exhibited low leaf extinction coefficient making the system more light use efficient compared to potato monoculture system.

8.2 Conclusions

Systematic incorporation of legume intercrops in smallholder potato farming systems is evidently a novel technology to conserve soils in the hilly terrains and optimize soil temperatures and moisture contents in the drier lowlands. This practice achieves sustainability through increased resource productivity, enhanced risk aversion and improved profitability. Consequently, potato-legume intercropping has a high potential to adapt farmers to the adverse effects of climate change. Even though we could not directly relate the increase in potato equivalent yields to increased SOM and soil nitrogen contents, it was apparent that this advantage would occur in the long-term with legume intercropping. Thus, potato-legume intercropping system is a resilient and effective practice capable of adapting potato to the changing climatic conditions and expand production to the midland elevation agro-food systems.

8.3 Implications of the study

8.3.1 Implications to potato and legume breeders

While intercropping potato with legumes is an option to enhance climate resilience, this is only possible if the genotypes used are well adapted to the system. To the breeders, the selection of potato varieties for high yield in closely planted sole-crop stands is likely to result in varieties which are also optimal for intercropping with legumes. In cases where reductions in irradiance receipts by potato grown in intercrops is experienced, only potato genotypes possessing shade tolerance exhibits the remedy to increase biomass accumulation (Schulz et al. 2019). Selection for high initial vigor may be important for potato relayed with late maturing legumes to avoid excessive growth retardation which persists later on. In this case, indeterminate legumes are appropriate. The legumes to be be bered should be shade tolerant, have short stature with low vigor, and preferably mature in less than 90 days. Legume varieties with erect leaves would allow more light to reach the associated potato. These legumes should have a high harvest index to lower vegetative vigour, and probably have adequate compensatory growth after potato harvest. In addition, early vigorous root proliferation by legume may be a useful selection trait for maintaining yield of potato under restricted water level (Puértolas et al. 2014).

8.3.2 Agronomic implications

Potato-legume intercropping seems less suitable for high nitrogen input agriculture or where soil is highly fertile, unless potato is intercropped at low density. Under very fertile soil conditions, N fixation potential is greatly reduced and the rapid growth of the legumes depresses potato growth. In such cases, low harvest index of both potato and legume lowers the nutrient use efficiency. Preferably, the legume breeds that can exude carboxylates and phosphate solubilizing enzymes are appropriate for P deficient soils while those that are high nodulating are suitable for N depleted soils. The potential synergy of legume intercropping and potato cultivars was observed in the drier midland and lowlands. Therefore, this synergy could represent an additive interaction if abiotic factors are the main limitations to potato yield.

8.3.3 Policy implications and recommendations

Systematic incorporation of legume intercrops in smallholder potato farming systems is evidently a novel technology to conserve soils in the highlands and optimize soil temperatures in the lowland and midlands. Consequently, this innovation has a high potential to adapt farmers to effects of climate change. Bearing this in mind, a proposal is made for a policy framework that should pay attention to the following components:

(i) **Develop agro-ecological specific intercropping:** potato-legume intercropping must be adapted to location-specific agro-ecological zones and target multipurpose legumes providing human food, livestock feed and enhancing soil fertility.

(ii) **Strengthen local seed system:** poor access to high-quality fodder and grain legumes are potential barriers to adoption of potato-legume intercropping. A functional seed production and dissemination system entailing proper assessment of seed demand must be ensured. Programs that allow integration of formal and informal seed sectors may be necessary to ensure enhanced production.

(iii) **Create attractive markets for fodder and grain legumes:** farmers will adopt potato-legume intercropping if the derived produce has a ready market and the practice ensures good returns on land, capital and labor.

(iv) **Develop capacity at all levels:** potato-legume intercropping should be integrated into formal and informal learning and extension systems, and implemented through field demonstrations, farmer trainings, exhibition visits and farmer field schools. Capacity building should include provision of essential public services, which facilitates access to markets and knowledge, and improves skills needed to innovate and improve resource use efficiency. Make the results/derived benefits of potato-legume intercropping available to the farmers to enhance public education and contribute to more effective management of resources in the future.

(v) **Support local research on the environmental and economic benefits of best management practices**: there is need to integrate potato-legume intercropping into climate change and agricultural innovation policies. This can be achieved through enhanced research. Generally, farmers tend to be sceptical about practices implying national standards when there is no local history of use. Alternative practices new to an area need to be locally tested in the field so that farmers can see the environmental and economic benefits first-hand. The government role in the agricultural innovation system should be focused in providing governance, funds for innovation activities, and incentives for private investment and adoption of innovation. The research approach should aim at crop diversification and must ensure transition of agriculture and food production towards agroecology.

(vi) **Provide incentives for intensification:** as for the long-term benefits of potato-legume intercropping (such as improved soil fertility), there is no evidence of a rapid productivity gain. It is however certain that these gains will occur over time, but the direct benefits to productivity are probably small. Incentives such as provision of farm machineries and legume seeds to the farmers implementing potato-legume intercropping will undoubtedly intensify the adoption of this technology.

(vii) **Design and validate a participatory rural appraisal decision-support tool:** the tool is needed to guide the prioritization protocols of custom tailored intercropping system, and should be evaluated through endline surveys. One aspect of the participatory approach would relate either to subsidies/direct support to farmers who would adopt potato-legume intercropping or to state environmental regulations if the problems would not be solved through voluntary participation. The farmers should be convinced that by voluntary action, they would more likely achieve satisfactory locally acceptable solutions to impoverished soil fertility and low potato productivity. Further, there should be a policy evaluation model that evaluates the impact of different potato-leume intercropping policy measures on trade and markets, through their effects on output prices, inputs prices or income.

8.4 Research gaps

In order to fully unravel the mechanisms underlying the observed benefits of potato-legume intercropping and unlock the technology to the smallholder farmers, the following research gaps need to be addressed:

(i) While the residue transformation into labile organic matter fractions reflected the role of soil microbes in nutrient cycling, the role of fauna e.g. the earthworm casts, bacterial strains and mycorrhiza under potato-legume mixture remains elusive. In addition, linkages between litter fauna, age of biomass cutting, residue biochemical composition and SOM dynamics should be assessed under different temperature and moisture regimes.

(ii) The increase in soil nitrogen balance was undoubtedly due to increased N_2 fixation. Nevertheless, whether the nitrogen fixed is directly transferred to potato intercrop remains a speculation. These concerns need further exploration if resource complementarity and facilitation mechanisms are to be fully understood.

(iii) The increase in phosphorus uptake by potato due to legume intercropping was alluded to microbial rhizospheric phosphorus facilitation and organic acid exudation. To validate such postulation, there is need to induce the activity of phosphorus solubilizing bacteria and organic acid production by different legumes in a microcosm set up. The phosphorus released should be mobilized to companion potato crop by endophytic bacterial strains under controlled environment before the experiment is furthered under field conditions.

(iv) It is expected that when crops are intercropped, there would be benefits from root interaction or avoidance, or even allellopathic exchange in the rhizosphere of the companion crops. Only little knowledge has been unraveled in this area under potao-legume intercropping systems.

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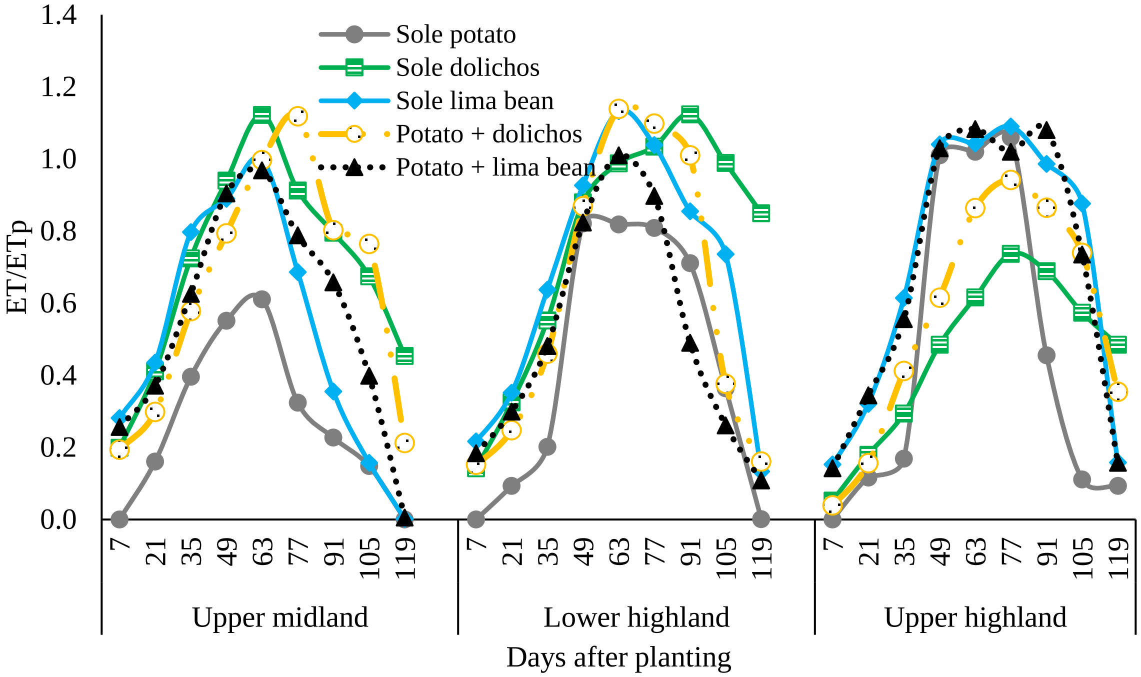
APPENDICES

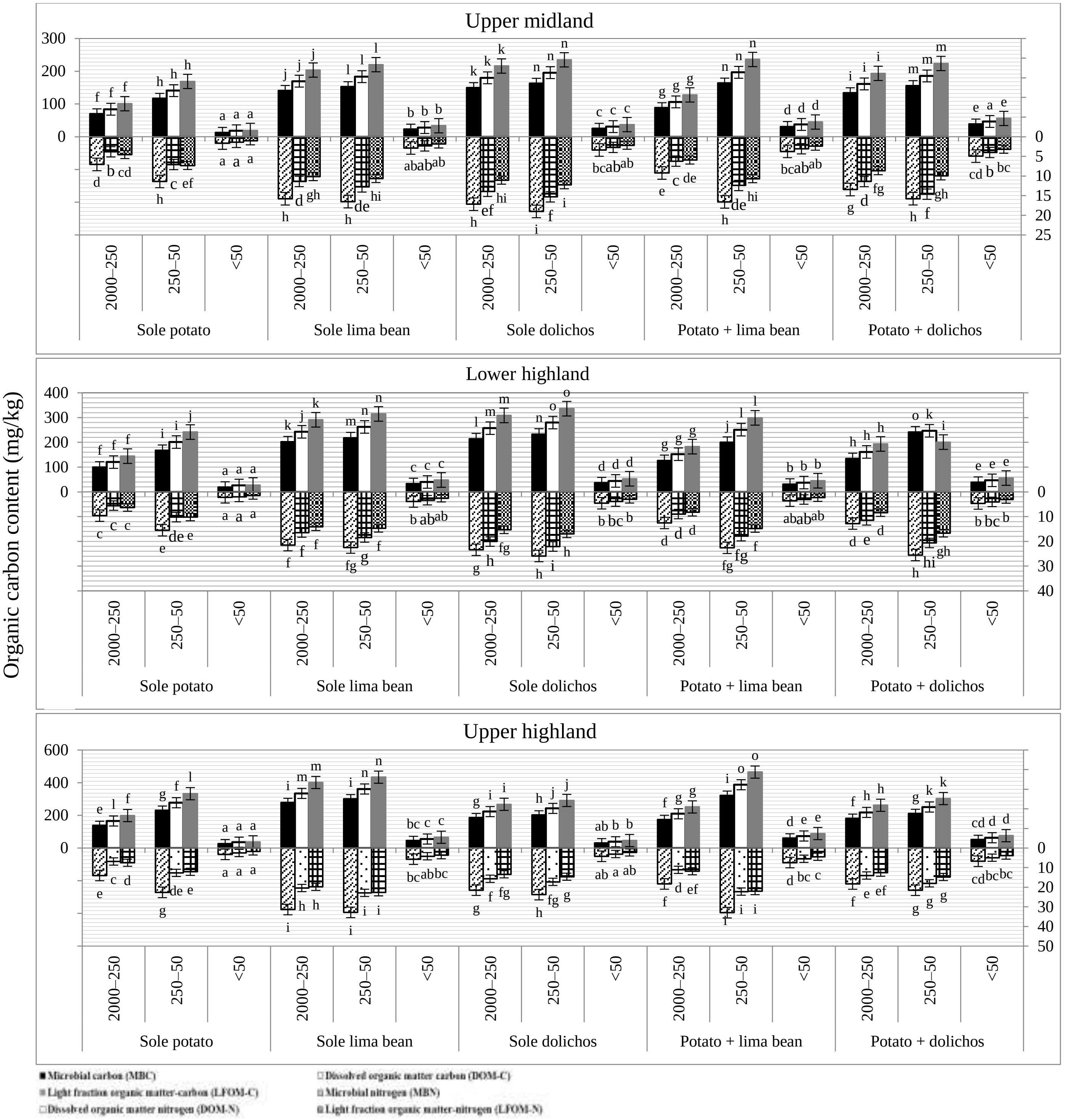
Appendix 1: Soil water balance components measured under different cropping systems at the depth of 0–30 cm.

Agro-ecological zone	Cropping system	ΔSWC	I	R	RO	DP	Ep	ET	∑
		mm							
Upper midland	Pure potato	-18.0a	92.1	298.7	14.4e	32.5c	118.8c	218a	6.5a
	Pure lima bean	22.2c	92.1	298.7	6.7d	16.7b	40.6a	334c	21.7b
	Pure dolichos	25.4c	92.1	298.7	3.8bc	14.3b	41.5a	329bc	31.4c
	Potato + lima bean	-3.6b	92.1	298.7	2.4ab	15.6b	52.8b	301b	17.8b
	Potato + dolichos	-2.3b	92.1	298.7	5.6cd	10.7a	55.4b	306b	16.4b
Lower highland	Pure potato	-3.4a	71.9	411.1	55.5d	66.4e	76.7c	274a	9.0a
	Pure lima bean	28.8c	71.9	411.1	15.5b	22.3b	10.4a	427c	32.6b
	Pure dolichos	29.2c	71.9	411.1	9.8a	12.3a	16.9b	432c	37.2c
	Potato + lima bean	6.2b	71.9	411.1	23.3c	48.9d	19.5b	362b	31.5b
	Potato + dolichos	6.5b	71.9	411.1	17.7b	33.7c	17.3b	379b	37.8c
Upper highland	Pure potato	5.6a	14.6	469.7	60.2c	94.7d	23.7c	282a	14.7a
	Pure lima bean	14.3c	14.6	469.7	44.7b	46.3a	7.7a	345bc	36.3c
	Pure dolichos	9.8b	14.6	469.7	71.1d	84.4c	24.6	277a	22.4b
	Potato + lima bean	10.9b	14.6	469.7	38.6a	40.9a	9.8ab	347c	40.3c
	Potato + dolichos	9.5b	14.6	469.7	68.1d	64.4b	11.8b	316b	18.9b

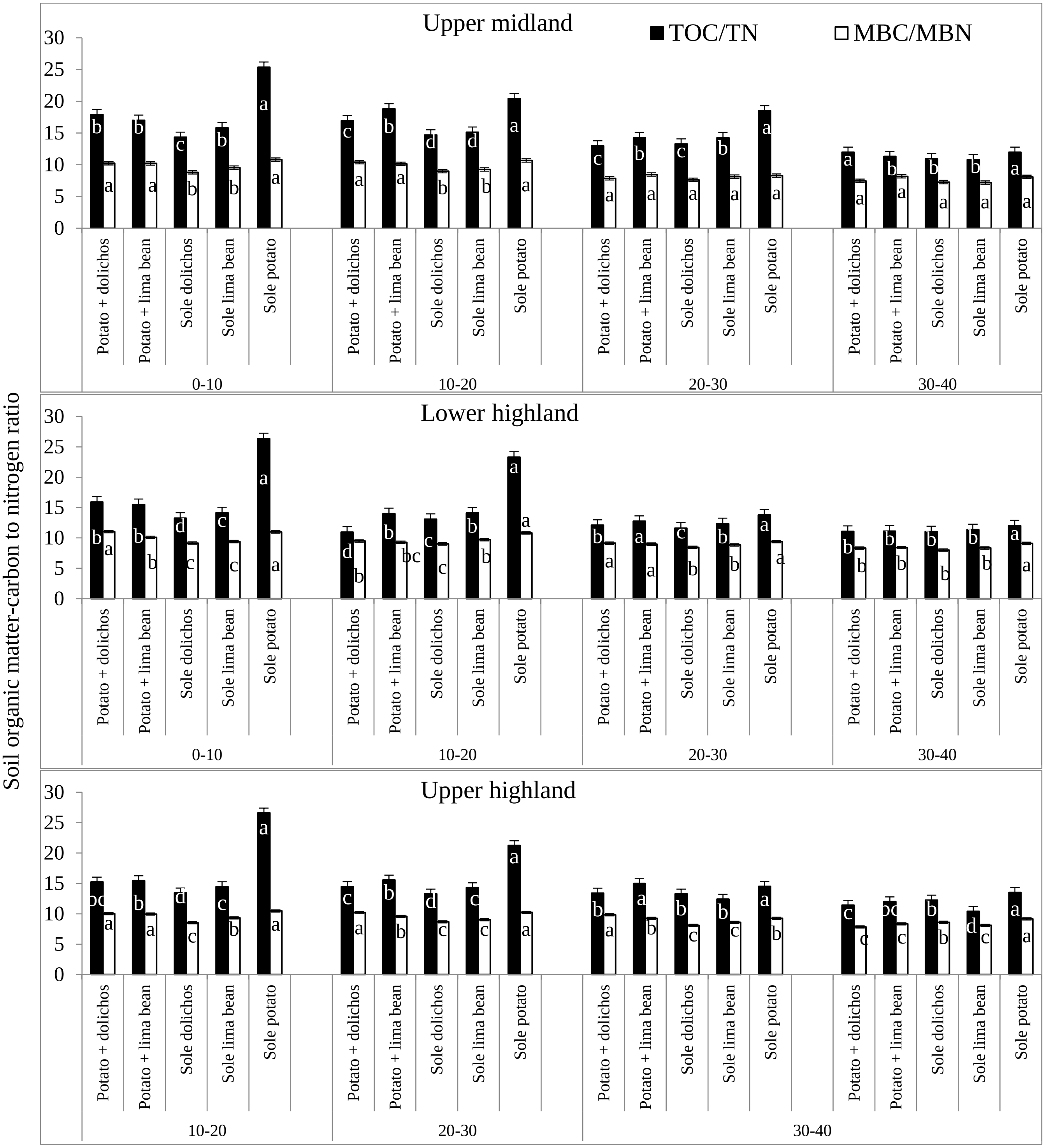
Soil water storage (ΔSWC), irrigation (I), rainfall (R), surface runoff (RO), deep percolation (DP), soil evaporation (Ep), evapotranspiration (ET) and total water balance (∑). Values followed by different letters within a column indicate significant differences at Tukey's $p \leq 0.05$. Values are 4 replicates expressed as averages over the four seasons.



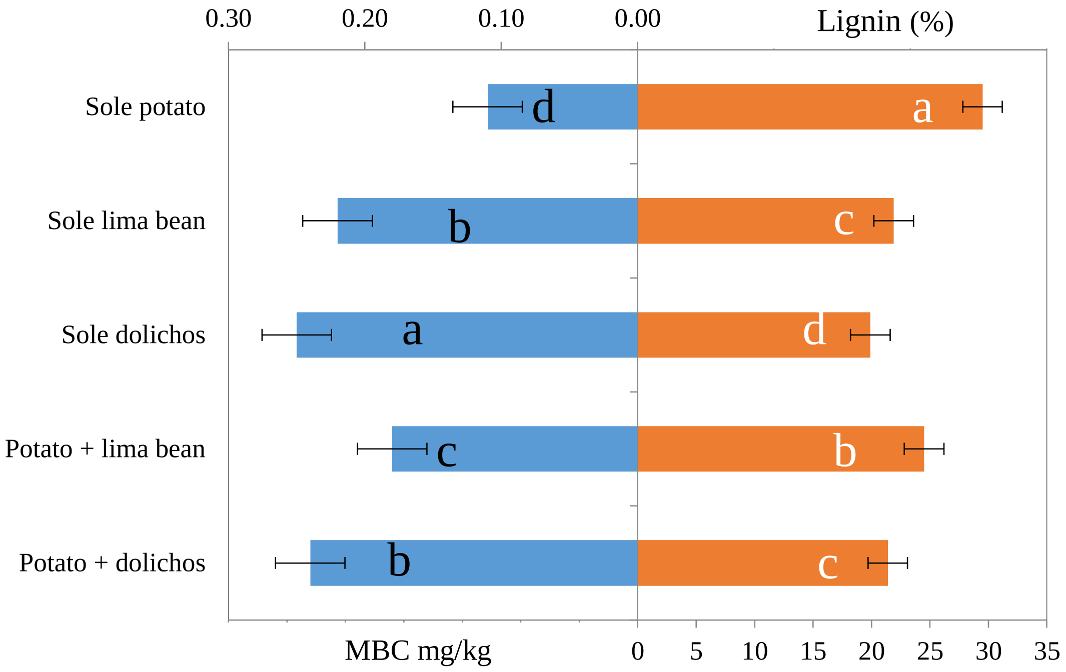
Appendix 2: Ratio of actual evapotranspiration (ETa) to potential evapotranspiration (ETp) under different treatments in the three agro-ecological zones. Values are 4 replicates expressed as averages.



Appendix 3: Distributions of SOM fractions within aggregate classes (μm) under different cropping systems. Bars with different letters for a given aggregate-size differ significantly between treatments (Tukey's $p \leq 0.05$).



Appendix 4: Carbon to nitrogen ratio of microbial biomass and total soil organic matter as influenced by soil depth (cm) and cropping systems. Bars with different letters within a soil depth denote significant differences between treatments ($p \leq 0.05$). Error bars present standard error of means. MBC and MBN=microbial biomass carbon and nitrogen respectively, TOC=total organic carbon; TN=total nitrogen.



- Increase in lignin content lowered MBC

- Residue lignin content by potato was lowered by legume intercropping

Appendix 5: Microbial carbon biomass (MBC) in relation to lignin content under different cropping systems.

Appendix 6: Seasonal variations in nitrogen leached under different cropping systems.

		2017 LR	2017 SR	2018 LR	2018 SR
	Cropping system	Leached N (kg N ha^{-1})			
Upper midland	Pure potato	9.5±0.18d^{C}	4.8±1.01d^{A}	7.9±0.21c^{B}	4.2±0.45c^{A}
	Pure lima bean	3.4±0.49c^{C}	1.8±0.61c^{A}	2.4±0.32b^{B}	1.7±0.09b^{A}
	Pure dolichos	2.3±0.36b^{B}	1.1±0.09b^{A}	2.1±0.31b^{B}	1.9±0.05b^{A}
	Potato + lima bean	1.6±0.59a^{B}	1.2±0.21b^{A}	1.3±0.28a^{A}	1.1±0.50a^{A}
	Potato + dolichos	1.3±0.17a^{B}	0.8±0.04a^{A}	1.4±0.33a^{B}	0.9±0.09a^{A}
Lower highland	Pure potato	37.0±2.95c^{C}	25.5±2.15c^{A}	30.7±3.01d^{B}	22.1±2.01c^{A}
	Pure lima bean	10.1±0.39b^{B}	4.1±1.04b^{A}	7.1±0.54c^{B}	4.9±1.54b^{A}
	Pure dolichos	9.5±1.12b^{C}	3.3±1.01ab^{A}	5.2±1.34b^{B}	2.9±0.36a^{A}
	Potato + lima bean	5.8±0.35a^{B}	3.1±0.56a^{A}	5.6±0.20b^{A}	3.2±0.96a^{B}
	Potato + dolichos	4.7±0.12a^{B}	3.4±0.28ab^{A}	4.3±0.56a^{B}	3.0±0.21a^{A}
Upper highland	Pure potato	46.6±3.42d^{C}	34.4±3.62d^{AB}	38.9±3.98c^{B}	27.8±2.89c^{A}
	Pure lima bean	14.0±2.05a^{B}	9.1±2.14a^{A}	10.8±2.23a^{A}	9.7±0.43a^{A}
	Pure dolichos	30.8±1.24c^{C}	25.3±1.12c^{B}	20.3±2.01b^{A}	20.8±1.43b^{A}
	Potato + lima bean	12.8±0.37a^{B}	10.1±1.09a^{A}	10.9±0.09a^{A}	13.1±1.11a^{B}
	Potato + dolichos	24.0±2.13b^{B}	19.9±0.51b^{A}	19.0±2.01b^{A}	20.7±0.89b^{A}

Analyses of variance

CS	Season	AEZ	CS* season	CS* AEZ	AEZ*season
**	**	**	**	ns	ns

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ns, not significant at the 0.05 probability level, SR, short rains season, LR, long rains season, CS, cropping system. Lower and uppercase letters indicate comparisons for means (± standard error) between the cropping systems and seasons, respectively at $p \leq 0.05$ by Tukey's HSD test.

Appendix 7: Seasonal nitrogen fixation (BNF) by legume intercropping under different cropping systems.

Agro-ecological zone	Cropping system	2017 LR	2017 SR	2018 LR	2018 SR
		BNF (kg N ha^{-1})			
Upper midland	Pure potato	-	-	-	-
	Pure lima bean	3.4a^{B}	2.3a^{A}	3.0a^{B}	2.0a^{A}
	Pure dolichos	10.4b^{B}	18.8b^{C}	4.9a^{A}	15.2c^{C}
	Potato + lima bean	9.8b^{B}	3.7a^{A}	8.8b^{B}	4.9b^{A}
	Potato + dolichos	18.9c^{A}	25.5b^{B}	18.2c^{A}	25.0d^{B}
Lower highland	Pure potato	-	-	-	-
	Pure lima bean	5.2a^{B}	3.6a^{A}	5.0a^{B}	3.1a^{A}
	Pure dolichos	12.8c^{A}	17.8c^{B}	11.5c^{A}	17.3c^{B}
	Potato + lima bean	7.9b^{A}	9.7b^{B}	8.0b^{A}	9.9b^{B}
	Potato + dolichos	22.2d^{A}	26.6d^{B}	21.6d^{A}	22.4d^{A}
Upper highland	Pure potato	-	-	-	-
	Pure lima bean	5.3c^{A}	3.3c^{B}	5.7c^{A}	6.4c^{B}
	Pure dolichos	1.4a^{A}	1.5a^{B}	1.5a^{A}	2.9a^{B}
	Potato + lima bean	8.4d^{B}	5.5d^{A}	8.0d^{B}	9.8d^{C}
	Potato + dolichos	3.2b^{A}	2.8b^{A}	3.1b^{A}	4.1b^{B}

SR, short rains season, LR, long rains season. Lower and uppercase letters indicate comparisons for means between the cropping systems and seasons, respectively at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons.

Appendix 8: Seasonal nitrogen uptake under different cropping systems.

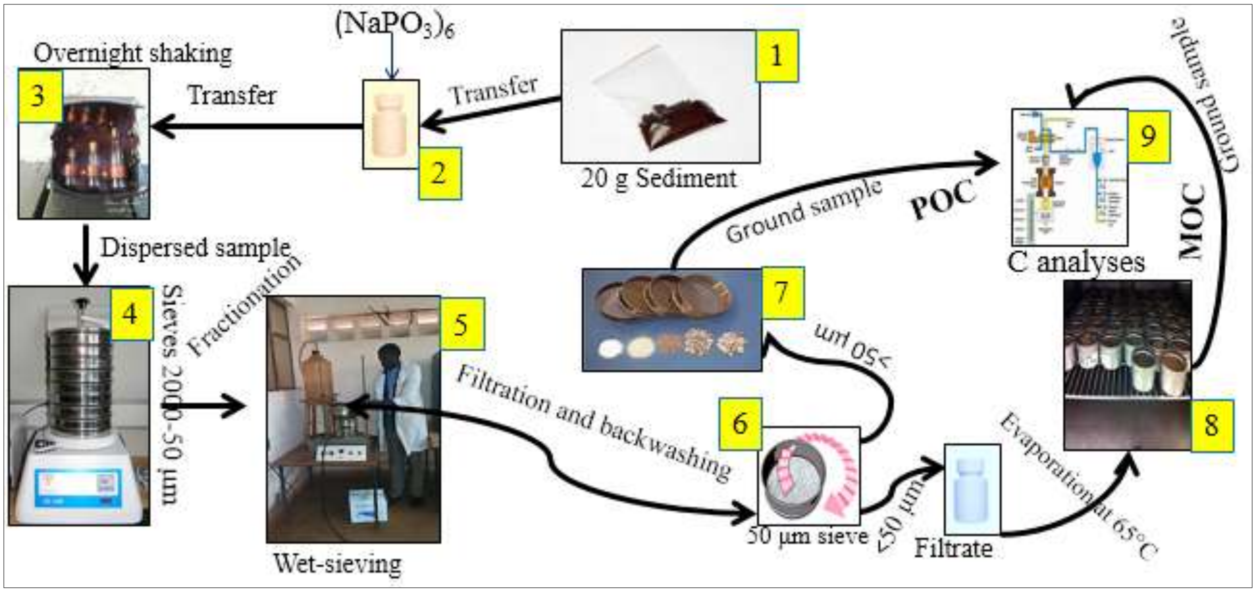
		2017 LR	2017 SR	2018 LR	2018 SR
Agro-ecological zone	Cropping system	N uptake (kg N ha^{-1})			
Upper midland	Pure potato	90.8b^{B}	70.8b^{A}	91.2b^{B}	64.2b^{A}
	Pure lima bean	49.9a^{C}	30.8a^{A}	36.6a^{B}	27.1a^{A}
	Pure dolichos	55.7a^{C}	40.8a^{B}	34.4a^{A}	32.5a^{A}
	Potato + lima bean	103.7c^{B}	82.0c^{A}	113.7c^{B}	70.1b^{A}
	Potato + dolichos	131.6d^{C}	114.8d^{B}	120.1c^{B}	101.2c^{A}
Lower highland	Pure potato	123.6c^{B}	98.1b^{A}	103.8c^{A}	99.8c^{A}
	Pure lima bean	49.2a^{C}	36.5a^{B}	39.9a^{B}	28.7a^{A}
	Pure dolichos	60.8b^{B}	48.7a^{A}	63.3b^{B}	60.9b^{B}
	Potato + lima bean	117.9c^{C}	92.9bc^{A}	123.3d^{BC}	128.6d^{B}
	Potato + dolichos	158.8d^{C}	120.5d^{A}	138.7e^{B}	125.3d^{A}
Upper highland	Pure potato	128.2d^{C}	119.7d^{B}	118.1d^{B}	101.5c^{A}
	Pure lima bean	49.7b^{A}	48.1b^{A}	45.5b^{A}	40.5a^{A}
	Pure dolichos	18.1a^{A}	27.8a^{B}	20.2a^{A}	32.9a^{B}
	Potato + lima bean	139.1e^{C}	134.8e^{C}	132.8e^{B}	129.8d^{AB}
	Potato + dolichos	72.6c^{CD}	69.2^{BC}	65.7c^{AB}	76.3b^{D}

SR, short rains season, LR, long rains season. Lower and uppercase letters indicate comparisons for means between the cropping systems and seasons, respectively at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons.

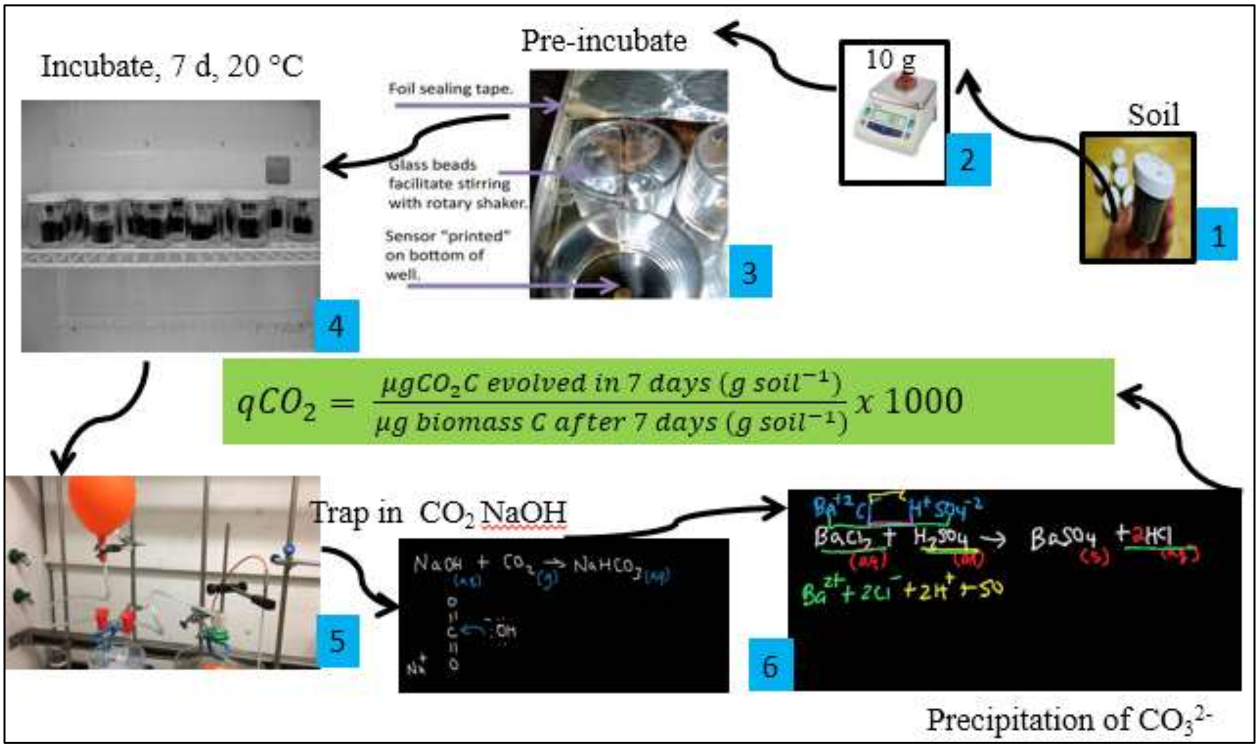
Appendix 9: Seasonal soil nitrogen balance under different cropping systems.

		2017 LR	2017 SR	2018 LR	2018 SR
Agro-ecological zone	Cropping system	N balance (kg N ha^{-1})			
Upper midland	Pure potato	-19.1a^{AB}	-17.8a^{C}	-14.9a^{D}	-18.1a^{BC}
	Pure lima bean	15.1d^{B}	8.7d^{A}	14.6d^{B}	6.1d^{A}
	Pure dolichos	27.5e^{C}	16.7e^{A}	20.8e^{B}	13.1e^{A}
	Potato + lima bean	3.0b^{B}	2.1b^{A}	3.1b^{B}	2.0b^{A}
	Potato + dolichos	6.3c^{C}	5.2c^{B}	5.9c^{B}	4.1c^{A}
Lower highland	Pure potato	-16.3a^{A}	-11.5a^{D}	-12.9a^{CD}	-13.2a^{BC}
	Pure lima bean	24.4d^{C}	19.6d^{B}	21.7c^{B}	14.2d^{A}
	Pure dolichos	32.9e^{B}	25.8e^{A}	30.4d^{B}	22.3e^{A}
	Potato + lima bean	7.5b^{B}	4.9b^{A}	8.8b^{B}	3.7b^{A}
	Potato + dolichos	10.2c^{B}	7.8c^{A}	9.9b^{B}	6.6c^{A}
Upper highland	Pure potato	-8.0a^{B}	-9.7a^{AB}	-11.0a^{A}	-10.7a^{A}
	Pure lima bean	26.6e^{B}	21.3d^{A}	20.4d^{A}	18.8d^{A}
	Pure dolichos	2.5b^{AB}	3.8b^{C}	2.4b^{A}	2.9b^{B}
	Potato + lima bean	9.1d^{C}	6.9c^{A}	7.3c^{B}	6.3c^{A}
	Potato + dolichos	3.5c^{B}	3.7b^{B}	2.9b^{A}	6.0c^{C}

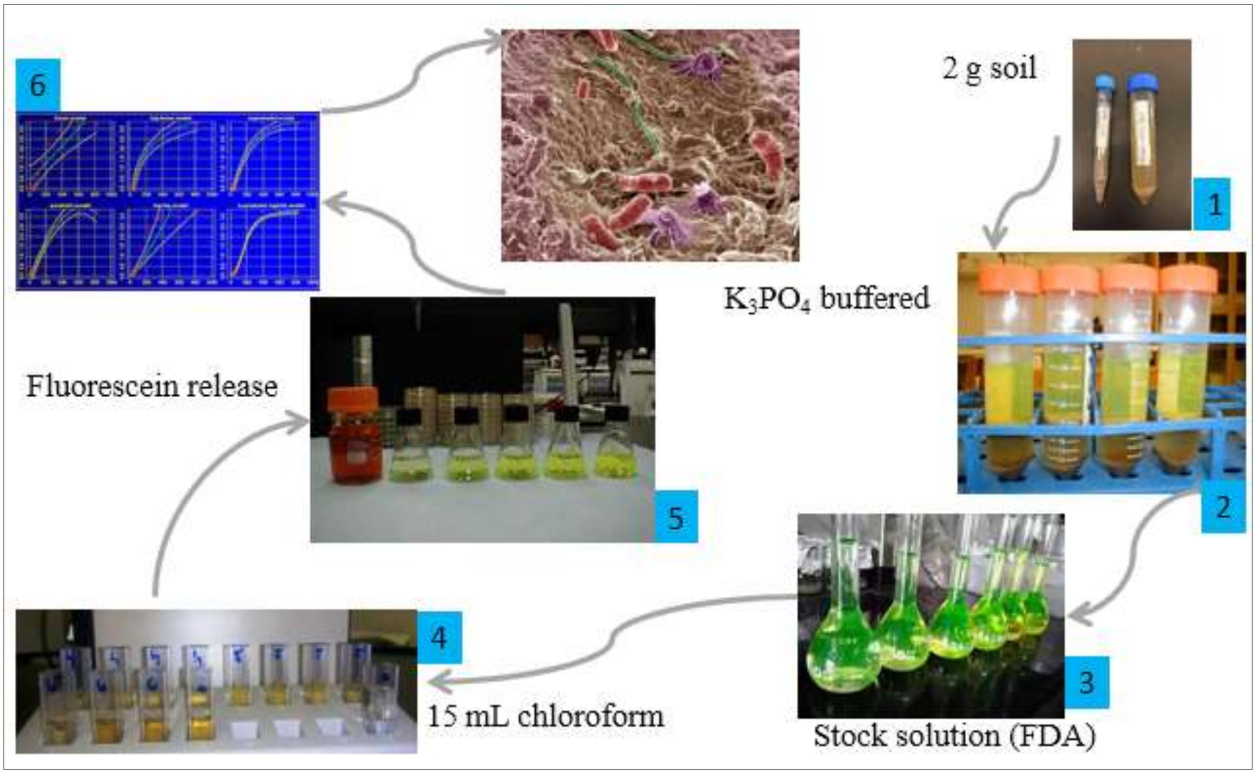
SR, short rains season, LR, long rains season. Lower and uppercase letters indicate comparisons for means between the cropping systems and seasons, respectively at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons.



Appendix 10: Schematic presentation of soil organic matter fractionation. Procedures are outlined in section 5.2.7.



Appendix 11: Schematic presentation of determination of soil microbial respiration. Procedures are outlined in section 5.2.9.



Appendix 12: Schematic presentation of fluorescein diacetate hydrolysis. Procedures are outlined in section 5.2.10.1.

(a) (b)

Appendix 13: Runoff plots at 2 weeks after planting in the lower highland (a) and upper highland (b) agro-ecological zones.