NITROGEN AND PHOSPHORUS USE EFFICIENCIES AND CROP WATER PRODUCTIVITY OF RAINFED POTATO UNDER INTERCROPPING WITH LEGUMES IN NYANDARUA, KENYA

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

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DEDICATION

As well as everything that I do, it is my genuine gratefulness and warmest regard that I dedicate this thesis to Allah Almighty my creator and my strong pillar. I also dedicate this work to Professor Nancy N. Karanja for the opportunity, trust, and support she gave me throughout the study period and l always be my inspiration. Lastly, I dedicate the work to my brother Mohamed Abdullahi Haile for always being there for me.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
CWP	Crop water productivity
DAE	Days after emergence
DAP	Diammonium phosphate
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
KSCAP	Kenya climate-smart agricultural projects
LAI	Leaf area index
LDCs	Least developing countries
N	Nitrogen
NUE	Nitrogen use efficiency
OM	Organic matter
NuPE	Nitrogen uptake Efficiency
P	Phosphorus
PEY	Potato Equivalent Yield
pH	A measure of the Hydrogen ion's concentration in the soil solution
PUE	Phosphorus use efficiency
PuPE	Phosphorus uptake Efficiency
SMC	Soil Moisture Content
SSA	Sub-Saharan Africa

ABSTRACT

Declining soil fertility and climate change have led to a reduction in potato yield and thus negatively affected the livelihood of communities that rely on the crop. A study was conducted in Nyandarua County, Kenya for two consecutive seasons to evaluate the potential of potato-legume intercropping in enhancing N and P uptake and use efficiencies on potato fresh tuber and equivalent yield (PEY). Potato equivalent yield compares system performance by converting the yield of legume crops into equivalent potato yield based on prevailing market prices. Treatments comprised two potato-legume intercrops; lima bean (*Phaseolus lunatus* L.) and lupin (*Lupinus albus* L.), and two inorganic fertilizers; Di-ammonium Phosphate (18:46:0), composite NPK (17:17:17), and a no input control. Treatment combinations were: (i) sole potato, (ii) potato-lima beans, and (iii) potato-lupin intercrops. Fertilizers were applied to each of the three cropping systems separately. Higher N uptake was found in sole potato (73.5 kg ha^{-1}), which was more than double that recorded in potato-lupin (35.9 kg ha^{-1}) and 60% more than that recorded in potato-lima beans intercrop (46.8 kg ha^{-1}). On the other hand, N use efficiency was higher in potato-lupin (240.6 kg PEY kg^{-1} N supply) and sole potato (238.6 kg PEY kg^{-1} N supply) and lowest in potato-lima beans (139.0 kg PEY kg^{-1} N supply). Intercropping resulted in a decrease in fresh tuber yield by more than 70% while equivalent yield decreased by almost 15 Mg ha^{-1}. The application of fertilizer did not enhance the recovery of the yield loss. Higher crop water productivity was observed in PL and PP (23.4 and 22.2 kg ha^{-1} mm^{-1} respectively) compared to PLi with an average of 13 kg ha^{-1} mm^{-1}. The study establishes that the choice of companion legumes in intercropping can significantly influence nutrient uptake and use efficiency, and thus the yield of the potato crop.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Potato (*Solanum tuberosum* L.) is a staple and cash crop for smallholder farmers and the third most important food crop globally after rice and wheat (FAOSTAT, 2019). In Kenya, potato is the second most important food crop after maize, which has been used to address food security challenges (Muindi et al., 2023; Mwakidoshi et al., 2021). Hence, the crop plays a pivotal role in income generation, particularly for the rural population (Muthoni and Mbiyu, 2017). It supports nearly 800,000 farmers and 2 million citizens across the production chain (FAOSTAT, 2019, Wang’ombe and van Dijk, 2013; Muthoni and Mbiyu, 2017). However, yields average 8-12 Mg/ha, at least half the potential mainly as a consequence of impoverished soil fertility coupled with an 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 (Muthoni et al., 2013; Haile et al., 2023).

Smallholder farms in Kenya's highlands typically have fields that have continuously been cropped for many decades, and soil fertility decline has been widely recognized as a widespread and severe constraint to crop production (Gitari et al., 2019a; Mwakidoshi et al., 2023; Okalebo et al., 1993). There is also significant concern about the effects of a changing climate, which will drastically affect potato production in many of these areas (Hijmans, 2003; Massawe et al., 2016). Water stress and high temperatures arising at critical stages of potato growth due to climate changes might lead to low crop water productivity (Gitari et al., 2018a; Nyawade et al., 2021). When water availability is inadequate to cover crop water requirements, low crop yields become inevitable (Cuthbert et al., 2019; Biamah et al., 2005).

Intensification of agriculture is often promoted through access to mineral fertilizers to help sustain crop production (Fisher, 2012). Phosphorus (P) fertilizer is an essential component of potato production systems because the crop has a relatively high P requirement (Fernandes and Soratto, 2016). However, the initiative's narrow focus on chemical inputs alone especially the increasing use of acidifying N mineral fertilizers (DAP), coupled with leaching losses of bases and continuous mining of nutrients through the export of potato harvest has elevated soil degradation which raises doubts about sustainability (Faridvand et al., 2021; Kadaja and Tooming, 2004; Mirriam et al., 2023). As evidenced by decreasing crop yields and a growing reliance on chemical fertilizers, agricultural productivity has decreased under the current mono-cropping systems, hence calling for an effective approach to its management.

Efficient use of nutrients and water can play a significant role in improving potato production. Conventional soil management interventions used to address these challenges, such as the use of manure and mulching are not easily accessible to smallholder farmers (Faridvand et al., 2021; Mwadalu et al., 2022). This leaves farmers no option but to modify the existing cropping systems. Intercropping is gaining popularity in developing countries as a viable technique for diversifying cropping systems to alleviate food insecurity. Legumes can be intercropped with potatoes to control soil erosion, optimize soil temperature, and increase soil moisture content given that arable land is shrinking, and demand for food crops is increasing (Gitari et al., 2020a; Nyawade et al., 2019c). Incorporating indeterminate legumes has been shown to yield higher compared to monoculture systems (Singh et al., 2016; Gitari et al., 2018a). Intercropping practices can also enhance nutrient uptake and productivity without incurring additional expenses on commercial fertilizers (Stagnari et al., 2017; Maitra et al., 2020). Nonetheless, besides having several studies on potato-legume intercropping systems, none has established the effects of such systems in combination with chemical fertilizer application, particularly at high altitudes areas like Nyandarua.

1.2 Statement of the problem

Potato is both an essential food and cash crop in Kenya's highlands, commonly cultivated by small-scale farmers, but its production varies from region to region (Gildemacher et al., 2009; Ndegwa et al., 2020). Despite its importance, low and declining yields are some of the key issues facing potato production in these areas (Muthoni et al., 2013). Several factors contribute to this trend, including, climate change, the use of less resilient cropping systems, and most crucially, low and diminishing soil fertility, as measured by reduction in essential nutrients such as nitrogen and phosphorus (Hijmans, 2003; Karanja et al., 2014; Mugo et al., 2021; Kisaka et al., 2023).

Potato production in Kenya's highlands is mainly done under mono-cropping systems, carried out continuously, and therefore, has minimal capacity to return organic matter and nutrients into the soil which reduces the availability of most needed nutrients for potato production (Gitari et al., 2019a). The decline in land productivity and environmental problems are inevitable under such mono-cropping systems. Intensification of soil fertility and productivity of the existing potato cropping systems in Nyandarua is increasingly required. Intercropping remains a priority that can increase the current potato cropping systems' productivity, given that the land resources are diminishing.

1.3 Justification of the study

The long-term sustainability of potato production in these high-latitude areas where temperatures and water scarcity are problem depends on improved soil fertility. Legumes can increase the soil organic matter content thus increasing the soil water retention capacity and water use efficiency. Intercropping shallow-rooted potato with deep-rooted legumes can enhance nutrient absorption in deep soil layers, increasing nutrient uptake efficiency, thus, assessing an improved cropping system that addresses the most important constraints of nutrient availability (N and P) would improve soil fertility and reduces the reliance on mineral fertilizers. There are also significant knowledge and information gaps in multiple aspects of intercropping to achieving in sustainable potato production.

1.4 Research objectives

1.4.1 General objective

To improve soil productivity and potato production through potato-legume intercropping and proper targeted fertilizer management.

1.4.2 Specific objectives

i. To evaluate the effect of potato-legume intercropping systems and fertilizer application on ground cover, soil moisture content, and soil temperature.
ii. To determine the effect of potato-legume intercropping systems and fertilizer application on potato yield and crop water productivity.
iii. To assess the effect of potato-legume intercropping systems and fertilizer application on nutrients (N and P) uptake and use efficiency.

1.5 Research questions

i. Does Nutrients (N and P) uptake and use efficiency have significant effects on ground cover, soil moisture content, and soil temperature?
ii. Does potato-legume intercropping systems and fertilizer application have significant effects on potato yield and crop water productivity?
iii. Does potato-legume intercropping systems and fertilizer application have significant effects on nutrient (N and P) uptake and use efficiency?

CHAPTER TWO

LITERATURE REVIEW

2.1 Potato production systems and production challenges in Kenya

Potato in Kenya is grown at altitudes of 1,500 to 3,000 meters above sea level (m.a.s.l.) by an estimated 800,000 farmers on approx. 161,000 hectares. Annual production stands at approximately three million tonnes over two growing seasons, with an annual value of KES 50 billion (500 million USD) (Mallory and Porter, 2007; Muthoni et al., 2013). Beyond the farm, the industry employs about 3.3 million people as market agents, transporters, processors, vendors, and exporters. National yields average is 8-12 Mg/ha, at least half the potential mainly because of increasing climate shocks coupled with low soil fertility (Kadaja and Tooming, 2004; Obalum et al., 2012). Potato-producing Counties include Meru, Bomet, Laikipia, and Nyandarua (Muthoni et al., 2013; Gitari et al., 2018b). Sherekea, Kenya Mpya, Shangi, Dutch Robijn, and Asante are some of the high-yielding varieties grown in the country.

Potato production in Kenya's highlands is mainly done under mono-cropping systems, carried out continuously (Gitari et al., 2019a), therefore, the soils in such areas are characterized by low nutrient availability resulting in nutrient exhaustion and low crop yields (Chianu et al., 2012; Kiage, 2013; Gitari et al., 2015; Nyawade et al., 2020a, 2021; Otieno et al., 2022). Cultivation of potatoes may lead to the loss of vital plant nutrients from the soil when done continuously with low application of organic and inorganic fertilizers (Jensen et al., 2012; Massawe et al., 2016). The problem exacerbates because most of the residues are removed from the field in preparation for the subsequent season. Such scenarios are common among small-scale farmers who don't have the financial capacity to buy fertilizers or lack the knowledge to do soil conservation measures to control soil erosion (Gitari et al., 2019a; Kadaja and Tooming, 2004).

The detrimental higher reductions in agricultural productivity are due to environmental problems and the continuous use of mono-cropping systems, affecting crop productivity (Soratto et al., 2022). Intercropping is an agricultural practice in which two or more crop species, or genotypes, grow and interoperate for a period of time (Brooker et al., 2014; Mallory and Porter 2007; Mugwe et al., 2009). Intercropping grain legumes and potatoes has been widely reported as an eco-functional practice with several advantages over the monocrop system of potatoes, including better land and water use efficiency, soil fertility maintenance, and reduced N losses from the agro-ecosystem (Nyawade et al., 2020a; Gitari et al., 2018a; Munisse et al., 2012). The critical reason farmers prefer multiple cropping systems to the mono-cropping system is the efficient use of water, space, and labor (Andrews and Kassam, 2015; Brooker et al., 2014).

Even though intercropping has ancient advantages, it is only recently that institutional attention has been paid to this growing method's disadvantages. Many limitations affecting potato production by intercropping include; yield decrease as the crops differ in their competitive abilities (Willey and Rao, 1980). Management of having different cultural practices and planning for the growing season seems to be a difficult task and a higher amount of fertilizers cannot be utilized probably as the component crops vary in their response to these resources implying improved implements cannot be used efficiently (Kimaro et al., 2018, 1998; Jensen et al., 2012).

2.2 Nutrients (N and P) uptake and use efficiency (NUE)

Nutrients are major limiting factors to plant productivity (Fisher et al., 2012). Amongst essential nutrients, nitrogen (N) and phosphorus (P) plays a major role in limiting the growth and productivity of potato (Ghosh et al., 2019; Cheptoek et al., 2021, 2022; Nasar et al., 2021). N, together with P, also governs the shoot-to-root ratio, resulting in greater biomass distribution to potato tubers when these nutrients are insufficient (Marschner et al., 1996). Potatoes take up approximately 40% to 50% of their N and K requirements and about 30 to 40% of P from the soil (De Haan et al., 2019). Nutrient uptake efficiency represents the portion of the nutrients used for the production of biomass and tubers after uptake (Ochieng' et al., 2021; Roy et al., 2023; White, 2009). Nutrient use efficiency implies the balance between economic yields obtained and the nutrients available (Salvagiotti et al., 2009; White et al., 2018; Goher et al., 2023; Seleiman et al., 2021; Zhao et al., 2023; Parecido et al., 2021). The most widely deficient mineral nutrient in agricultural soils is nitrogen (Beeckman et al., 2018). The optimal response of potato crop to the application of N fertilizer varies from one cultivar to another, which means that it requires critical attention for the various cultivars (Milroy et al., 2019; Ghosh et al., 2019; Gitari et al., 2018b). Nitrogen contributes to potato vegetative and reproductive growth, leading to increased tuber development (Ju et al., 2009; Woli et al., 2016).

Phosphorus plays a vital role in enhancing plant height, marketable tuber yield, and tuber numbers (Martins et al., 2018; Ranjan et al., 2013; Fernandes and Soratto, 2016).

Nonetheless, the potato has relatively low P uptake and use efficiency (Sandan, 2016; Gitari et al., 2020b). The total P requirement for potato crop is about 25 to 45 kg P ha^{-1}; therefore, to sustain potatoes' growth and production, higher plant-available soil P is needed (Soratto et al., 2015; Rosen and Bierman, 2008). For instance, to achieve an annual yield potential of 30 Mg/ha, potatoes need 6 to 9 times more usable soil P than crops such as wheat and sugar beet (Ruark et al., 2014; Hopkins et al., 2014; Goher et al., 2023). Some authors highlighted that sufficient potato P supply increases vegetative growth and Phosphorus significance in increasing root growth and cell division (Westermann and Kleinkopf, 1985; Jenkins, 1999). The roots of plants are in close contact with the soil and are responsible for absorbing water and soil nutrients (Wang et al., 2005; Zhu and Zhang. 2017). Root size and architecture are significant factors that affect plants' accessibility to nutrients and moisture (Zhu and Zhang. 2017). Furthermore, due to its poor mobility, P uptake by most crops is heavily reliant on root interception. Nevertheless, because potatoes have shallow rooting systems to utilize such nutrients (N and P) sufficiently, they are subjected to losses through leaching, immobilization, volatilization, and run-off (Nyawade et al., 2019a). Potassium and nitrogen are found in the largest amounts in a potato plant, followed by Ca and Mg (Table 1). NUE is a critically important concept for evaluating crop production systems and can be greatly impacted by fertilizer management as well as soil- and plant-water relationships.

Table 1: Recommended fertilizer applications and the relative whole plant nutrient uptake for potato

Nutrient	Fertilizer application	Total uptake Kg/ha	Available tests
All	Pre-planting	-	-
Nitrogen	Planting and post-planting	235	Soil and plant
Phosphorus	Planting and post-planting	31	Soil and plant
Potassium	Planting	336	Soil and plant
Zinc	Planting	0.12	Soil and plant
Manganese	Planting	1.00	plant
Calcium	Planting and post-planting	91	Soil and plant
Sulphur	Planting and post-planting	22	Soil and plant

Source: (Westermann, 2005).

2.3 Effect of soil temperature on soil moisture content and their impact on nutrient use efficiency

The soil temperature is determined by heat flux in the soil as well as heat exchanges between the soil and the atmosphere (Elias et al., 2004). Soil moisture is a driving force of major soil processes and a key consideration for the use of soils (Famiglietti et al., 1998; Basu et al., 2010). Increased soil temperatures reduce water viscosity, allowing more water to percolate through the soil profile and reduce soil moisture (Malhi and McGill, 1982). Furthermore, less shade combined with higher soil temperatures results in higher evaporation rates, which restricts water movement into the soil profile. Insufficient soil moisture is one of the most critical stress factors for crop yield and the most limiting factor for crop cultivation in the world (Neenu et al., 2014; Seleiman et al., 2021; Rahimi et al., 2022; Nyawade et al., 2021). Several soil formation mechanisms, including organic matter turnover, structural formation, clay translocation, and gluing, are significantly dependent on soil water content (Cook et al., 2008; Wolka et al., 2018). Soil water content is one of the primary factors influencing soil nutrients and serves as a solvent and carrier of food nutrients for plant growth (Schwingshackl et al., 2017; Liao et al., 2016; Opena and Porter, 1999).

Soil temperature influences nutrient uptake by altering soil water viscosity and root nutrient transport (Brouder and Volenec, 2008). Soil temperature affects soil microbial activities and the movement of plant nutrients in the soil, which will have an additional significant impact on plant growth and yield (Kifle and Gebretsadikan, 2016; Reddell et al., 1985; Wang et al., 2005; Singh, 1969; Rykaczewska, 2015). Some researchers have reported a direct reduction in tuber numbers with increasing periods of water stress in plants (MacKerron and Jefferies, 1986; Nyawade et al., 2021 The harvesting of potato tubers loosens the dry soil, and the lack of soil cover and dry conditions make the soil vulnerable to soil erosion (Le Houérou, 1996; Nyawade et al., 2019).

2.4 Role of chemical fertilizer applications on nutrient use efficiency

Chemical fertilizer refers to any of a variety of synthetic compound substances created specifically to boost crop yield. Some chemical fertilizers, for instance, are "nitrogenous"-that is, they contain nitrogen-whereas others are phosphate-based. Potassium is found in other fertilizers. Chemical fertilizers that are complex (or blended) often contain a combination of ammonium phosphate, nitro-phosphate, potassium, and other nutrients. There is a demand for increased productivity of potatoes to improve the livelihood of smallholder potato farmers in Kenya (Gildemacher et al., 2009) The fertilizers application has been recognized as one of the most cost-effective approaches to boost potato production and food security has been improved due to increasing inputs of chemical fertilizers (Tilman et al., 2002).

Chemical fertilizers not only provide plant nutrition but also promote the soil's water-holding capacity which functions as storage of moisture and reduces the leaching of nutrients, as a result, increasing nutrient uptake and use efficiency (Levy et al., 1999). Increased use of chemical fertilizers, on the other hand, not only contributes to food security but also causes soil deterioration, greenhouse gas emissions, and water contamination (Tilman et al., 2001; Link et al., 2006; Ju et al., 2009; Wauters and Mathijs, 2013). To deliver the anticipated economic, social, and environmental benefits, sustainable nutrient management must be both efficient and effective. As fertilizer costs rise, both productivity and NUE must rise to provide a sufficient quantity and quality of yield. These factors are crucial among small-scale farmers who do not have access to costly fertilizers or lack the knowledge to do soil conservation to promote fertilizer best management practices to intensify potato production such as intercropping.

2.5 Legume intercropping system and its influence on nutrient use efficiency

Integration of legumes into potato production systems can increase nutrient availability and efficiency without raising fertilizer costs (Gitari et al., 2019b; Mafongoya, 2006). Intercropping can lead to high resource use efficiency (light, water, and nutrients) (Kheroar and Patra, 2014; Raza et al., 2021). Intercropping potatoes with cover crops such as legumes with deeper roots can improve the system's complimentary use of water and nutrients (Ren et al., 2019; Alhammad et al., 2023; Ugent, 1970; Fan et al., 2016). Through soil erosion, plant nutrients, soil organic matter, and fine clays are eroded which in turn, affects the soil's physical and chemical properties (Adimassu et al., 2019; Kokulan et al., 2018; Nyawade et al., 2019c). A Spatio-temporal niche is created by introducing P-mobilizing plants such as lupin and lima beans, which can access N and P from deep soil layers under the intercropping system (Isaac et al., 2012; Gitari et al., 2020b; Nyawade et al., 2020a).

Such intensification of the soil not only affects potato growth and yield but also regenerates soil organic matter and improves soil fertility (Ren et al., 2019; Błażewicz-Woźniak and Konopińsk, 2012). Legumes can produce carbon-dependent exudates that can make fixed P, available for non-leguminous crops (Wang et al., 2014; Hasanuzzaman et al., 2018). Legumes can fix atmospheric N that can be translocated to the companion crops where it is made available after root nodules or plant materials have decomposed (Jena et al., 2022; Sousa et al., 2022; Mirriam et al., 2022). Better use of resources is based on the microclimate improvement that occurs when at least two crops are grown in association (Govinden et al., 1984; Jenkins, 1999; Gitari et al., 2018a). Gitari et al. (2018b) reported that intercropping potatoes with beans and peas decreased its N uptake significantly by between 22 and 27% compared with potatoes grown in a pure stand whereas the uptake of the element was not affected under potato- dolichos intercropping system. Phosphorus use efficiency in the potato-dolichos intercrop was 21% higher compared with the pure potato stand. Further, the authors reported that N use efficiency (NUE) of potato under intercropping with dolichos, climbing bean, and the garden pea was significantly higher by 30, 19, and 9% compared with the pure potato stand.

2.6 Crop water productivity (CWP) under potato-legume intercropping system

Most livelihoods in SSA are based on rain-fed smallholder agriculture, and agricultural production is vulnerable to climate change (FAO, 2016). Since the first half of the nineteenth century, there has been a general decline in rainfall patterns in Africa (Nicholson, 1994). Crop water productivity is the relationship between the obtained marketable yield and the total amount of water utilized during production by the plant through evapotranspiration, its unit is kg m^{-3} (Kadigi et al., 2004; Maitra et al., 2022). CWP enables the assessment of the possible rise in crop yield because of improvised water use (Angus and van Herwaarden, 2001; Vitale et al. 2023). Increasing temperatures, in conjunction with the decrease in rainfall, have a detrimental influence on vegetation cover, which makes a significant contribution to soil degradation due to the exposure of the soil surface to wind and water erosion, resulting in low Crop water productivity. The development of a more viable and sustainable rainfed-based potato cultivation system is required (Liao et al., 2016; Zhang et al., 2020).

Intercropping has been implemented internationally because of its effectiveness in conserving soil water. In Kenya, potatoes are commonly intercropped with legumes such as Dolichos (*Lablab purpureus* L.) (Gitari et al., 2019a, Nyawade et al., 2019b; Nyawade et al., 2019c; Nyawade et al., 2020b), Lima bean (*Phaseolus lunatas* L.) (Gitari et al., 2019a, Nyawade et al., 2019b; Nyawade et al., 2021; Nyawade et al., 2020b), Garden pea (*Pisum sativum* L.) (Gitari et al., 2018a, b; Nyawade et al., 2019a), Climbing bean (*Phaseolus vulgaris* L.) (Gitari et al., 2018b; Nyawade et al., 2019a), Hairy vetch (*Vicia sativa* L.) (Nyawade et al., 2020a). It has been established that legume intercropping with potatoes is one of the most important soil and water conservation technologies of recent times. Intercropping can improve soil and water conservation by covering the soil surface and decreasing water loss by run-off and evaporation (Franco et al., 2018; Fan et al., 2016; Nyawade et al., 2021; Raza et al., 2022). Various studies suggested that under intercropping systems, the higher canopy of legume cover crops generates a microenvironment with lower temperatures and reduced solar radiation reaching the soil surface (Nyawade et al., 2019b; Willey, 1985; Wang et al., 2022).

There are significant knowledge and science gaps in multiple aspects of intercropping despite its historical usage, including the benefits of various crop combinations, crucial to achieving sustainable agricultural production. Information about the effect of potato intercropping with legumes on crop water productivity and nutrient uptake is scarce.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

This study was conducted at Gathara ward in Nyandarua County, Kenya located about 90 km from Nairobi City at latitude 0° 36' S and longitude 36° 37' E, with an elevation of approximately 2600 m above sea level (Figure. 1). According to Jaetzold et al. (2006), the area is classified as a Pyrethrum-Wheat Zone (identified as *UH 2 vl i or two*) receiving average annual precipitation of about 1,200 mm in a bimodal pattern. The first season commonly known as "long-rains", starts towards the end of March to mid-July, and the second season, known as "short-rains" starts in October and ends in December. Temperatures are fairly constant throughout the year, with the long-term average annual temperature being 13 °C (Kamau et al., 2019). The study was conducted for a period of two seasons, with the first season running from June to September 2020 and the second from November 2020 to February 2021. The average monthly rainfall in the first and second seasons in this study was 112 mm and 190 mm, respectively while the average temperature for the first season was 15 °C and the second season was 16 °C (Fig. 2). Soils in the study site are classified as Planosols (Jaetzold et al., 2006). Before the study, the soils were slightly acidic (pH of 5.7), with relatively low available P (16.5 mg kg^{-1}), total C (28.3 g kg^{-1}), and N (2.2 g kg^{-1}).

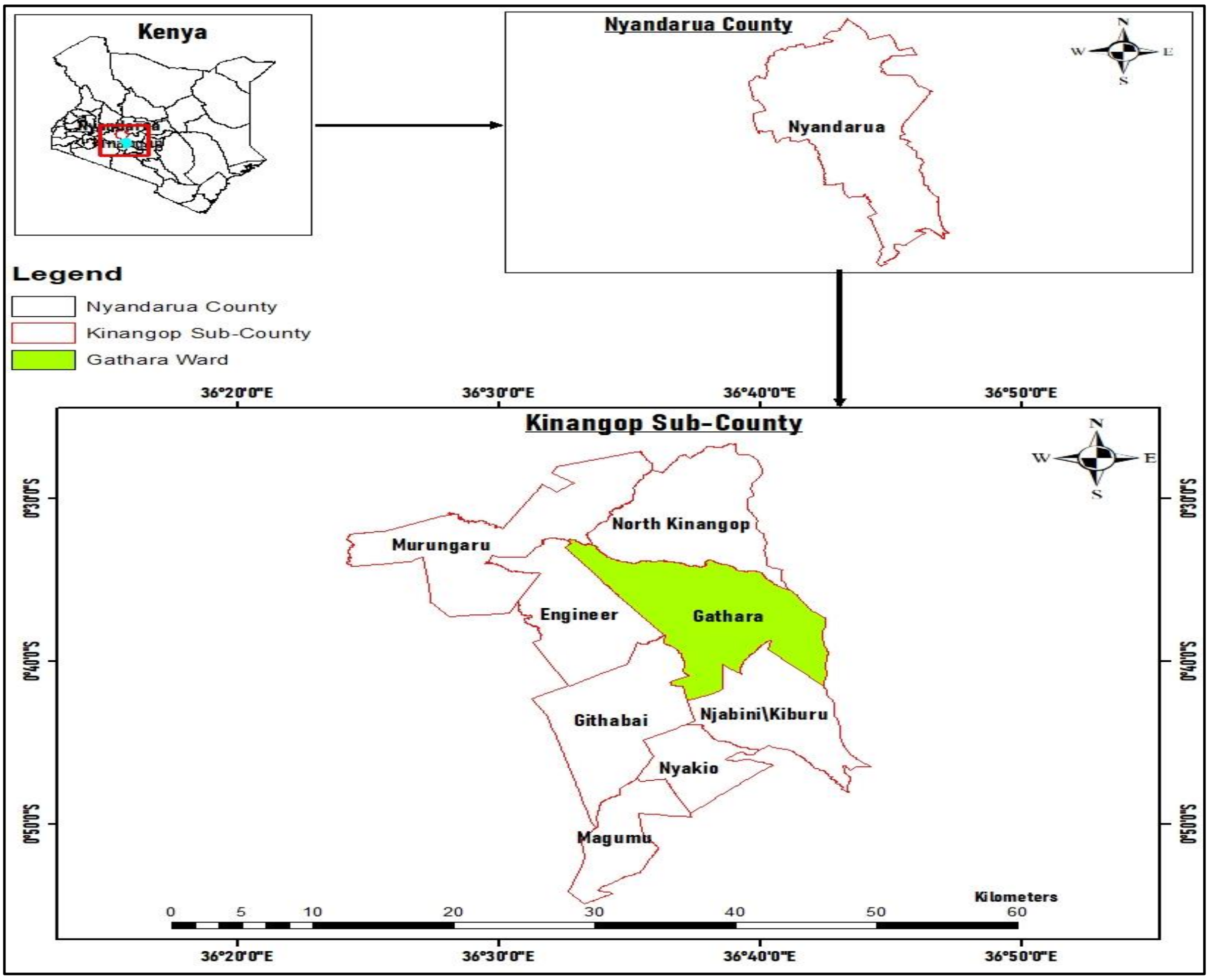


Figure 1: Map of Kenya indicating the study site

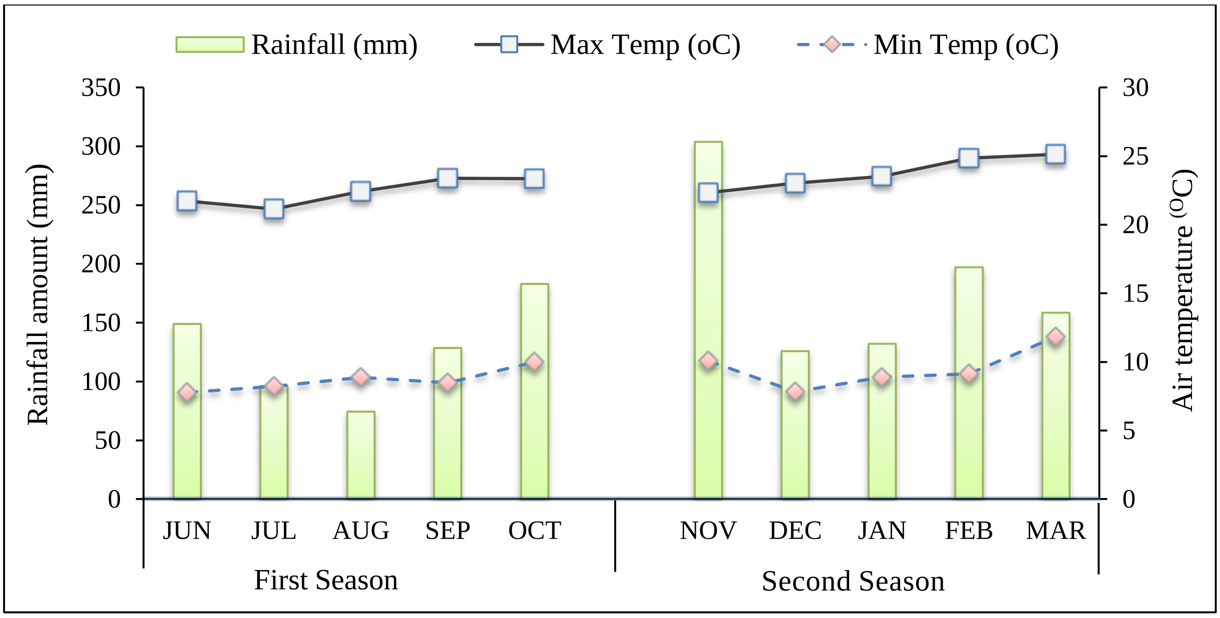
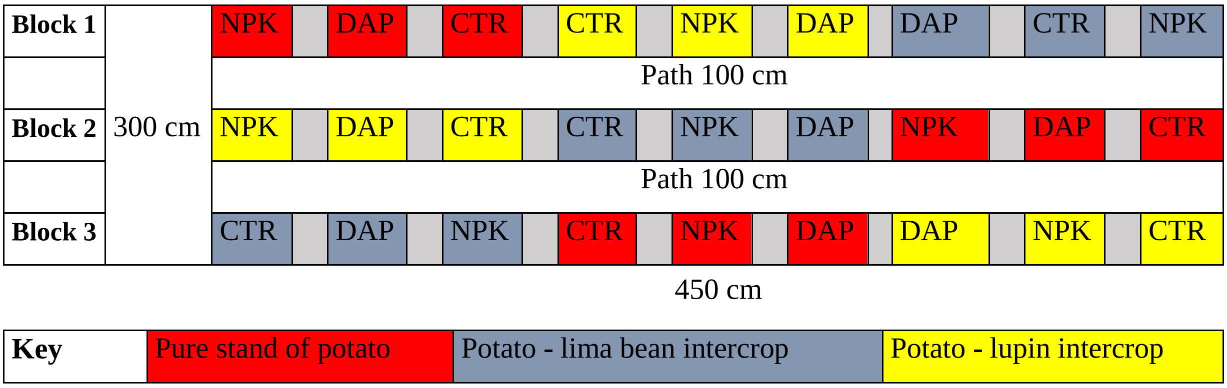


Figure 2: Mean monthly total rainfall and minimum (min temp) and maximum (max temp) temperature during the study period. Source (Agricultural Training Center (ATC), Njabini, Nyandarua).

3.2 Establishment of the field trials

The study area was chosen due to its suitability for the production of potatoes; it is one of the major crops grown here. Prior to the establishment of the field trials, the farm used in the study had been under fallow for three consecutive years. The farm was divided into 4.5 m by 4 m plots, with 1.5 m paths between the plots on all sides, and the treatments were randomly allocated in these plots (Figure.3). Treatments comprised intercrops of potato (*Solanum tuberosum* L. cv. Sherekea) and two legumes; lima bean (*Phaseolus lunatus* L.) and lupin (*Lupinus albus* L.), and two inorganic fertilizer types; Di-ammonium Phosphate (18:46:0) and composite NPK (17:17:17). Thus, the treatment combinations were: (i) sole potato; (ii) potato-lima beans and (iii) potato-lupin intercrops. The fertilizers were applied to each of the three cropping systems separately. A no-input control for each cropping system was also included for reference. This gave a total of 9 treatment combinations and these were replicated 3 times in a randomized complete block design (RCBD).

Intercropping arrangement constituted 2 rows of potatoes alternating with 2 rows of legumes. Under pure stands, potato rows were 0.75 m apart. In intercropping, rows were set 0.75 m apart between potato rows (potato to potato rows), 0.5 m between legume rows (legume to legume rows), and 0.5 m between potato and legume rows (potato to legume rows). In each plot, 0.1 m deep furrows were made in preparation for planting, and the respective fertilizers (where fertilizers were to be applied) were then spread evenly in the furrows and incorporated with the topsoil (Figure.4). Pre-sprouted potato tubers were planted at a spacing of 0.3 m within the rows to give a plant density of 44,444 plants ha^{-1}. Legumes were planted at a spacing of 0.3 m within the rows to give a plant density of 66,667 plants ha^{-1}.



Block 1	300 cm	🟥 NPK		🟥 DAP		🟥 CTR		🟨 CTR		🟨 NPK		🟨 DAP		🟦 DAP		🟦 CTR		🟦 NPK
		Path 100 cm																
Block 2		🟨 NPK		🟨 DAP		🟨 CTR		🟦 CTR		🟦 NPK		🟦 DAP		🟥 NPK		🟥 DAP		🟥 CTR
		Path 100 cm																
Block 3		🟦 CTR		🟦 DAP		🟦 NPK		🟥 CTR		🟥 NPK		🟥 DAP		🟨 DAP		🟨 NPK		🟨 CTR

450 cm

Key	🟥 Pure stand of potato	🟦 Potato - lima bean intercrop	🟨 Potato - lupin intercrop

Figure 3: Layout of the experimental plots

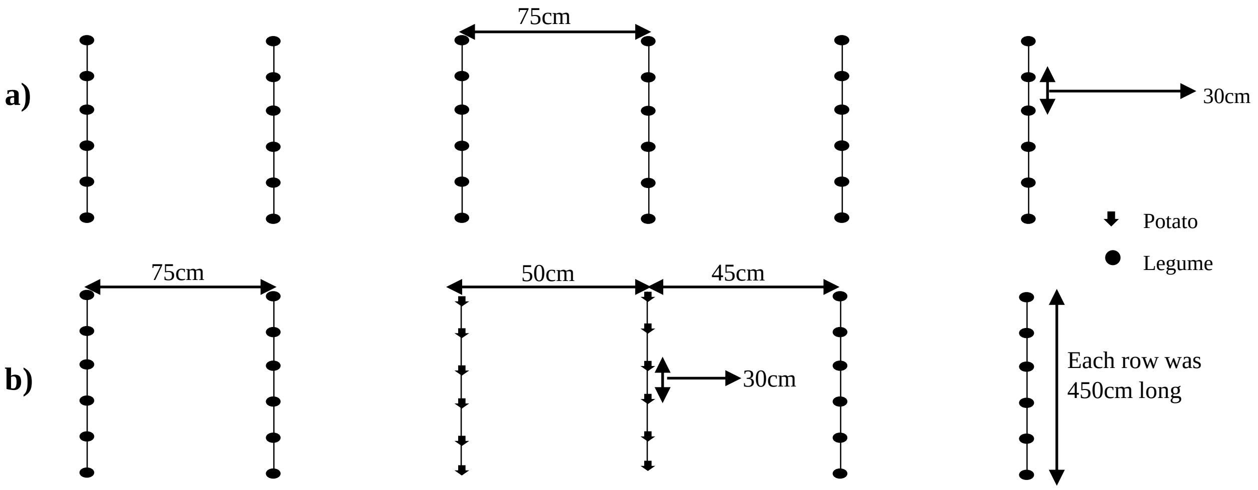


Figure 4: Row configurations of a pure stand of potato (**a**) and a potato-legume intercropping (**b**).

3.3 Soil characterization

Soil samples were collected before the start of the first season and the end of the second season using a soil auger to a depth of 30 cm. The samples were composited and analyzed for soil pH (soil: water ratio of 1: 2.5) using a pH meter by Rhoades et al. (1982), total N using the Kjeldahl digestion method as described by Willis et al. (1996), and soil organic carbon using modified Walkley and Black wet oxidation method (Yeomans and Bremner, 1988). Extraction for available phosphorus was done using the Mehlich-3 method (Mehlich. 1984) and determined using a UV-vis (Murphy and Riley, 1962). Soil texture was determined using the hydrometer method (Bouyoucos, 1936). Soil physical and chemical properties of the experiment site at 0-30 cm depth are given in Table 2.

Table 2: Soil characteristics of the surface horizon (0-30 cm) before the start and at the end of the experiment, source: (Landon, 1991).

Property	Parameter	Unit	Baseline	Rating	End line	Rating
Physical	Sand	%	21	Low	-	-
	Clay	%	49	High	-	-
	Silt	%	29	Moderate	-	-
	Soil texture class	Silt clay loam				
Chemical	Soil pH (H_2O) 1:2.5	-	5.7	Moderate	5.4	Low
	Soil organic carbon	(g kg^{-1})	28.3	Low	31.6	Low
	Total N	(g kg^{-1})	2.2	Moderate	2.6	Moderate
	Available P	(mg kg^{-1})	16.5	Low	34.1	High

3.4 Crop management and harvesting

To control potato late blight, the potato crop was sprayed once per month starting 14 days after crop emergence using Ridomil Gold MZ 68 WG (containing Mefenoxam 40 g and Mancozeb 640 g kg^{-1} as the active ingredients). Fertilizer was applied only on the potato crop rows (except on the control plots where no fertilizers were applied) at the rates commonly used by smallholder farmers of 200 kg ha^{-1}, which is equivalent to 34 kg N ha^{-1}, 14.8 kg P ha^{-1}, and 28.2 kg K ha^{-1} for NPK fertilizer and 36 kg N ha^{-1} and 40.1 kg P ha^{-1} for DAP fertilizer. Therefore, DAP fertilizer supplied 2½ times the amount of P supplied by NPK fertilizer. Weeding and hilling of potato crop was done manually twice, at 14 days and 45 days after potato emergence using a hand hoe. Potato tuber and legume yields were determined from the central 3 m by 2 m area of each plot. Harvesting of lima beans started 90 days after crop emergence and thereafter, every 30 days until the end of the second season.

On the other hand, lupin was harvested once at the end of the second season when all the pods were dry. Legume grains were then separated from the pods by shelling and winnowing. The grains were then weighed and the values were recorded in a field book. For potatoes, harvesting was carried out 120 days after crop emergence using fork hoes. However, before harvesting was done, the haulms were removed by cutting the stems at 0.01 m above the soil 14 days before harvesting the tubers to ensure the skin was firm enough to avoid being bruised when transported. The fresh weight of potato tuber was taken and also recorded in a field book. The weight of potato tubers and legume grain yield were then converted to Mg ha^{-1} based on the harvested area.

3.5 Determination of ground cover, soil temperature, and soil moisture content

Ground cover, soil moisture content, and soil temperature were measured between tuber initiation and maturation of the potato. Ground cover was measured using a point frame from several randomly selected places in each plot as introduced by Levy and Madden (1933). The frame was placed in a vertical position between the rows and mean points taken and expressed in percentage following (Eq. 1) given by Evans and Love (1957).

$$\text{Ground cover} = \frac{\text{No. of pins that hit plant leaves}}{\text{Total No. of pins}} \times 100 \qquad (1)$$

Procheck® handheld meter was used to determine both soil temperature and moisture content. The model of the device used had sensors that measure both soil temperature (°C) and soil moisture content (*v/v*). The probes were driven at 9 random points between potato and legume rows to a depth of 0.3 m in each plot. The temperature and moisture values from the LCD screen sensors were recorded and the average values were taken.

3.6 Computation of crop water productivity

Crop water productivity (CWP) was calculated from the soil water balance equation and potato equivalent yield (Allen et al., 1998; Gitari et al., 2018a) (Eq. 2).

$$\text{CWP} = \frac{\text{PEY}}{\text{P+CR+}\Delta\text{SW+I}-\text{R}} \qquad (2)$$

Potato equivalent yield (PEY, reported in kg ha^{-1}) compares system performance by converting the yield of legume crops into equivalent potato yield based on prevailing market prices and was computed using Eq. 5.

$$PEY = PY + \frac{LY \times LP}{PP} \qquad (3)$$

Where PY and LY denote the yield of potatoes and legumes in kg ha^{-1}, respectively, while PP and LP indicate the market prices of potatoes and legumes (US$ kg^{-1}), respectively. The market prices at the end of the study for potato tubers and lupin and lima bean dry grains were US$ 0.4, $1.5, and $1.0 kg^{-1}, respectively. P = precipitation; CR = capillary rise of water (Given that the groundwater table was more than 25 m below the soil surface, the capillary rise was assumed to be negligible (Karuku et al., 2014). ΔSW = change in moisture storage in the root zone between planting and harvesting period; I = irrigation (There was no irrigation done in this study) R = runoff (The run-off was also negligible because there was only a gentle slope at the experimental site. The growing season's choice (Off-season) also played a key role in minimizing deep seepage and run-off).

3.7 Determination of nutrients (N and P) uptake and use efficiency

Three randomly selected whole potato plants (haulms and tubers) were harvested, cut into about 0.05 m long pieces, and weighed at the tuber bulking stage and harvest, and were placed in labeled khaki bags before being transported to the laboratory for processing and analysis. The samples were oven-dried (70 °C) and ground to pass through a 2 mm sieve, and analyzed for N and P content. Then, the samples were digested using a block digester and total N was determined using the distillation and titration method as described by Lindner and Harley (1942) while total P was determined using the colorimetric procedure as described by Novosamsky et al. (1983). Nutrient uptake (kg ha^{-1}) was then computed using Eq. 5.

$$\text{Total nutrient uptake} = \text{Haulm nutrient uptake} + \text{Tuber nutrient uptake} \tag{5}$$

Nutrient uptake (N or P) efficiency (kg of N or P uptake kg^{-1} N or P supply) was computed as a ratio between crop uptake and supply (both in kg ha^{-1}) of the specific nutrient element using Eq. 3 as described by Sandana (2016) and Valle et al. (2011).

$$\text{Nutrient uptake efficiency} = \frac{\text{Total plant nutrient uptake}}{\text{Nutrient supply}} \tag{6}$$

Nutrient supply was estimated as the specific nutrient (N or P) in the soil to a depth of 0.3 m at the time of planting added to the portion supplied by fertilizers. Nutrient use efficiency was estimated as a ratio between potato equivalent yield (PEY) and nutrient supply using Eq.

$$\text{Nutrient use efficiency} = \frac{\text{PEY}}{\text{Nutrient supply}} \tag{7}$$

3.8 Statistical data analysis

Generalized linear models (GLM) were used to test the effects of intercropping systems and fertilizer type on soil chemical properties using the package lme4 (Bates et al. 2015) in R statistical software (R Core Team 2021). Intercropping system and fertilizer type were considered fixed factors. Two-way interactions between intercropping systems and fertilizer type were also tested to assess the strength of relationships between these two factors in influencing ground cover, soil moisture and temperature, and crop performance indices (crop water productivity, nutrient uptake and use efficiencies, and potato equivalent yield). Several models were built from which the best-fitting ones were chosen. Maximum likelihood (ML) was used to estimate the model parameters and the model selection was based on Akaike Information Criterion (AIC), where models with the lowest AIC values were chosen.

Analysis of variance (ANOVA) was used to assess significant differences between the selected models as described in detail by Kamau et al. (2019). When analysis of variance (ANOVA) showed significant effects of intercropping systems or fertilizer type, means separation was performed using Tukey’s Honest Significant Difference (HSD) tests at $\alpha = 0.05$.

CHAPTER FOUR

RESULTS

4.1 Effect of the intercropping system and fertilizer application on ground cover and soil moisture content and soil temperature

Generally, intercropping systems had the greatest effects on ground cover, soil moisture content, and soil temperature across the two seasons, but the magnitude of these effects differed among the three variables (Table 3). Ground cover was consistently and significantly higher in potato-lima bean intercrops in the two seasons. In the first season, the potato-lima bean intercrop recorded an average ground cover of 92.8%, which was significantly higher compared to that recorded in the potato-lupin intercrop (85.0%), and potato pure stand (78.0%). Similar differences were observed in the second season, but with lower magnitudes especially for potato pure stand. For soil moisture content, intercropping systems did not have significant effects, although the differences were similar to those of ground cover. On the other hand, soil temperature was consistently lower in potato-lima beans intercrops. However, significant differences were observed only in the first season. Differences based on fertilizer types were observed in ground cover only, where higher values were recorded in soils that received the two fertilizers, DAP (94.4%) and composite NPK (96.1%) compared to the control (87.6%) in the first season. There were no significant differences in soil moisture content and soil temperature based on the fertilizer type.

Figure 5: Canopy overlaps by potato grown in a pure stand (a) and intercropped with lupin (b) and lima bean (c). Photos were taken at the tuber bulking stage of the potato.

Table 3: Ground cover, soil moisture content, and soil temperature (means ± SE) as influenced by intercropping system and fertilizer type.

Cropping system	Fertilizer type	Ground cover (%)			Soil moisture (mm m^{-1})			Soil temperature (°C)		
		S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††
Pure potato stand	Control	75.6 (2.6)	36.1 (5.4)	55.8 (4.4)	280.4 (9.5)	189.8 (13.0)	235.1 (11.0)	18.9 (0.4)	21.3 (0.4)	20.1 (0.3)
	DAP	76.1 (1.8)	46.1 (6.0)	61.1 (4.0)	267.4 (10.5)	184.1 (11.8)	225.8 (10.5)	19.3 (0.5)	21.4 (0.4)	20.4 (0.4)
	NPK	82.2 (2.9)	41.1 (6.9)	61.7 (5.0)	290.3 (11.7)	187.6 (8.8)	239.0 (11.3)	19.5 (0.6)	21.7 (0.4)	20.6 (0.4)
	Mean†	***78.0 (1.5)***^{C}	***41.1 (3.5)***^{C}	***59.5 (2.6)***^{C}	***279.4 (6.2)***	***187.2 (6.4)***	***233.3 (6.3)***	***19.2 (0.3)***^{AB}	***21.5 (0.2)***	***20.4 (0.2)***
Potato-lupin	Control	81.1 (3.5)	71.1 (3.5)	76.1 (2.6)	287.2 (10.3)	184.3 (16.8)	235.8 (13.0)	19.5 (0.2)	20.9 (0.2)	20.2 (0.2)
	DAP	88.3 (2.7)	72.8 (4.6)	80.6 (3.0)	250.6 (13.0)	216.0 (29.3)	233.3 (16.1)	19.7 (0.2)	21.1 (0.4)	20.4 (0.2)
	NPK	85.6 (2.6)	77.2 (2.5)	81.4 (1.9)	274.2 (12.9)	199.3 (16.3)	236.7 (12.1)	19.4 (0.3)	20.7 (0.3)	20.0 (0.2)
	Mean†	***85.0 (1.7)***^{B}	***73.7 (2.1)***^{B}	***79.4 (1.5)***^{B}	***270.7 (7.2)***	***199.9 (12.4)***	***235.3 (7.9)***	***19.5 (0.1)***^{A}	***20.9 (0.2)***	***20.2 (0.1)***
Potato-lima bean	Control	87.8 (2.4)^{b}	78.9 (3.3)	83.3 (2.1)^{b}	288.0 (14.8)	198.9 (18.8)	243.4 (14.0)	18.7 (0.2)	21.5 (0.4)	20.1 (0.3)
	DAP	94.4 (1.7)^{a}	83.3 (3.4)	88.9 (2.1)^{ab}	296.1 (16.4)	194.3 (19.2)	245.2 (15.1)	18.8 (0.2)	21.2 (0.2)	20.0 (0.3)
	NPK	96.1 (1.6)^{a}	85.6 (3.5)	90.8 (2.1)^{a}	284.3 (12.8)	230.6 (29.0)	257.4 (16.3)	18.9 (0.3)	21.8 (0.3)	20.3 (0.3)
	Mean†	***92.8 (1.2)***^{A}	***82.6 (2.0)***^{A}	***87.7 (1.3)***^{A}	***289.4 (8.4)***	***207.9 (13.1)***	***248.7 (8.7)***	***18.8 (0.1)***^{B}	***21.5 (0.2)***	***20.2 (0.2)***
p-values	Cropping system	<0.001	<0.001	<0.001	0.1819	0.404	0.3027	0.0252	0.0513	0.6351
	Fertilizer type	0.0042	0.2013	0.0406	0.3416	0.6318	0.6656	0.6599	0.8329	0.7679
	CS*FT	0.3803	0.8347	0.9975	0.3256	0.6032	0.9818	0.9001	0.5632	0.7039

Abbreviation: S1 = Season 1; S2 = season 2; CS = Cropping system; FT = Fertilizer type. † This value gives the aggregate effect of the intercropping system. †† The value gives average across the two seasons. These two means have been bolded and italicized for emphasis. Within columns, means followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on the intercropping system while lowercase letters indicate the differences based on fertilizer type. However, in cases where no differences were detected in either the cropping system or fertilizer type, letters of mean separation were left out to avoid the table being congested and to clearly show where actual differences occurred.

4.4 Influence of intercropping and fertilizer application on potato equivalent yield and crop water productivity

In the first season, the highest fresh tuber yield was recorded in potato pure stand (51.9 Mg ha^{-1}) compared to potato-lupin (23.7 Mg ha^{-1}) and potato-lima beans (30.7 Mg ha^{-1}) intercrops (Table 4). Thus, intercropping resulted in a decrease in fresh tuber yield by more than 70% relative to potato pure stand. In the second season, the decrease was notably higher, with fresh tuber yield in potato-legume intercrops being less than half that recorded in potato pure stand. Similar differences in fresh tuber yield were recorded in the two-season average. However, when all yields (legume grains and potato tubers) were converted to potato equivalent yield, the gap between the intercrops and potato pure stand was reduced. In the second season, for example, the equivalent yield in potato-lupin intercrop (28.6 Mg ha^{-1}) was significantly higher compared to that recorded in potato pure stand (16.5 Mg ha^{-1}). On the other hand, the differences in equivalent yield between potato-lima bean intercrop (8.8 Mg ha^{-1}) and potato pure stand were not significant. Similarly, the equivalent yield for the two-season average did not differ between the intercropping systems. Based on fertilizer type, significant differences were only observed in potato-lupin intercrop in the first season, with the highest fresh tuber yield in plots that received DAP (32.6 Mg ha^{-1}) and composite NPK fertilizer (30.1 Mg ha^{-1}) compared to no input control (19.1 Mg ha^{-1}). Similar differences were observed for potato equivalent yield in the first season.

Crop water productivity was significantly influenced by the intercropping system. Intercropping potato with lupin and potato pure stand showed significantly higher CWP of 23.4 and 22.2 kg ha^{-1} mm^{-1}, respectively, compared to potato-lima bean with 13 kg ha^{-1} mm^{-1} (figure. 6).

Table 4: Effect of the intercropping system and fertilizer type on potato fresh tuber yield and legume grain yield and potato equivalent yield (means ± SE).

Cropping system	**Fertilizer type**	**Potato fresh tuber yield (Mg ha^{-1})**			**Legume grain yield (Mg ha^{-1})**			**Potato equivalent yield (Mg ha^{-1})**		
		S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††
Pure potato stand	Control	36.9 (7.1)	15.0 (3.4)	26.0 (6.0)	N/A[1]	N/A	N/A	36.9 (7.1)	15.0 (3.4)	26.0 (6.0)
	DAP	66.5 (8.6)	20.8 (5.8)	43.7 (11.2)	N/A	N/A	N/A	66.5 (8.6)	20.8 (5.8)	43.7 (11.2)
	NPK	52.2 (8.3)	13.6 (4.8)	32.9 (9.6)	N/A	N/A	N/A	52.2 (8.3)	13.6 (4.8)	32.9 (9.6)
	Mean†	***51.9 (5.9)***^{A}	***16.5 (2.6)***^{A}	***34.2 (5.3)***^{A}	N/A	N/A	N/A	***51.9 (5.9)***^{A}	***16.5 (2.6)***^{B}	***34.2 (5.3)***
Potato-lupin	Control	19.1 (1.6)^{b}	3.8 (0.5)	11.4 (3.5)	N/A	8.0 (5.7)	4.0 (2.4)	19.1 (1.6)^{b}	33.8 (9.4)	26.4 (6.3)
	DAP	32.6 (3.3)^{a}	6.1 (0.5)	19.4 (6.1)	N/A	4.1 (1.6)	2.1 (1.2)	32.6 (3.3)^{a}	21.6 (6.5)	27.1 (4.1)
	NPK	30.1 (2.9)^{ab}	6.1 (1.2)	18.1 (5.6)	N/A	6.6 (2.2)	3.3 (1.8)	30.1 (2.9)^{ab}	30.7 (7.8)	30.4 (3.7)
	Mean†	***27.3 (2.5)***^{B}	***5.3 (0.6)***^{B}	***16.3 (2.9)***^{B}	N/A	***6.2 (2.6)***	***3.1 (1.7)***	***27.3 (2.5)***^{B}	***28.6 (4.6)***^{A}	***27.9 (4.9)***
Potato-lima bean	Control	20.2 (4.8)	5.8 (2.0)	12.9 (4.0)	0.2 (0.0)	0.6 (0.3)	0.4 (0.2)	20.7 (4.9)	7.2 (1.4)	14.0 (3.8)
	DAP	35.9 (3.2)	8.4 (2.1)	22.1 (6.4)	0.2 (0.0)	0.7 (0.2)	0.4 (0.2)	36.8 (3.2)	10.1 (2.3)	23.2 (6.1)
	NPK	36.2 (4.9)	7.0 (1.1)	21.6 (6.9)	0.2 (0.1)	0.8 (0.3)	0.5 (0.2)	36.3 (4.7)	9.0 (1.9)	22.9 (6.6)
	Mean†	***30.7 (3.4)***^{B}	***7.1 (1.0)***^{B}	***18.9 (3.4)***^{B}	***0.2 (0.1)***	***0.7 (0.4)***	***0.4 (0.1)***	***31.3 (3.4)***^{B}	***8.8 (1.1)***^{B}	***20.0 (3.2)***
p-values	Cropping system	<0.001	<0.001	0.0038	ND[2]	ND	ND	<0.001	<0.001	0.0559
	Fertilizer type	<0.001	0.1507	0.0927	ND	ND	ND	<0.001	0.1771	0.7841
	CS*FT	0.2569	0.5595	0.9098	ND	ND	ND	0.2461	0.0525	0.2301

1 megagram (Mg) = 10^6 grams (g). Abbreviation: S1 = Season 1; S2 = season 2; CS = Cropping system; FT = Fertilizer type. † This value gives the aggregate effect of the intercropping system. †† The value gives an average across the two seasons. These two means have been bolded and italicized for emphasis. [1] N/A Not applicable for potato pure stand and in the first season for lupin; [2] ND Analysis not conducted since the legumes are different; Within columns, means followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on the intercropping systems while lowercase letters indicate the differences based on fertilizer type. However, in cases where no differences were detected in either the cropping system or fertilizer type, letters of mean separation were left out to avoid the table being congested and to clearly show where actual differences occurred.

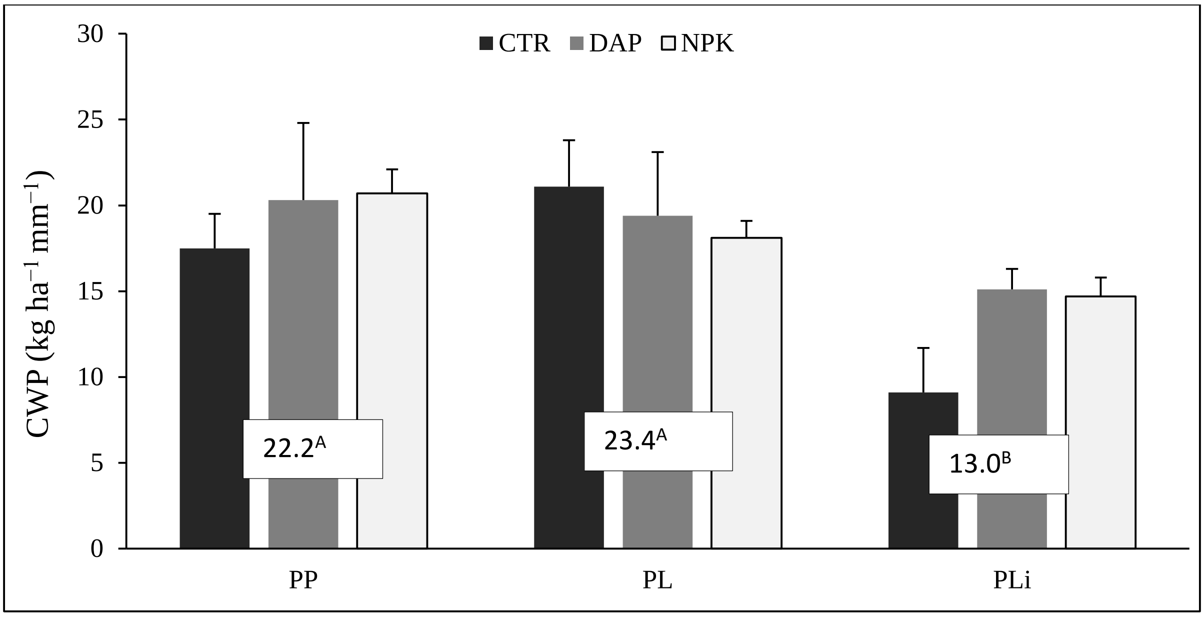


Figure 6: Crop water productivity (CWP) as influenced by the intercropping system (means and SE). (PP) pure potato stand, (PL) potato-lupin, (PLi) potato-lima bean. Values in the text box letters indicate the means of intercropping system and those followed by uppercase letters are significantly different at ($p > 0.05$).

4.3 Effect of intercropping system and fertilizer application on nutrients uptake, and use efficiency

Intercropping systems had the greatest influence on N uptake, uptake efficiency, and use efficiency (Table 2). N uptake and uptake efficiency were consistently and significantly higher in potato pure stand and lowest in potato-lupin intercrop across the two seasons. For example, the two-season average N uptake in potato pure stand was 73.5 kg ha^{-1}, which was more than double that recorded in potato-lupin intercrop (35.9 kg ha^{-1}) and almost 60% more than that recorded in potato-lima beans intercrop (46.8 kg ha^{-1}). The highest N use efficiency in the first season was recorded in potato pure stand (360.7 kg PEY kg^{-1} N supply), compared to that recorded in potato-lima beans (216.6 kg PEY kg^{-1} N supply) and potato-lupin intercrops (189.3 kg PEY kg^{-1} N supply). In the second season however, the highest N use efficiency was recorded in the potato-lupin intercrop (291.9 kg PEY kg^{-1} N supply) compared to the potato pure stand (116.5 kg PEY kg^{-1} N supply) and potato-lima beans intercrop (61.4 kg PEY kg^{-1} N supply). Based on fertilizer type, significant differences were observed only in potato-lupin intercrop in the first season for N uptake, with the highest values in soils that received DAP (61.2 kg ha^{-1}) and composite NPK fertilizer (55.9 kg ha^{-1}) compared to the control (36.8 kg ha^{-1}).

For P, only intercropping systems had significant influence, with differences similar to those of N (Table 3). For example, in the first season, P uptake was greater in potato pure stand with an average of 30.0 kg ha^{-1} compared to 18.1 kg ha^{-1} in potato-lupin and 19.1 kg ha^{-1} in potato-lima beans intercrops. There were no significant differences in P uptake efficiency based on intercropping systems. On the other hand, P use efficiency showed contrasting differences in the two seasons. In the first season, P use efficiency was higher in potato pure stand (498.0 kg PEY kg^{-1} P supply) and lowest in potato-lupin intercrop (388.2 kg PEY kg^{-1} P supply). In the second season however, the highest values were observed in potato-lupin (381.1 kg PEY kg^{-1} P supply) and lowest in potato-lima beans (128.1 kg PEY kg^{-1} P supply).

Table 5: Crop N uptake, uptake efficiency and use efficiency (means ± SE) as influenced by intercropping system and fertilizer type.

Cropping system	Fertilizer type	N uptake (kg ha^{-1})			N uptake efficiency (kg N uptake kg^{-1} N supply)			N use efficiency (kg PEY kg^{-1} N supply)		
		S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††
Pure potato stand	Control	82.5 (30.3)	37.1 (3.9)	59.8 (18.1)	0.70 (0.3)	0.32 (0.0)	0.51 (0.2)	311.0 (59.9)	126.3 (28.8)	218.7 (50.9)
	DAP	122.9 (65.9)	42.1 (14.0)	82.5 (36.1)	0.80 (0.4)	0.27 (0.1)	0.53 (0.2)	429.4 (55.8)	134.2 (37.3)	281.8 (72.5)
	NPK	110.9 (29.1)	45.4 (8.1)	78.2 (22.6)	0.73 (0.2)	0.30 (0.1)	0.51 (0.1)	341.6 (54.6)	89.0 (31.4)	215.3 (63.1)
	Mean†	***105.4 (10.5)***^{A}	***41.5 (4.6)***^{A}	***73.5 (7.2)***^{A}	***0.74 (0.1)***^{A}	***0.29 (0.0)***^{A}	***0.52 (0.1)***^{A}	***360.7 (33.5)***^{A}	***116.5 (17.8)***^{B}	***238.6(34.9)***^{A}
Potato-lupin	Control	36.8 (8.4)^{b}	13.9 (1.5)	25.3 (9.4)	0.31 (0.1)	0.12 (0.0)	0.21 (0.1)	160.4 (13.6)	535.3 (117.1)	347.8(115.5)
	DAP	61.2 (12.0)^{a}	24.1 (2.7)	42.7 (14.5)	0.40 (0.2)	0.16 (0.0)	0.28 (0.1)	210.7 (21.2)	139.6 (42.1)	175.1 (26.4)
	NPK	55.9 (15.1)^{ab}	23.4 (9.2)	39.7 (16.9)	0.37 (0.2)	0.18 (0.0)	0.28 (0.1)	196.9 (19.3)	200.9 (50.9)	198.9 (24.4)
	Mean†	***51.3 (12.3)***^{B}	***20.5 (3.3)***^{B}	***35.9 (7.6)***^{B}	***0.36 (0.1)***^{B}	***0.15 (0.0)***^{B}	***0.25 (0.0)***^{B}	***189.3 (11.8)***^{B}	***291.9 (82.2)***^{A}	***240.6(42.2)***^{A}
Potato-lima	Control	53.1 (0.6)	21.2 (1.0)	37.2 (9.2)	0.45 (0.0)	0.18 (0.0)	0.31 (0.1)	174.5 (40.8)	60.1 (11.7)	117.3 (31.9)
	DAP	71.4 (22.5)	23.1 (9.1)	47.3 (12.6)	0.46 (0.3)	0.15 (0.1)	0.31 (0.2)	234.5 (20.4)	65.3 (14.9)	149.9 (39.5)
	NPK	81.9 (22.1)	30.3 (9.3)	56.1 (12.9)	0.54 (0.3)	0.20 (0.1)	0.38 (0.2)	240.8 (30.7)	58.7 (12.3)	149.7 (43.3)
	Mean†	***68.8 (8.5)***^{AB}	***24.9 (3.8)***^{B}	***46.8(10.3)***^{AB}	***0.48 (0.1)***^{AB}	***0.18 (0.0)***^{B}	***0.33(0.1)***^{AB}	***216.6 (19.1)***^{B}	***61.4 (6.6)***^{B}	***139.0(21.2)***^{B}
p-value	Cropping system	0.0032	<0.001	0.0229	<0.001	<0.001	0.0138	<0.001	0.0035	0.0476
	Fertilizer type	0.0431	0.1051	0.3257	0.5819	0.2569	0.8954	0.0751	0.0509	0.6732
	CS x FT	0.8949	0.7642	0.9919	0.9424	0.1966	0.9937	0.5119	0.1075	0.1704

Abbreviation: S1 = Season 1; S2 = season 2; CS = Cropping system; FT = Fertilizer type. † This value gives the aggregate effect of the intercropping system. †† The value gives average across the two seasons. These two means have been bolded and italicized for emphasis. Within columns, means followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on the intercropping systems while lowercase letters indicate the differences based on fertilizer type. However, in cases where no differences were detected in either cropping system or fertilizer type, letters of mean separation were left out to avoid the table being congested and to clearly show where actual differences occurred.

Table 6: Crop P uptake, uptake efficiency and use efficiency (means ± SE) as influenced by intercropping system and fertilizer type.

Cropping system	Fertilizer type	P uptake (kg ha^{-1})			P uptake efficiency (kg P uptake kg^{-1} P supply)			P use efficiency (kg PEY kg^{-1} P supply)		
		S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††	S1 (Jun-Sep 2020)	S2 (Nov-Feb 2021)	***Mean***††
Pure potato stand	Control	27.8 (10.8)	10.6 (5.1)	19.2 (6.0)	0.62 (0.3)	0.24 (0.2)	0.43 (0.2)	527.0 (58.8)	335.0 (76.4)	431.0 (134.9)
	DAP	35.1 (16.8)	13.1 (7.1)	24.1 (8.7)	0.41 (0.3)	0.16 (0.1)	0.28 (0.1)	508.7 (51.9)	244.9 (68.1)	376.8 (132.4)
	NPK	27.2 (9.2)	10.6 (4.4)	18.9 (5.4)	0.32 (0.2)	0.13 (0.1)	0.22 (0.1)	458.3 (58.4)	160.3 (56.5)	309.3 (113.7)
	Mean†	***30.0 (5.8)***^{A}	***11.4 (2.6)***	***20.7 (3.6)***	***0.45 (0.1)***	***0.17 (0.1)***	***0.31 (0.1)***	***498.0 (34.2)***^{A}	***246.7 (42.1)***^{AB}	***372.4 (71.7)***
Potato-lupin	Control	10.1 (3.8)	3.8 (1.1)	6.9 (2.1)	0.22 (0.1)	0.10 (0.0)	0.15 (0.1)	425.3 (36.0)	526.5 (69.6)	475.9 (106.2)
	DAP	23.9 (11.6)	5.5 (2.0)	14.7 (6.1)	0.29 (0.2)	0.10 (0.0)	0.18 (0.1)	384.6 (38.7)	254.7 (76.9)	319.7 (48.2)
	NPK	20.5 (9.3)	9.2 (4.6)	14.9 (4.8)	0.26 (0.2)	0.23 (0.2)	0.24 (0.1)	354.8 (34.8)	362.1 (91.7)	358.4 (43.9)
	Mean†	***18.1 (4.4)***^{B}	***6.1 (3.5)***	***12.1 (4.6)***	***0.29 (0.1)***	***0.13 (0.1)***	***0.19 (0.1)***	***388.2 (20.9)***^{B}	***381.1 (32.6)***^{A}	***384.7 (58.6)***
Potato-lima	Control	18.0 (5.0)	5.0 (1.4)	11.5 (3.4)	0.40 (0.2)	0.12 (0.0)	0.26 (0.1)	462.8 (58.3)	159.4 (30.9)	311.1 (84.5)
	DAP	22.3 (10.6)	8.0 (3.9)	15.2 (5.5)	0.27 (0.2)	0.10 (0.0)	0.18 (0.1)	428.1 (37.3)	119.2 (27.2)	273.6 (72.1)
	NPK	16.8 (6.9)	7.4 (3.9)	12.1 (3.8)	0.20 (0.1)	0.10 (0.0)	0.14 (0.1)	433.8 (55.3)	105.8 (22.2)	269.8 (78.0)
	Mean†	***19.1 (3.6)***^{B}	***6.8 (3.9)***	***12.9 (4.3)***	***0.25 (0.1)***	***0.10 (0.0)***	***0.19 (0.1)***	***441.6 (37.1)***^{AB}	***128.1 (15.7)***^{B}	***284.9 (42.7)***
p-value	Cropping system	0.0177	0.0647	0.0843	0.0551	0.2705	0.0963	0.0137	<0.001	0.0732
	Fertilizer type	0.0738	0.2753	0.4086	0.0591	0.5272	0.3768	0.1231	0.1751	0.0506
	CS x FT	0.5699	0.5707	0.9234	0.0691	0.0679	0.3756	0.0706	0.5844	0.1046

Abbreviation: S1 = Season 1; S2 = season 2; CS = Cropping system; FT = Fertilizer type. † This value gives the aggregate effect of the intercropping system. †† The value gives average across the two seasons. These two means have been bolded and italicized for emphasis. Within columns, means followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on the intercropping systems while lowercase letters indicate the differences based on fertilizer type. However, in cases where no differences were detected in either cropping system or fertilizer type, letters of mean separation were left out to avoid the table being congested and to clearly show where actual differences occurred.

CHAPTER FIVE

DISCUSSIONS

5.1 Ground cover, soil moisture content and soil temperature under different potato-cropping systems and fertilizer application

In the present work, it was found that Ground cover was higher in potato-legume intercrops than in sole potato crop. This could be attributed to the fact that legumes germinate earlier, and establish ground cover before the emergence of potatoes. However, intercropping systems showed little impact on soil temperature and moisture, which could have been caused by high rainfall amounts experienced during the study period as can be noted in Fig. 1. This is contrary to several studies which have shown significant contribution of legumes in enhancing soil moisture content. For example, Ren et al. (2019) reported that intercropping potato with hairy vetch (*Vicia villosa* Roth) increased water availability and use efficiency. Nyawade et al. (2019) reported that intercropping potatoes with dolichos (*Lablab purpureus* L.) and lima bean (*Phaseolus lunatus* L.) resulted in soil moisture content increase by up to 38% compared to sole potato stand. The authors associated the increased soil moisture content to higher canopy in legume intercrops by between 26–57%, which also reduced soil temperatures by up to 7.3 °C in the upper soil layer (0–0.3 m). Gitari et al. (2018b) also reported significantly higher soil moisture content when the potato was intercropped with either dolichos (*Lablab purpureus* L.), garden pea (*Pisum sativum* L.), or climbing beans (*Phaseolus vulgaris* L.), than when the potato was grown pure stand. Nonetheless, these three studies cited here were conducted in drier and hotter areas that receive smaller amounts of rainfall. This gives greater emphasis on the importance of ground cover in soil moisture retention in drier areas. However, in our study, the significance of ground cover in soil moisture retention seems to weaken due to higher rainfall amounts. Increased ground cover could also be important in soil erosion control as suggested in other studies. For example, in the study by Nyawade et al. (2019), the authors reported that when compared to potato pure stand, potato-legume intercrops reduced soil and nutrient loss by up to 80%. Application of fertilizers showed little effect on ground cover, which could be an indication that, other factors instead of, or in addition to, the amount of available N and P would be implicated in the observed differences in ground cover, soil temperature, and soil moisture content.

5.3 Potato equivalent yield and crop water productivity under different potato-cropping systems and fertilizer application

The high fresh tuber yield in pure potato stands compared to intercrops could be an indication that there was competition for the available resources between the legumes and potato crops. This yield gap was expected to be compensated by benefits drawn from legumes (by increasing potato equivalent yield). However, the results obtained did not support our hypothesis, as the inclusion of the legumes caused a decrease in both fresh tuber and equivalent yield, which was especially prominent in the second season. For example, fresh tuber yield in potato-lima beans was more than 3 times lower than that recorded in control plots, which indicates that there could have been competition for soil nutrients between the two crops. Gitari et al. (2020) reported that beans have a shallow rooting system, and could probably extract N and P from the same soil stratum as potatoes thus decreasing potato yield. Increased crop cover, especially in the second season could also have reduced light interception by the potato crop caused by the shading effect of these legumes, which may have subsequently lowered the photosynthetic potential of potatoes thus lowering tuber yield. Similar observations were reported by Gitari et al. (2018b), Mushagalusa et al. (2008), and Singh et al. (2016).

Based on our results however, it seems like shading was the more influencing factor in reducing the yield of potato crop than competition for the available nutrients. It has been suggested that shading can have a significant impact on the yield of potato crop. For example, Ghosh et al. (2002) reported that shading the crop immediately before the initiation of tuber formation had a significant negative impact on the number and the overall weight of tubers. In addition, the authors reported that low light intensity accompanied by high temperature increases the production of substances that inhibit tuber formation. In our study, even though DAP supplied two and a half times the amount of P compared to composite NPK fertilizer, there were no significant differences in potato tuber yield between crops that received either DAP or NPK. This may be an indication that shading could have had a greater impact on potato tuber yield than the availability of nutrients. The equivalent yield obtained from the potato-lima beans intercrop was lower than the sole potato crop which meant that potato tuber yield loss could not be recovered from lima beans grain yield. This could partly be attributed to the low grain yield of lima beans and the lower prices compared with that of lupin.

The higher crop water productivity observed under intercropping systems, particularly in potato-lupin, could be an indication that there could have been more soil moisture was taken up by the plants and used for transpiration instead of being lost through direct evaporation from the soil surface, implying that the water was effectively used as also observed by Nyawade et al. (2018) and Gitari et al. (2018b). Under potato-lupin, a high canopy cover may have reduced evaporative water loss while promoting efficient water use. It is assumed that with a high density of canopy and high soil moisture content under the potato-lupin intercropping system, water absorption would be increased, resulting in high transpiration which explains the high CWP under potato-lupin intercropping system compared with mono-cropping systems of potato. This coincides with the findings by Nyawade et al. (2019b) who reported that in comparison to a pure stand of potato, intercropping potato with legumes resulted in substantially higher crop water productivity ranging between 4.04 and 9.67 kg ha^{-1} m^{-3}. Nyawade et al. (2018) also reported potato intercropping with lima beans kept soil moisture content above 33%; their study also showed higher crop water productivity under potato-lima intercropping relative to pure stand by 38% and significantly higher dry matter equivalent yield. The present study highlights the great potential of potato-lupin intercrops, which can be easily adopted by smallholder farmers to boost their incomes.

5.2 Nutrients (N and P) uptake and use efficiency under different potato-cropping systems and fertilizer application

Previous studies suggested that legumes such as lupin (*Lupinus albus* L.) exude low molecular weight organic acids (e.g., citric, malic, and succinic acids) that have been shown to solubilize fixed P in the soil (Egle et al. 2003). Exudation of organic acids can also stimulate microbial activity in the rhizosphere, which enhances solubilization of P and other nutrients, making them available not only to the legume but also to the companion crop. Such complementarity in nutrient release and acquisition is especially significant when there is an overlap between the rhizosphere of the legume and the companion crop (Schulze et al. 2006). On the contrary, this present study showed consistently lower N and P uptake under intercropping than in sole potato crops. This could be an indication that there could have been increased competition for the available nutrients between the legumes and potato crop, which then decreased the amount of these nutrients available for potato uptake.

The fact that legumes take a shorter time to emerge from the soil after planting compared to potatoes may give them a higher competitive advantage in nutrient uptake, as they would have established a stronger rooting system, before the emergence of potatoes. This suggestion is consistent with what was reported by Gitari et al. (2018a), who observed that some legumes such as garden pea (*Pisum sativum* L.) and climbing bean (*Phaseolus vulgaris* L.) reduced nutrient uptake by potatoes when intercropped with the two legumes. However, in the same study by Gitari et al. (2018a), potatoes intercropped with dolichos (*Lablab purpureus* L.), which is a deeper-rooted legume, showed significantly higher N and P uptake compared to the sole potato crop. The authors suggested that the deeper rooting system could have decreased competition for available N and P and thus, enhanced the uptake of the two nutrients by potatoes. In this study, increased competition for available nutrients coupled with reduced radiation intercepted by potato crop, as a result of greater legume cover, could also contribute to the lower nutrient use efficiency in potato-legume intercrops relative to the sole potato crop.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

i. The potato-Lima beans intercropping system maintained a high ground cover (85%) throughout the study period and it was effective in increasing soil moisture content. Application of fertilizers showed little effect on the ground cover this could be an indication that other factors may have contributed to the difference observed in ground cover, soil moisture content, and soil temperature.

ii. Potato equivalent yield was also lower, especially in potato-lima beans intercrop, which shows that the tuber yield lost due to intercropping could not be recovered from lima beans grain yield. This study also showed little crop water productivity differences between potato pure stand and potato-lupin intercrop.

iii. Contrary to the hypothesis, this study has shown consistently lower N and P uptake under potato-legume intercrops than in sole potato crop. In addition, increased competition for available nutrients could contribute to the lower nutrient use efficiency under potato-legume intercropping system relative to sole potato.

6.2 Recommendations

i. Integration of legumes into potato cropping systems is likely to contribute to improved quality of diet of the families who are dependent on potatoes for their nutrition and this knowledge gap requires some attention

ii. Since the study was conducted for two seasons, and seasonal differences could have affected the observed results, there is a need to further explore these intercrops to establish the impact of the two legumes on nutrient uptake and use efficiency over a longer period.

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APPENDICES

Analysis of variance (ANOVA)

Appendix 1: ANOVA for ground cover

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2571.6	1285.8	4.67	
Block.*Units* stratum					
CS_code	2	5116.0	2558.0	9.29	<.001
Fert_code	2	3823.5	1911.7	6.94	0.0406
CS_code.Fert_code	4	4950.6	1237.7	4.49	0.9975
Residual	151	41595.1	275.5		
Total	161	58056.8			

Appendix 2: ANOVA for soil moisture content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	7.522	3.761	1.01	
Block.*Units* stratum					
CS_code	2	36.536	18.268	4.90	0.3027
Fert_code	2	1.097	0.549	0.15	0.6656
CS_code.Fert_code	4	10.068	2.517	0.68	0.9818
Residual	151	562.549	3.725		
Total	161	617.772			

Appendix 3: ANOVA for soil temperature

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	37.91	18.96	1.80	
Block.*Units* stratum					
CS_code	2	0.11	0.05	0.01	0.6351
Fert_code	2	2.60	1.30	0.12	0.7679
CS_code.Fert_code	4	1.92	0.48	0.05	0.7039
Residual	151	1591.03	10.54		
Total	161	1633.57			

Appendix 4: ANOVA for total N uptake

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	684	342	0.09	
Block.*Units* stratum					
CS_code	2	37420	18710	4.77	0.0229
Fert_code	2	4284	2142	0.55	0.3257
CS_code.Fert_code	4	3391	848	0.22	0.9919
Residual	43	168506	3919		
Total	53	214284			

Appendix 5: ANOVA for total P uptake

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr
Block stratum	2	145.2	72.6	0.22	
Block.*Units* stratum					
CS_code	2	2654.1	1327.1	4.09	0.0843
Fert_code	2	93.7	46.8	0.14	0.4086
CS_code.Fert_code	4	232.3	58.1	0.18	0.9234
Residual	43	13963.8	324.7		
Total	53	17089.1			

Appendix 6: ANOVA for N uptake efficiency (NUpE)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0394	0.0197	0.11	
Block.*Units* stratum					
CS_code	2	1.9015	0.9508	5.39	0.0138
Fert_code	2	0.2085	0.1042	0.59	0.8954
CS_code.Fert_code	4	0.1606	0.0401	0.23	0.9937
Residual	43	7.5846	0.1764		
Total	53	9.8946			

Appendix 7: ANOVA for P uptake efficiency (PUpE)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.00054	0.00027	0.00	
Block.*Units* stratum					
CS_code	2	0.71799	0.35900	4.31	0.0963
Fert_code	2	0.13164	0.06582	0.79	0.3768
CS_code.Fert_code	4	0.05885	0.01471	0.18	0.3756
Residual	43	3.57756	0.08320		
Total	53	4.48657			

Appendix 8: ANOVA for N use efficiency (NUE)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	244851	122426	7.64	
Block.*Units* stratum					
CS_code	2	295395	147697	9.22	0.0476
Fert_code	2	81787	40894	2.55	0.6732
CS_code.Fert_code	4	279871	69968	4.37	0.1704
Residual	16	256224	16014		
Total	26	1158129			

Appendix 9: ANOVA for P use efficiency (PUE)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1251231	625616	6.72	
Block.*Units* stratum					
CS_code	2	1658801	829401	8.90	0.0732
Fert_code	2	2131403	1065702	11.44	0.0506
CS_code.Fert_code	4	1954245	488561	5.24	0.1046
Residual	16	1490581	93161		
Total	26	8486262			

Appendix 10: ANOVA for tuber yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	559.0	279.5	1.03	
Block.*Units* stratum					
CS_code	2	3058.7	1529.4	5.64	0.0038
Fert_code	2	1107.8	553.9	2.04	0.0927
CS_code.Fert_code	4	235.9	59.0	0.22	0.9098
Residual	43	11655.6	271.1		
Total	53	16617.0			

Appendix 11: ANOVA for potato equivalent yield (PEY)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4492.9	2246.5	7.81	
Block.*Units* stratum					
CS_code	2	5132.8	2566.4	8.93	0.0559
Fert_code	2	552.9	276.4	0.96	0.7841
CS_code.Fert_code	4	4109.3	1027.3	3.57	0.2301
Residual	16	4600.0	287.5		
Total	26	18888.0			

Appendix 12: ANOVA for (CWP)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	512.26	256.13	7.84	
Block.*Units* stratum					
CS_code	2	586.48	293.24	8.98	0.002
Fert_code	2	62.67	31.34	0.96	0.404
CS_code.Fert_code	4	466.55	116.64	3.57	0.029
Residual	16	522.56	32.66		
Total	26	2150.52			