Lupin and Lima Beans Diminish Potatoes' N and P Uptake, Uptake Efficiency and Use Efficiency

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8 authors, including:

Mustafa Haile
Ministry of Agriculture and Irrigation of the Republic of Spmalois

Nancy Karanja
University of Nairobi

Shadrack Nyawade
International Potato Center

Potato Research
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Lupin and Lima Beans Diminish Potatoes' N and P Uptake, Uptake Efficiency and Use Efficiency

Mustafa A. Haile[1] · Nancy N. Karanja[1] · Shadrack O. Nyawade[2] · Harun I. Gitari[3] · Gladys Cheruto[1] · Lukelysia Nyawira[4] · Muhammad Ali Raza[5] · Solomon Kamau[1]

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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 seasons to evaluate the potential of potato-legume intercropping in enhancing N and P uptake and use efficiencies and 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 as follows: (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 the equivalent yield decreased by almost 15 Mg ha^{-1}. The application of fertilizer did not enhance the recovery of the yield loss. 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.

Keywords Lima bean (*Phaseolus lunatus* L.) · Lupin (*Lupinus albus* L.) · Nutrient use efficiency · Potato equivalent yield · Potato-legume intercrops

✉ Solomon Kamau
solkam08@gmail.com; solkam08@uonbi.ac.ke

Extended author information available on the last page of the article

Introduction

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). The crop is an important source of livelihood to many farmers in the developing countries in Africa, especially in the highlands where the crop is grown in large quantities. Nonetheless, majority of these farmers get sub-optimal yields as a result of declining soil fertility coupled with the use of poor quality seeds, pests and diseases and insufficient fertilizer use below the recommended rates (Muthoni et al. 2013; Wang'ombe and van Dijk 2013). For example, the average yield in sub-Saharan Africa is 8 Mg ha^{-1}, which is less than half the global average of 21 Mg ha^{-1} and less than a fifth of the yield obtained by some farmers in Europe and America of more than 40 Mg ha^{-1} (CIP 2022). Furthermore, climate change is expected to decrease the yields further in many of these sub-Saharan countries (Funk et al. 2008; Ogola and Ouko 2021; Parker et al. 2019). This is mainly due to the fact that the potato crop is highly sensitive to drastic changes in weather conditions. For instance, water stress and high temperatures at critical stages of potato growth, such as tuber initiation or tuber bulking stage, can significantly reduce the yield of the crop (Gitari et al. 2018a; Nyawade et al. 2019). Therefore, the adoption of strategies that increase productivity in a sustainable way and enhance resilience to climatic stresses (called climate-smart agriculture technologies) is becoming increasingly popular (Ogola and Ouko 2021).

Phosphorus (P) and nitrogen (N) are essential nutrient elements for potato production. However, the concentration of these two elements is increasingly becoming low in most agricultural soils in low-income countries due to overexploitation of soil resources as a result of continuous cultivation with little or no replenishment (Kamau et al. 2019a; Muthoni and Nyamongo 2009). Monocropping and intensification of tillage operations may also lower nutrient concentration since tillage exposes soil to higher temperatures and soil organic matter to microbial attack, thus exacerbating the decline in crop productivity (Mbau et al. 2015). Considering the threats posed by climate change and the limitations in the use of fertilizer in this most vulnerable part of the world, an effective approach is needed. Legumes, for example, can be intercropped with potatoes to control soil erosion, reduce soil temperature and increase soil moisture content, and are therefore an important component of climate-smart agriculture technologies. Some legumes like lupin (*Lupinus albus* L.) have been shown to have extensive first-order lateral roots (Kerley 2000) that produce organic acids which can solubilise bound forms of P, thus increasing not only the availability of P, but also that of micronutrients in their rhizosphere which can benefit the companion crops (Felderer et al. 2015; Schulze et al. 2006). Besides nutrient mobilisation, studies have also shown transfer of biologically fixed N from the legumes to companion crops. For example, Thilakarathna et al. (2016) reported that legumes can transfer up to 26% of the biologically fixed N through decomposition of roots and nodules or the return of crop residues. When the crop is actively growing however, the main mechanisms for N transfer is through root exudation and mycorrhizae-mediated transfers (Lesuffleur et al. 2013; Meng et al. 2015; Thilakarathna et al. 2016). Fixation of N by legumes could also reduce competition for available N with companion crops. Therefore, intercropping can enhance nutrient uptake and increase crop productivity without incurring additional expenses on fertilizers (Brooker et al. 2014; Stagnari et al. 2017). Despite the potential of such beneficial associations in addressing the decreasing crop yield, there is limited knowledge about how such systems in combination with optimal inorganic fertilizer application affect the yield of crops like potato. Therefore, the objectives of this study were to determine the effects of potato-legume intercropping and fertilizer application on (i) N and P uptake, uptake efficiency and use efficiency, and (ii) yield of potato crop. Nutrient uptake efficiency is the ratio between crop uptake and supply of a specific nutrient element (in this case N or P) and determines the ability of the crop to take up nutrients from the soil (Gitari et al. 2018a), whereas nutrient use efficiency is a measure of crop yield per unit of nutrient supply from the soil and fertilizer (Weih et al. 2018). In this study, we used potato equivalent yield (PEY) as the measure of crop yield. We hypothesised that (i) N and P uptake, uptake efficiency and use efficiency, and yield of potato crop will increase where legumes are integrated, and (ii) the four crop performance indices will be enhanced where fertilizers are applied.

Materials and Methods

Description of the Study Site

This study was conducted at Gathaara 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. According to Jaetzold et al. (2006), the area is classified as a Pyrethrum-Wheat Zone (identified as *UH 2 vl i or two*) receiving an average annual precipitation of about 1200 mm in a bimodal pattern. The first season commonly known as "long-rains", starts towards the end of the month of March to mid-July, and the second season, known as "short-rains" starts from 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. 2019b). 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 season in our 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. 1). 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}).

Establishment of the Field Trials

The study area was chosen due to its suitability in 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

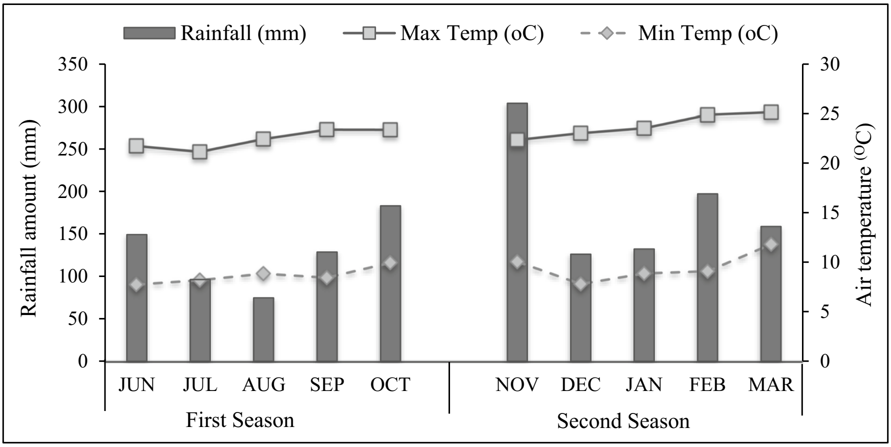

Fig. 1 Mean monthly rainfall, minimum (min temp) and maximum (max temp) temperature during the study period

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 to these plots. 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 as follows: (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 randomised 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. 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}.

Crop Management and Harvesting

To control potato late blight, the potato crop was sprayed once per month starting at 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 the potato crop were 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 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. 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.

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 potato. Ground cover was measured using a point frame from several randomly selected points in each plot as described 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).

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

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.

Estimation of Nutrient Uptake and Use Efficiency and Crop Performance Indices

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

$$\text{Nutrient uptake} = \text{Haulm nutrient uptake} + \text{Tuber nutrient uptake} \tag{2}$$

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).

$$\text{Nutrient uptake efficiency} = \frac{\text{Nutrient uptake}}{\text{Nutrient supply}} \tag{3}$$

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. 4.

$$\text{Nutrient use efficiency} = \frac{\text{PEY}}{\text{Nutrient supply}} \tag{4}$$

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.

$$\text{PEY} = \text{PY} + \frac{\text{LY} \times \text{LP}}{\text{PP}} \tag{5}$$

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.

Statistical Data Analysis

Generalised 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 as fixed factors. Two-way interactions between intercropping systems and fertilizer type were also tested in order to assess the strength of relationships between these two factors in influencing ground cover, soil moisture and temperature and crop performance indices (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 details by Kamau et al. (2020). 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 $\alpha = 0.05$.

Results

Changes in Ground Cover, 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 1). 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 which 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.

Crop Nutrient Uptake and Use Efficiency in Response to Intercropping

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

Table 1 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. †These values give the aggregate effects of the intercropping system and have been presented in bold and italics for emphasis. ††These values give averages across the two seasons. 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 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 2 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. †These values give the aggregate effects of the intercropping system and have been presented in bold and italics for emphasis. ††These values give averages across the two seasons. 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 3 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. †These values gives the aggregate effects of the intercropping system and have been presented in bold and italics for emphasis. ††These values give averages across the two seasons. 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 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, 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).

Influence of Intercropping and Fertilizer Application on Crop Performance Indices

In the first season, the highest fresh tuber yield was recorded in potato pure stand (51.9 Mg ha^{-1}) compared to potato-lupin (27.3 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 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 control (19.1 Mg ha^{-1}). Similar differences were observed for potato equivalent yield in the first season.

Discussion

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 a 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

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 g (g). Abbreviation: S1 season 1, S2 season 2, CS cropping system, FT fertilizer type. †Theses values give the aggregate effects of the intercropping system and have been presented in bold and italics for emphasis. ††These values give average across the two seasons. [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 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

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 potato was intercropped with either dolichos (*Lablab purpureus* L.), garden pea (*Pisum sativum* L.) or climbing beans (*Phaseolus vulgaris* L.), than when 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 the 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.

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 solubilise fixed P in the soil (Egle et al. 2003). Exudation of organic acids can also stimulate microbial activity in the rhizosphere, which enhances solubilisation 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 rhizosphere of the legume and the companion crop (Schulze et al. 2006). Our study however showed consistently lower N and P uptake under intercropping than in sole potato crop. This could be an indication that there could have been increased competition for 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 sole potato crop. The authors suggested that the deeper rooting system could have decreased competition for available N and P and thus, enhancing the uptake of the two nutrients by potatoes. In our 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.

The high fresh tuber yield in pure potato stand compared to intercrops could be an indication that there was competition for the available resources between the legumes and potato crop. 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 the 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, despite the fact that 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 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 "Estimation of Nutrient Uptake and Use Efficiency and Crop Performance Indices" section above).

Conclusions

Contrary to our hypothesis, this study has shown consistently lower N and P uptake under potato-legume intercrops than in sole potato crop. 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 implies that the choice of companion legumes to be used in intercropping can significantly influence nutrient uptake and use efficiency, and thus determine yield of potato crop. Nonetheless, integration of legumes into potato cropping systems is likely to contribute improved quality of diet of the families who are dependent on potatoes for their nutrition and this gap in knowledge requires some attention. Since the study was conducted over a period of two seasons, and that 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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Data Availability Data is available upon request.

Declarations

Competing Interests The authors declare no competing interests.

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Authors and Affiliations

Mustafa A. Haile[1] · Nancy N. Karanja[1] · Shadrack O. Nyawade[2] · Harun I. Gitari[3] · Gladys Cheruto[1] · Lukelysia Nyawira[4] · Muhammad Ali Raza[5] · Solomon Kamau[1]

1 Department of Land Resource Management and Agricultural Technology, Faculty of Agriculture, University of Nairobi, P.O. Box 29053-00625, Nairobi, Kenya

2 The CGIAR Research Program On Roots, Tubers and Bananas (RTB), International Potato Center, Sub-Saharan Africa Regional Office, ILRI Campus, Old Naivasha Road, P.O. Box 25171-00603, Nairobi, Kenya

3 Department of Agricultural Sciences and Technology, School of Agriculture and Enterprise Development, Kenyatta University, Nairobi, Kenya

4 World Agroforestry, United Nations Avenue, P.O. Box 30677-00100, Nairobi, Kenya

5 College of Agronomy, Sichuan Agricultural University, Chengdu, China