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Nitrogen and phosphorous uptake by potato (*Solanum tuberosum* L.) and their use efficiency under potato-legume intercropping systems

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ABSTRACT

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

1. Introduction

Potato cultivation under intercropping systems has been practised globally due to its effectiveness in soil and water conservation resulting in increased yield and economic returns compared with monocropping (Hinsinger et al., 2011; Gericke et al., 2012; Nyawade, 2015; Zhang et al., 2016b). High productivity in potato production systems has been achieved by incorporating crops such as radish, maize and bean (Mushagalusa et al., 2008; Singh et al., 2016; Zhang et al., 2016b). However, competition between companion crops for the available resources such as moisture, light and nutrients like nitrogen (N) and phosphorous (P) is a common occurrence (Gitari et al., 2017). These two elements are essential nutrients that are important in potato production and their deficiency may result in yield losses (Fernandes and Soratto, 2012; Hopkins et al., 2014; Sandana, 2016; Musyoka et al., 2017). Nevertheless, these mineral elements are inherently low in most tropical soils such as Nitisols (Alfisols), which dominate potato-growing areas in Kenya (Jaetzold et al., 2006; IUSS Working Group WRB, 2015). The low available P is also due to its adsorption onto soil constituents such as organic matter, clays and sesquioxides (Hinsinger et al., 2011; Hopkins et al., 2014; Gitari, 2013; Hill et al., 2015).

Nitrogen and phosphorous are usually supplied to crops mainly through inorganic fertilizers, and this takes about 20% of operating costs in potato production (Stark et al., 2004; Rens et al., 2018). In Kenya, as many other sub-Saharan countries, potato growers are mainly small-scale farmers who primarily use the government-subsidised ammonium-based fertilizers such as di-ammonium phosphate and calcium ammonium nitrate. Adding P to a low pH soil renders it unavailable through fixation by Fe and Al. In addition, its uptake by most crops largely depends upon root interception due to its low mobility (Hill et al., 2015). However, the potato has a shallow rooting system to exploit fully such P and N hence; they are susceptible to loses principally through immobilization, volatilization, leaching and runoff under poor agronomic management (Hopkins et al., 2014; Rens et al., 2018). This

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results not only in yield losses but also adversely affect the environment through processes such as eutrophication of surface water bodies (Zhaohui et al., 2012; Jones et al., 2013). This is an indication that potato-based cropping systems are still vulnerable to nutrient loss pathways resulting in poor crop growth and low tuber yield. For instance, the average tuber yield in Kenya is 8–15 t ha^{-1}, which is more than three times lower than the 30–40 t ha^{-1} that are achievable under field conditions (Muthoni et al., 2013; Gitari et al., 2016). Therefore, identification and integration of suitable intercrops in potato cropping systems could be a potential strategy to curb such losses.

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

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

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

2. Materials and methods

2.1. Site description

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

2.2. Experimental design and layout

This study was conducted for four consecutive seasons from 2014 short rains to 2016 long rains. The treatments included potato (cv. Shangi) as a pure stand (abbreviated as PS) and potato intercropped with either garden pea (*Pisum sativum* L. cv. Green feast) (PG), dolichos (*Lablab purpureus* L. cv. Uncinatus) (PD) and climbing bean (*Phaseolus vulgaris* L. cv. Kenya tamu) (PB). The trial was laid out in a randomized complete block design with four replications for each treatment. The dimension of the experimental plot was 6 by 4 m accommodating six potato rows spaced at 0.9 m. At the onset of each growing season, presprouted seed potato tubers (35–55 mm in diameter) were planted in rows at an inter-seed spacing of 0.3 m, a seed rate of 1.8 t ha^{-1} and a plant density of 36,400 plants ha^{-1}. The legumes were planted between potato rows at a rate of 20 kg of seed ha^{-1} with two seeds sown at a spacing of 0.25 m within a row such that the final plant density was 88,000 plants ha^{-1}. Shangi was preferred for its popularity among smallholder farmers in the country. It matures within 90 days with an attainable yield of 40–50 ha^{-1} under field conditions (Muthoni et al., 2013; Gitari et al., 2017). The legume varieties used in this study are the most common ones among the local farmers, hence the high chances of adoption of the proposed potato-legume intercropping systems.

2.3. Agronomic practices

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

2.4. Data collection

Plant canopy cover was measured every seven days starting from 28 to 84 DAP using a sighting frame. The frame was placed between potato rows and the vegetation was observed through each of the ten thin gun sight tubes arranged at fixed intervals along a crossbar. A similar sampling frequency was used for soil moisture content using a digital moisture meter-HSM50 (Omega®). The probe of the meter was inserted at a depth of 0.2 m from different points of the plot. Harvesting was carried out manually from 12 m^2 central area per plot at 65 and 75 DAP for pea, 84 DAP for potato and bean, and 120 DAP for dolichos. From the harvesting area, 10 potato plants were randomly selected and their haulm biomass was harvested, weighed and cut into 5 cm long pieces. The tubers were dug out, weighed and 10 tubers were randomly picked and sliced into 10 mm wide strips. Sub-samples of 500 g for haulm biomass and tubers were oven-dried at 70 °C for 72 h and their weights were recorded. The samples were then ground using a tissue grinder and passed through a 1.0 mm sieve for nutrient (N and P) analysis. Nitrogen was determined by Kjeldahl method (Bremner, 1996) whereas P was analysed colourimetrically using a UV–vis spectrophotometer as described by Murphy and Riley (1962). Nutrient (N and P) uptake for tubers and haulms was determined as the product of tissue's dry weight and nutrient concentration, and summing up the two gave the plant nutrient uptake (Eq. (1)).

$$\text{Plant nutrient uptake} = \text{Haulm nutrient uptake} + \text{Tuber nutrient uptake} \quad (1)$$

Nutrient (N and P) uptake efficiency was computed as a ratio of total potato nutrient uptake and nutrient supply (Eq. (2)) (Valle et al., 2011; Sandana, 2016).

$$\text{Nutrient uptake efficiency} = \frac{\text{Total plant nutrient uptake}}{\text{Nutrient supply}} \quad (2)$$

Where nutrient supply was estimated as the sum of elements (N and P) in the soil at planting time (in 0–0.3 m depth) added to that applied through fertilizers. Nutrient use efficiency, which indicates productivity of the entire cropping system, was calculated by dividing potato equivalent yield (PEY) by nutrient supply (Eq. (3)).

$$\text{Nutrient use efficiency} = \frac{\text{PEY}}{\text{Nutrient supply}} \quad (3)$$

Where PEY was computed using Eq. (4).

$$\text{PEY}(\text{kgha}^{-1}) = \text{PY}(\text{kgha}^{-1}) + \frac{\text{LY}(\text{kgha}^{-1})\text{xLP}(\text{US\$kg}^{-1})}{\text{PP}(\text{kgha}^{-1})} \quad (4)$$

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

2.5. Statistical data analysis

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

3. Results

3.1. Rainfall and temperature patterns

The 2014 short rains season at the beginning of the experiment received a lower amount of rainfall (about 380 mm) compared with the cumulative rainfall of 740, 720, and 840 mm recorded for 2015 long rains, 2015 short rains and 2016 long rains, respectively (Fig. 1). Nearly constant temperatures were experienced throughout the four seasons with an average minimum and maximum temperature of 16.2 and 28.9 °C, respectively.

3.2. Crop canopy cover and soil moisture content

All the treatments had developed substantive canopy cover at 28 days after planting (DAP) across four seasons. The canopy cover increased gradually to reach the peak levels of 73, 69, 67 and 58% for PD, PG, PB and PS, respectively at 56 DAP then started to decline gradually except in potato-dolichos cropping system, which had maintained a substantial cover of 52% until the potato's physiological maturity stage (Fig. 2a). Canopy cover was significantly ($p \leq 0.001$) higher under potato-legume cropping systems by 47, 29 and 26% in PD, PG and PB, respectively as compared with PS across seasons.

Soil moisture content (SMC) was significantly ($p \leq 0.001$) higher under potato-legume cropping systems compared with potato pure stand. Across seasons, SMC was 21% in PD, 18% in PG and 17% in PB compared to 16% in PS (Fig. 2b). The lowest SMC values were observed in 2014 short rains, and they were less than 20% in all treatments. In 2015 long rains, the highest SMC of 25, 23, 22 and 21% were recorded at 56 and 70 DAP for PD, PG, PB and PS, respectively. All treatments recorded SMC of above 20% between 28 and 70 DAP in 2015 short rains, whereas such a record was made only at 56 DAP in 2016 long rains.

3.3. Effect of potato-legume cropping systems on nutrient (N and P) uptake, uptake efficiency and use efficiency

Nitrogen uptake, N uptake efficiency and N use efficiency were significantly affected by the type of potato-legume intercrop, but these differences differed from season to season (Table 1). Either potato N uptake in PB and PG was lower than in PS by 22 and 27%, respectively but comparable in PD. Intercropping potato with peas or beans reduced N uptake efficiency significantly by 37% in comparison with PS. However, intercropping with dolichos resulted in comparable N uptake efficiency of 0.66 and 0.69 kg total N uptake kg^{-1} N supply in PD and PS, respectively. The N use efficiency (NUE) in PG, PB and PD were significantly higher by 6, 14 and 21% than in PS.

Similarly, P uptake, P uptake efficiency and P use efficiency were significantly affected by the type of potato-legume intercrop, and they varied with seasons (Table 2). Phosphorous uptake was highest in PS (29 kg P ha^{-1}) and PD (28), but declined by 29 and 39% in PB and PD, respectively compared with PS. Phosphorous use efficiency (PUE) was lowest in PS (321 kg potato equivalent yield kg^{-1} P supply) and it increased by 6, 15 and 22% in PG, PB and PD, respectively compared with PS.

3.4. Effect of potato-legume cropping systems on potato and legume yield

Tuber dry yield, number of tubers per plant, fresh tuber yield, legume grain yield and potato equivalent yield were significantly affected by the type of potato-legume intercrop, although these differences differed with seasons (Table 3). Dry tuber yield was lower in PD, PB and PG by 2, 16 and 17%, respectively compared with PS. The least number of tubers per plant (7) was recorded in PG and PB, and it differed significantly from the highest (9) in PS and PD. Fresh tuber yield was highest (36 t ha^{-1}) in PS, but this was not significantly different from that recorded in PD. Nevertheless, the yield decreased significantly by 5.6 t in PB and 6.5 t in PG when compared with PS. Among the legumes, dolichos had the lowest grain yield that ranged between 1.8 and 1.9 t ha^{-1} across the seasons whereas intermediate (2.5–2.7 t ha^{-1}) and highest yields (3.1–3.5 t ha^{-1}) were recorded in pea and bean plots, respectively.

3.5. Relationship between N and P uptake efficiency and use efficiency and potato yield components

Nitrogen uptake efficiency (NUpE) and P uptake efficiency (PUpE) correlated positively and strongly ($p < 0.001$) with tuber dry weight, number of tubers $plant^{-1}$ and fresh tuber yield $plant^{-1}$ (Table 4). Nitrogen use efficiency (NUE) and P use efficiency (PUE) also indicated significant ($p < 0.001$) correlations with tuber dry weight and fresh tuber yield $plant^{-1}$. The relationship between the number of tubers $plant^{-1}$ and NUE and PUE was also significant ($p < 0.001$) though weaker ($r = 0.39$).

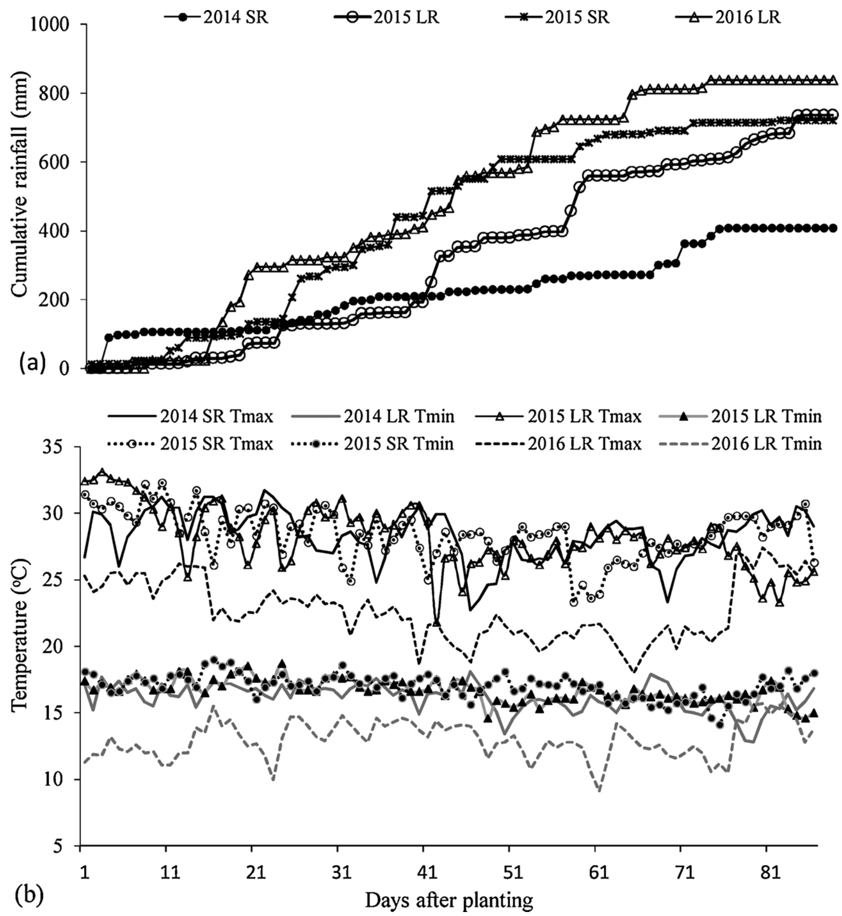

Fig. 1. Rainfall and temperature for the period between potato planting and harvesting. Tmax = maximum temperature, Tmin = minimum temperature, LR = long rains and SR = short rains. (Source: Kenya Meteorological Department, Kabete Weather Station).

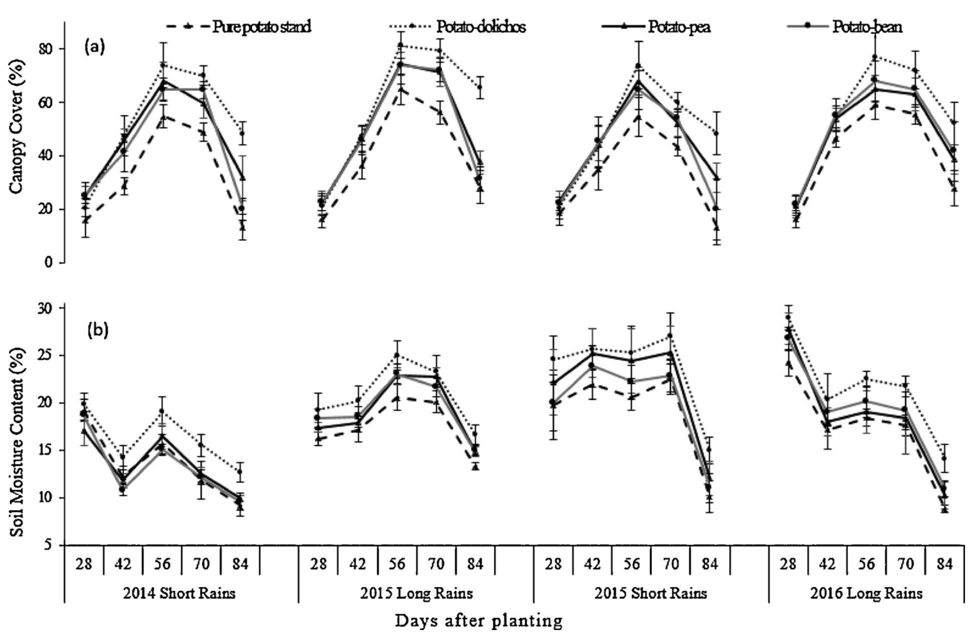

Fig. 2. Canopy cover (a) and soil moisture content (b) in different potato-legume cropping systems.

4. Discussion

Potato production in sub-Saharan countries such as Kenya is mainly carried out by smallholder farmers who are dependent on Agriculture for their livelihood. Incorporating legumes into such production systems would have far-reaching benefits such as enhancing better nutrient utilization, hence improving the productivity of potato-based cropping systems. Rooting depth and canopy cover have been cited as the pivotal factors in controlling N and P uptake for potato, and hence the productivity of the potato-legume cropping systems (Mushagalusa

Table 1
Nitrogen uptake, uptake efficiency and use efficiency as influenced by potato-legume cropping systems.

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

Analyses of variance (*p* values)

Variable	Cropping system	Season	System × Season
Plant N uptake	< 0.001	< 0.001	0.049
N uptake efficiency	< 0.001	< 0.001	0.049
N use efficiency	< 0.001	< 0.001	< 0.001

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

Table 2
Phosphorous uptake, uptake efficiency and use efficiency as influenced by potato-legume cropping systems.

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

Analyses of variance (*p* values)

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

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

et al., 2008; Zhang et al., 2016a). As it has been postulated, any intervention that promotes uptake of these mineral elements may increase their use efficiencies (Zebarth et al., 2008; Wang et al., 2015; Gitari et al., 2016; Sandana, 2016; Musyoka et al., 2017; Nyiraneza et al., 2017). However, in potato-based intercropping systems, the type of companion crop plays a big role in determining nutrient uptake and use efficiency as well as the yield, and this could be partly linked to the growth attributes of these companion crops (Zhang et al., 2016a).

Table 3
Potato tuber yield components, legume grain yield and potato equivalent yield as influenced by potato-legume cropping systems.

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

Analyses of variance (*p* values)

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

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

Table 4
Correlation (Pearson) between potato yield components and N and P uptake and use efficiency.

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

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

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

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

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

The high N and P uptake efficiency observed in a potato-dolichos treatment similar to the control is a clear indication that optimum potato production is feasible under dolichos intercropping systems. This has far-reaching benefits such as reducing environmental hitches related to N and P losses to surface water bodies (Sinclair and Rufty, 2012; Jones et al., 2013; Ruark et al., 2014). Nevertheless, N and P uptake varied with season, which could be attributed to the differences in rainfall patterns. Water plays a great role in determining the plant's ability to take up nutrients in the soil (Ierna and Mauromicale, 2012; Su et al., 2014). For instance, the important role that is played by water in solubilizing P, hence making it available for potato uptake, was clear in the 2014 short rains. This season experienced extreme weather situations with cumulative rainfall of 380 mm, which is 24% below the basal potato water requirement of 500 mm (Ierna and Mauromicale, 2012). These findings are in agreement with Zebarth et al. (2008) and Nyiraneza et al. (2017) who reported that P uptake varies from season to season due to differences in rainfall pattern. Thus, weather conditions greatly influence plant's ability to take up nutrients with low uptake occurring in seasons with inadequate rainfall as also observed by other studies (Westermann, 2005; Tein et al., 2014).

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

5. Conclusion

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

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