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Effect of potato-bean intercrop arrangement, plant spacing and fertiliser usage on plant growth and tuber yield in different environments

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Abstract

In Uganda, potato (*Solanum tuberosum*. L) is an important cash and food crop but its productivity has stagnated at around 3.5 t ha^{-1}, far below potential (20 t ha^{-1}), mainly due to soil exhaustion resulting from land shortages, and poor agronomic practices. It is vital to enhance production and efficient use of land resources by embracing elements of the systems of crop intensification. The study aimed at generating knowledge on the best combinations of crop management practices to increase productivity and improve land use. A split-split plot randomised complete block experiment was established in the districts of Kabale (high altitude), Rukiga (mid altitude), and Mbarara (descriptor of elevation) for two consecutive seasons (2018B and 2019A). The study investigated the effect of intercropping potato and beans (*Phaseolus vulgaris*) (in ratios of 1P:1B, 1P:2B, 2P:2B vs. sole potato, and sole bean), at two plant spacing levels (75 cm × 30 cm and 60 cm × 50 cm), and fertiliser usage (NPK and No NPK) on the growth and yield of potato. Results indicated that performance was favourable at high altitude. Intercropping potato and beans at the studied plant densities increased the quantity and quality of potato yield. Whereas the intercrop arrangements of 1P:1B and 1P:2B out yielded sole potato in tuber yield in the favourable highland areas; 1P:1B was at per with sole potato in terms of marketable yield. Intercropping potato with beans in the

1P:2B arrangement increased potato yields by 1.2 t ha^{-1} and also contributed highly to efficient utilisation of land resources (LER = 2.54) compared to sole potato. Addition of NPK increased potato yield, more so at the 75 cm × 30 cm spacing.

Key words: Intercrop ratios, land equivalent ratios, NPK, plant density, *Phaseolus vulgaris*, *Solanum tuberosum*, Uganda

Introduction

Potato (*Solanum tuberosum*) is one of the major cash crops and staple to many households in Uganda (Aheisibwe *et al.*, 2015). The main potato production hub in the country are the south western highlands at elevations between 1500-3000 metres above sea level, which contribute 60% to the total annual national production (Bonabana-Wabbi *et al.*, 2013; Namugga *et al.*, 2017). Potato is a known hunger and nutritional security crop that can store well and is a good source of calories, proteins and vitamins. It's short maturity period of 3-4 months in some areas enables farmers to grow the crop up to 3 times a year making it a superlative pathway for enhancing house hold incomes (Priegnitz *et al.*, 2019). Van Campenhout *et al.* (2016) reported that majority of low-resource farmers in Uganda depend on potato sales to secure house hold needs like education, medical, fuel, soap and clothing.

Despite potato's great prominence, its productivity over the years in the country has gradually reduced to levels below potential (Namugga *et al.*, 2017). Land scarcity as result of very rapid population growth, especially in highland areas, is one of the limiting factor to potato production. A report by Uganda Bureau of Statistics (UBOS) (2019) indicated an annual population growth rate of approximately 3%, with the then total population estimates of 35.5 million people projected to increase to 55.4million people by 2030. The average land holding per household is 1.1hectare, less so (0.6 acres) in highland areas that produce potato (Mbowa and Mwesigye, 2016). As a result, land fragmentation, over cultivation with monocultures of potato, soil exhaustion, and accumulation of pests and diseases over the years are prevalent (Carswell, 2002; Namugga *et al.*, 2017); causing a vicious cycle of poor yields.

In other countries, a system of crop intensification (SCI) has been reliably used to increase production in several cropping systems (Adhikari *et al.*, 2018). Cases in point being in India, Malawi, Nepal, Mali, Ethiopia, and Kenya, among others, which have yielded noticeable improvement in performance of such crops as wheat, sugarcane, rice, teff, finger millet, and vegetables. Binju *et al.* (2014) define SCI as an approach that aims at the productive use of available natural resources to achieve higher output with fewer inputs of land, labor, capital, and water. The approach majorly looks at the adoption of good crop establishment and management practices, and crop protection measures. This requires pertinent information on modalities of optimisation of resources and combinations. In Uganda, there has been no intentional use of SCI, and efforts to increase production has been mostly of extensification of land under production. Therefore, this study assessed modalities of an integrated approach to potato production.

Materials and methods

Study site

The study was carried out in two high altitude districts (Kabale; E 29.97621^0, S 01.14570^0, 1865 metres above sea level (m.a.s.l) and Rukiga; E 030.01781^0, S 01.14570^0, 1847 m.a.s.l and one mid altitude district (Mbarara; E 030.71562^0, S 00.55344^0, 1418 m.a.s.l) of Uganda. The mean annual rainfall of the high altitude areas is 1145 mm, and average temperatures range between 12.2-24.3 ^{o}C. For the mid altitude area, mean annual rainfall is about 1073mm, and average temperatures range from 16.5-27.6 ^{o}C (Uganda National Meteorological). Table 1 shows the soil physical and chemical properties of the sites of the study.

Experimental design

The experiments were conducted in the three locations for 2 growing seasons: 2018B (October - February) and 2019A (April - July) guided by rainfall patterns as the experiments were totally rain-fed. A split- split plot randomised complete block experiment with two replications was established at each location. Plant row arrangements of potato-bean intercrop in ratios of 1P:1B, 1P:2B, 2P:2B, sole potato and sole bean were the main plot factor; Potato spacing at two levels of 75 cm × 30 cm, and 60 cm × 50 cm was the sub-plot factor; and fertiliser treatments as NPK (17:17:17) and No NPK, the sub-sub plot factor. Plot sizes of 3.65 m × 17 m were maintained for main plots, 3.65 m × 8 m for sub plots, and 3.65 m × 3.5 m for sub-sub plots. All the treatment units were separated by 1m spacing between plots, and 2m between replications.

The potato seed for both sole and intercrop treatments was directly planted by hand in furrows of approximately 3cm depth at a spacing of 75 cm × 30 cm or 60 cm × 50 cm as per the treatment. Planted furrows were finished by digging ridges of height 26.9 cm and 21.8 cm for potato planted at 75 cm × 30 cm, and 60 cm × 50 cm spacing, respectively. The height of the ridges depended on the inter-row spacing that determined the quantity of soil available for raising the seedbeds. For each of the spacings, two bean seeds per hill were directly planted by hand at a depth of approximately 3 cm in the depression between the finished potato ridges. Sole bean treatments were included as part of the design to enable calculations of cropping

Table 1. Soil physical and chemical properties for the three study sites (depth of 0-15 cm)

Site	Chemical properties								Physical properties				
	pH	N	SOM	Av P	K	Na	Ca	Mg	BD	Sand	Clay	Silt	Texture
Units		%		(ppm)	— — cmols kg^{-1} — — —				(g cm^{-3})	%			
Kabale	6.6	0.09	2.8	6.69	0.3	0.09	10.3	2.04	1.44	43	41	15	SC
Rukiga	5.9	0.17	2.5	2.6	0.2	0.05	5.7	1.8	1.47	46	24	29	SL
Mbarara	6.6	0.1	2.2	10.9	0.3	0.07	9.39	3.28	1.61	60	21	20	SC

SOM = Soil organic matter, Av P = available Phosphorous, SC = Sandy Clay, SL = Sandy Loam, BD = bulk density advantage of intercrops versus monocrops. Both crops were planted at the same time.

The first weeding and hilling up of potato ridges was done three weeks after planting whereas the second was done two weeks after the former to suppress emerging weeds. At 21 days after planting (DAP), less vigorous bean seedlings were rogued out during weeding to maintain a population of one plant per hill. The intercropping proportions of potato and beans with their respective total number of plants per unit area per treatment (plant density) are presented in Table 2.

Table 2. Plant densities of potato and beans in the different experimental units

Plant arrangement	Crop	Plants per 75 cm × 30cm	Approximate plants/ha	Plants per 60 cm × 50cm	Approximate plants/ha
1P:1B	Potato	65	50,880	48	37,573
	Beans	65	50,880	48	37,573
1P:2B	Potato	65	50,880	48	37,573
	Beans	130	101,761	96	75,147
2P:2B	Potato	65	50,880	48	37,573
	Beans	52	40,705	32	25,049
Sole potato	Potato	65	50,880	48	37,573
Sole bean	Beans	65	50,880	48	37,573

Fertiliser application to the treatments using NPK 17:17:17 was carried out in two split doses one at planting and the other at 3 weeks after planning (WAP). At planting, fertiliser was placed below the seed before soil cover whereas the second dose was administered at weeding as a top dress following guidelines by Mehdi *et al.* (2016) at a rate of 23 g per tuber recommended by the National Potato Research Program. As such, 750 g and 552 g of NPK, calculated based on seed numbers per plot, were applied to sole and intercropped potato of spacing 75 cm × 30 cm and 60 cm × 50 cm, respectively. Sole bean plots were given 130 g split quantity at planting following recommendations by Mehdi *et al.* (2016) using the rate of 20 kg/ha recommended for beans by the National Beans Research Program.

Prophylactic spraying of fungicides and curative spraying was routinely done at 2 weeks intervals against fungal diseases, especially late blight (caused by *Phytophthora infestans*) for potato. Mistress® 72 composed of Cymoxanil 8% w/w +Mancozeb 64% w/w was used at a rate of 30 g per 20 L, alternated with victory ® 72 WP

(Metalaxyl +Mancozeb) at a rate of 250 g per 100L. Insect pests for both crops were controlled at 2 weeks intervals by spraying with Dudu-Ethoate 40® (Dimethoate) at a rate of 40 ml per 20 L.

Data collection

Potato leaf area

Potato leaf area (cm^2) was measured from 8 randomly selected plants per plot from inner rows at physiological maturity. Leaf area (cm^2) was calculated from values of leaf length (length from the stalk to apex of a fully grown middle leaflet) using the formula adopted by Firman and Allen (1989) and Getie *et al.* (2015) below;

$$\log_{10} (\text{leaf area, cm}^2) = 206 \times \log_{10} (\text{leaf length, cm}) - 0.458$$

Yield parameters

At physiological maturity, potato de-haulming was done using kitchen knives two weeks before tuber harvest to allow skin hardening. Tubers were then removed manually from the rows by hoeing. For beans, plants were allowed to completely dry in the field and later harvested by hand pulling. Total potato tuber yield per plot and total bean yield per plot were recorded at harvest. The total yield of potato and beans (grams/ plot) was presented in tonnes per hectare(t ha^{-1}) through calculations following guidelines of Ejigu *et al.* (2017). Marketable tuber yield was determined for healthy, pest damage free tubers measuring 35millimetres and above. Un-marketable tubers were determined as those shrivelled, wrinkled, diseased/pest damaged, and measuring less than 35 millimetres. Marketable tubers were presented as percentages using formula by Muhinyuza *et al.* (2014) and (Eaton *et al.*, 2017) as below:

$$\% \text{ marketable tubers} = (\text{No. Marketable tubers} \div \text{Total No. tuber per plot}) \times 100\%$$

Land equivalent ratio (LER) was used to represent land use efficiency as a measure of intercropping advantage for crop mixtures as compared to their respective sole counterparts. This was done following the methods of Kidane *et al.* (2017):

Land Equivalent Ratio (LER) = Partial Land Equivalent Ratio for Potato (PLER P) + Partial Land Equivalent Ratio for Beans (PLER B)

Where:

Partial Land Equivalent Ratio for Potato (PLER P) = (yield of potato when intercropped with beans divided by yield of sole potato); Partial Land Equivalent

Ratio for Beans (PLER B) = (yield of beans when intercropped with potato divided by yield of sole beans); LER value less than 1 shows no yield advantage from the intercrops but rather a negative effect on crop yield. The LER greater than 1 indicates a yield advantage of intercropping compared to monocropping.

Data analysis

The statistical data analysis was done using Genstat 14th edition. The effect of intercropping arrangement with beans, plant spacing, and fertiliser use on potato growth and yield parameters for different locations in the two seasons was analysed using analysis of variance (ANOVA) for split-split plot design. One way ANOVA was then carried out on calculated data for Land Equivalent Ratios (LERs) to determine the effect of plant arrangement in intercrops as the factor influencing land use efficiency. Separation of significant treatment means by the least significant difference (LSD) at $P<0.05$.

Results

Effect of intercrop arrangement, spacing, fertiliser, and location on potato leaf area

Solely, intercrop arrangement, plant spacing, and fertiliser did not significantly influence leaf area of potato ($P<0.05$), however, the interaction between intercrop arrangement*plant spacing*location significantly influenced this parameter ($F_{df\,6;\,704} = 8.14$, $P<0.001$). Of the three locations, Mbarara, the low altitude location, had potato plants with the lowest leaf area. Differences between intercrop arrangements and spacings were mostly discernible in the high altitude areas of Kabale and Rukiga. The highest leaf area of 13.66 cm^2 for sole potato treatments was obtained at a spacing of 60 cm × 50 cm in Kabale when compared to the 75 cm × 30 cm spacing, but the reverse was true in Rukiga (Fig. 1). For the intercrops, 1P:1B performed highest on average with respect to leaf area (11.12 cm^2 1P:1B vs. 10.09 cm^2 for sole). The 1P:2B arrangement in Kabale had the lowest leaf area for both spacings; in Rukiga, this was only true for the 60 cm × 50 cm, which was not different from 2P:2B (Fig. 1).

Effect of intercrop arrangement, spacing, fertiliser and location on potato tuber yield, and combined potato-bean yield

Intercrop arrangement significantly influenced the yield of potato, and hence combined potato+bean yield in 2019A only ($P<0.001$) but the interaction between plant arrangement*location influenced potato and combine potato+bean yield in both seasons ($P<0.01$) (Table 3). The highland locations of Kabale and Rukiga produced tuber yields of >10 t ha^{-1} whereas Mbarara, the relatively lower altitude location,

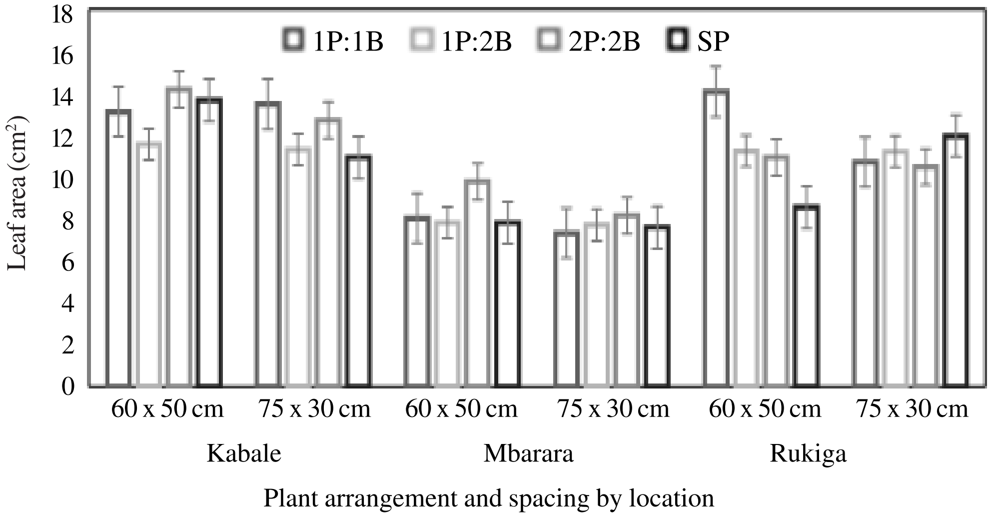

Figure 1. Potato leaf area (cm^2) as influenced by the interaction of plant arrangement, spacing, and location.

averaged 1.8 t ha^{-1}. In 2018B in Kabale, all the intercrops arrangements superseded the sole potato in tuber yield but in Rukiga, the 1P:1B arrangement was outstanding. In 2019A, it was the 1P:2B arrangement that was outstanding in tuber yield in Kabale and Rukiga (Table 3). The combined potato-Bean yields followed a similar trend.

The results also indicated a significant ($P < 0.05$) interaction between spacing and fertiliser on potato yield and combined potato- beans yield in season 2018B. Potato yield and total combined yield consistently increased with fertiliser use regardless of the spacing, but the highest yield response to NPK was obtained at the 75 cm × 30 cm spacing (Fig. 2). Highest potato yield of 7.7 t ha^{-1} and combined yield of 8.1 t ha^{-1} were obtained from NPK treated plots of 75 cm × 30 cm spacing; whilst the least potato yield of 4.6 t ha^{-1} and combined yield of 4.9 t ha^{-1} were obtained from 60 cm × 50 cm spacing in No NPK plots (Fig. 2).

Effect of plant arrangement, spacing, fertiliser and location on marketable tuber yield

Plant arrangement on its own did not influence marketable yield, i.e., the quality of tubers (tuber size >35 mm) but the interaction of plant arrangement*spacing was significant in the highland areas of Kabale and Rukiga ($P < 0.05$; $P<0.01$, respectively). In Kabale, the highest % marketable yields (74.5%) was in sole potato at 60 cm x 50 cm spacing and the lowest in the 1P:2B arrangement in the same spacing (58.2%) (Table 4). In Rukiga, the highest tuber quality was also in the 60 cm x 50 cm spacing in 1P:1B (69%), and the lowest in the 75 cm × 30 cm spacing in 2P:2B (55.2%) (Table 4).

Table 3. Mean crop yields (t ha^{-1}) for potato and combined potato+beans in the arrangements and locations
2018B

Location	Potato yield (t ha^{-1})					Combined potato and bean yield (t ha^{-1})				
	1P:1B	1P:2B	2P:2B	SP	Mean	1P:1B	1P:2B	2P:2B	SP	Mean
Kabale	12.4	11.4	10.4	7.9	**10.5**	12.8	12.4	10.9	7.9	**11**
Mbarara	0.8	1.2	1.6	2.0	**1.4**	1.1	1.8	1.9	2.0	**1.7**
Rukiga	13.0	9.1	8.9	9.0	**10.0**	13.3	9.8	9.1	9.0	**10.3**
Mean	**8.7**	**7.2**	**7.0**	**6.3**	**7.3**	**9.0**	**8.0**	**7.3**	**6.3**	**7.7**
Lsd					**5.6****					
2019A										
Kabale	14.7	17.9	17.1	16.6	**16.6**	15.2	18.2	17.4	16.6	**16.9**
Mbarara	2.2	2.4	2.0	2.0	**2.2**	3.1	3.7	2.6	2.0	**2.9**
Rukiga	14.8	16.6	14.1	14.8	**15.1**	15.4	17.0	14.5	14.8	**15.4**
Mean	**10.6**	**12.3**	**11.1**	**11.1**	**11.3**	**11.2**	**13.0**	**11.5**	**11.1**	**11.7**
Lsd					**2.3*****					

1P:1B = one row of potato to one row of beans; 1P:2B = one row of potato to two rows of beans 2P: 2B = two rows of potato to two rows of beans; SP = sole potato; SB = sole bean. 2018 A - the second rainy season (mid-August- mid-December). 2019A – the first rainy season (February- June); ***Significant at 0.001; ** Significant at 0.01; * Significant at 0.05; ns not significant statistically; LSD for interaction mean

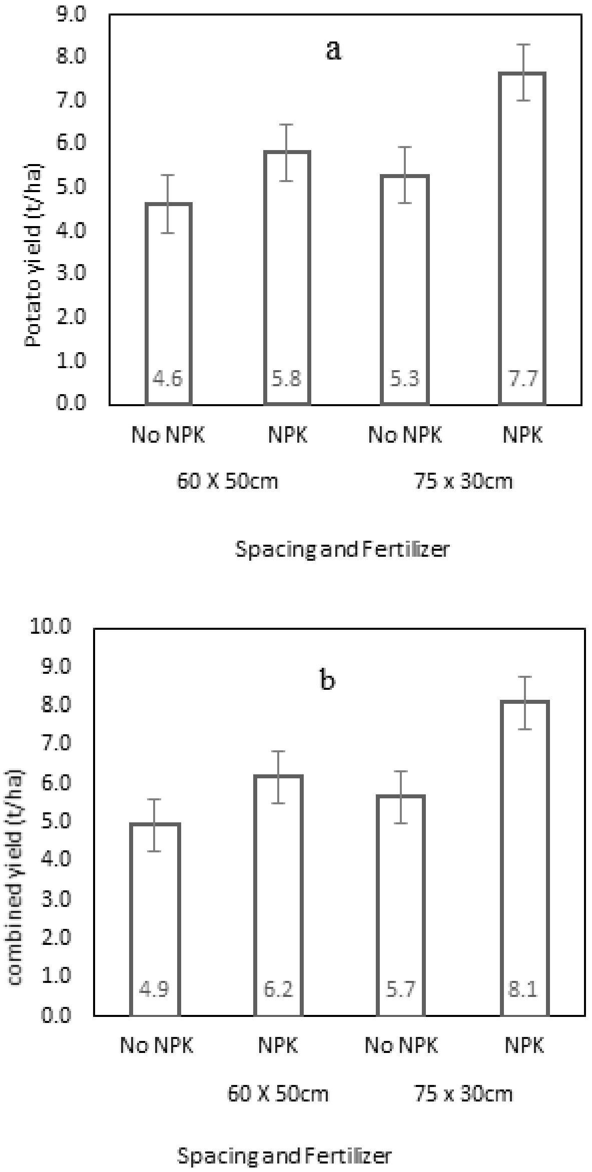

Figure 2 (a). Potato yield (t ha^{-1}) and (b) Combined potato+beans (t ha^{-1}) as influenced by the interaction between spacing and fertiliser.

Fertiliser interacted with plant arrangement, spacing and fertiliser but only in Mbarara district ($F_{df\,3;\,16}$ = 3.37; $P<0.05$), where addition of NPK contributed to an increase in the proportion of marketable tubers in all arrangements except 1P:2B in the 60 cm × 50 cm spacing. In the 75 cm × 30 cm spacing, the reverse was true, with only 1P:2B arrangement showing an increase in marketable tubers on addition of NPK.

Table 4. Mean marketable (%) potato tuber yield as influenced by plant arrangement and spacing in the three locations

Location	Spacing	Marketable yield (%) Plant arrangement				
		1P:1B	1P:2B	2P:2B	SP	Mean
Rukiga	60x 50cm	69.0	66.5	65.3	62.7	**65.9**
	75x30cm	67.0	65.0	55.2	67.9	**63.8**
	Mean	**68.0**	**65.8**	**60.3**	**65.3**	**64.9**
	LSD					14.5**
Kabale	60x 50cm	67.7	58.2	59.8	74.5	**65.1**
	75x30cm	62.2	65.6	64.6	60.0	**63.1**
	Mean	**65.0**	**61.9**	**62.2**	**67.3**	**64.1**
	LSD					19.2*
Mbarara	60x 50cm	15.9	17.3	17.6	16.2	**16.8**
	75x30cm	16.7	14.5	22.8	30.1	**21.0**
	Mean	**16.3**	**15.9**	**20.2**	**23.2**	**18. 9**
	LSD					11.4^{ns}

***Significant at 0.001; ** Significant at 0.01; * Significant at 0.05; ns not significant statistically; LSD for interaction mean

Land use efficiency of planting potato and beans in different intercrop arrangements

Plant arrangement significantly (P < 0.001) affected total land equivalent ratio (TLER) and partial land equivalent ratio for beans (PLER B) but not the partial land equivalent ratio for potato (PLER P). The TLERs for potato+beans ranged from1.92 to 2.54 (Table 5). Intercrop arrangements of 1P:2B exhibited the highest efficiency in resource utilisation with a LER of 2.54.

Discussion

Effect of plant arrangement and spacing on potato leaf area in the different locations

Leaf area is a very important plant growth parameter for determination of crop productivity (Juzl and Stefl, 2002).This parameter greatly dictates the plant's light interception and photosynthetic potential that consequently represents productivity

Table 5. Land Equivalent Ratios for sole and intercrop arrangements

Plant arrangement	PLER B	PLER P	TLER
2potato: 2Bean	0.69	1.22	1.95
1potato: 1 Bean	0.74	1.22	1.92
1potato: 2Bean	1.44	1.10	2.54
Sole bean	1.00	-	1.00
sole potato	-	1.00	1.00
Grand mean	0.97	1.14	1.85
Lsd	0.32***	0.28^{ns}	0.44***

Pooled data for the three locations and two seasons; ***Significant at 0.001; **Significant at 0.01; *Significant at 0.05; ^{ns} not significant

(Weraduwage *et al.*, 2015). Plant spacing is one of the most importantly known management practices in potato production (Binalfew *et al.*, 2015). Studies have shown that leaf area per plant increases with increase in spacing. In this study, in particular instances, potato plants grown at 60 cm × 50 cm spacing of both sole and intercrops across locations generally had an edge in leaf area compared to the 75 cm × 30 cm counterparts, but this was dependent on plant arrangement. The 60 cm × 50 cm spacing had fewer potato plants per unit area compared to the 75 cm × 30 cm spacing (table 2), which could explain the variation. Again, the intercrops with lower potato plant densities i.e. 1P:1B and 2P:2B (as opposed to 1P:2B) had bigger leaves albeit to different extents in the two spacings. At lower plant densities plants experience limited intra- or inter- specific competition for resources and limited mutual shading of lower placed leaves (Masarirambi *et al.*, 2012) resulting into proportional increase in the leaf area. Also, the limited competition for solar radiations facilitated lateral leaf expansion to attain a wider leaf area. This enabled potato plants to efficiently display their foliage so as to attain maximum interception of direct sunlight in their canopies. Streck *et al.* (2014) their study on cassava in Brazil also noted that lower plant density at wider cassava spacing enhanced the growth of larger sizes of cassava leaves due to reduced competition for nutrients, sunlight and water. This response promoted total ground cover whilst increasing the leaf area. Other studies, notably, Masarirambi *et al.* (2012), Mangani *et al.* (2015), Binalfew *et al.* (2015) and Nxumalo et al., (2020) agree with the current study that leaf area reduces with increase in plant densities and vice versa. The fact that the intercrop arrangements of 2P:2B and 1P:1B at high altitude locations had wider leaves (mean 12.85 cm^2 and 12.08 cm^2, respectively) than sole potato (11.28 cm^2) could be due to the fact that crop mixtures allowed neutralisation of the stiff intraspecific competition for resources that exists normally among pure stands. Also, intercropping especially at a wider spacing may have greatly contributed to increased leaf area due to the nitrogen contribution from beans that enhanced canopy enlargement (Meena and Lal, 2018).

Potato yield and combined potato+bean yield as influenced by plant arrangement, spacing and fertiliser in the three locations

Intercrops of potato and beans were superior to the sole potato with regard to potato and combined potato+bean yields (t ha^{-1}). This could be explained by the presence of the bean (legume) crop in the arrangements. Rezig *et al.* (2010) also noted that potato-green bean intercropping systems contributed to an increase in potato yield that they attributed to an increase in water use efficiency (from 8.69 kg m^{-3} to 10.15 kg m^{-3}) and radiation use efficiency (from 4.47 g MJ^{-1} to 4.77g MJ^{-1}) using the sole crop as the baseline. Production of dry matter is reported to depend on efficient water and radiation use (Sharaiha and Hadidi, 2002). In addition, intercropping with legumes contributes greatly to restoration of soil organic carbon stocks, and nitrogen fixation through the activities of the nitrogen fixing bacteria as well as reduced pest and disease pressure (Meena and Lal, 2018). Gitari *et al.* (2020) also reported maximum potato productivity at higher legume proportions of 3.7: 8.8 plants /m^2 potato:climbing bean (*Phaseolus vulgaris* L.) or potato:dolichos (*Lablab purpureus*) than 4.4:5.2 plants/m. This could explain the good performance of the 1P:2B intercrop arrangement.

With respect to spacing, higher potato yields were obtained from closer spacing (75 cm × 30 cm) as opposed to a wider spacing of (60 cm × 50 cm). Zebarth and Rosen (2007) mentioned that potato yield can be expressed as a function of stem density per unit area, thus the variation in potato yield at both spacings could have resulted from varying plant densities for which 75 cm × 30 cm spacing accommodated more plants (50,880 plants/ha) than 60 cm × 50 cm (37,573plants/ha) in sole arrangements. In a similar manner, intercrops of 1P:2B accommodated more plants (152,641 plants/ ha) at 75 cm × 30 cm spacing than 112,720 plants/ha at 60 cm × 50 cm spacing. The higher plant density at 75 cm × 30 cm spacing could have contributed to earlier ground cover by green leaves that could have enabled efficient radiation interception, less lateral branching and earlier tuber set. In a similar study, Dagne *et al.* (2003) reported high potato yields obtained at higher plant populations due to more potato tubers being harvested per unit land area. Arega *et al.* (2018) also found a significant increase in potato yield at 75 cm × 30 cm than at 85 cm x 20 cm. Rahemi *et al.* (2005) earlier deduced that soil nutrition and plant spacing were some of the key factors affecting potato growth and yield.

Results of the current study indicated that addition of NPK at higher potato plant densities greatly enhanced potato yield. Kolodziejczyk (2014) revealed that every increase in the quantity of available soil nitrogen resulted into a proportional increase in potato yield. Therefore high potato and overall yields obtained from the current study could have resulted from the role played by nitrogen in promoting early vegetation cover and enhanced leaf surface area for light interception. Furthermore, nitrogen and phosphorous have been reported to play an important role in canopy maintenance, tuber initiation, tuber bulking and dry matter accumulation (USAID-Inma Horticulture Value Chain Team, 2011), a phenomenon that could explain the high tuber yields with addition of NPK irrespective of spacing. Results that are in line with the findings by Mohammed *et al.* (2018) who reported an increase in total tuber yield of potato in treatments amended with nitrogen and phosphorous.

Irrespective of spacing, plant arrangement and fertiliser usage, high altitude areas (Kabale and Rukiga) outperformed mid altitude areas (Mbarara) in potato growth and yield. Minda *et al.* (2018) also reported high altitude areas to be the most suitable for potato production because of the high potato yields obtained compared to the yield from mid-altitude areas. They postulated that the major atmospheric drivers influencing potato growth and yield included precipitation, and minimum and maximum temperatures. Their study showed that as precipitation increased with elevations, temperatures consequently dropped, resulting in increased leaf area index (LAI) thus improving potato growth. LAI is an indicator of the crop's photosynthetic rate and is shown to be directly proportional to the potato yields.

Effect of plant arrangement, spacing and fertiliser on marketable tuber yield in the three locations

Marketable tuber yield was a function of spacing and intercrop arrangement that can be explained by plant density per unit area. Tuber quality portrayed by tuber size is determined by several factors including plant density per unit area (Kushwah and Singh, 2008), stem density (Bussan *et al.*, 2007), and processes like metabolism and material translocation (Burke, 2017), radiation interception, tuber bulking and dry matter accumulation (Rosen and Bierman, 2008). Plant spacing is also an important agronomic factor that determines plant density per unit area (Bussan *et al.*, 2007). In this study, more marketable tubers were obtained from 60 cm × 50 cm spacing compared to the 75 cm x 30 cm counterpart. As explained earlier, the lower plant density signifies minimised plant competition and an enhanced lateral leaf expansion (Streck *et al.*, 2014), and increased vascular bundles in the leaves which are the source system for dry matter accumulation (Weibing *et al.*, 2022). This phenomenon contributes to increased tuber quality and crop yield by providing more photosynthates to the sink organs (tubers) (Weibing *et al.*, 2022). The result agree with findings by Bussan *et al.* (2007) who reported that the proportions of small potato tubers directly increased with an increase in potato stem densities and vice versa.

Any observed benefits in tuber quality in intercrops in specific instances may have resulted from the additional benefits of legumes including efficient use of environmental resources, improvement of soil properties, reduction of pests, diseases and weed damage (Mousavi and Eskandari, 2011). Furthermore, the activities of the nitrogen-fixing rhizobacteria in legumes may have contributed to tuber yield and quality by making soil nitrogen more available for potato growth (Raei *et al.*, 2015). Hauggaard-Nielsen *et al.* (2008) mentioned that legumes in an intercrop contribute between 10 to 15% increment in soil nitrogen compared to sole cropping systems. (Zebarth and Rosen, 2007; Burke, 2017).

Likewise, application of nitrogen, phosphorus, and potassium (NPK) fertiliser to the sole, 1P:1B, and 2P:2B intercrops at 60 cm ×50 cm positively influenced tuber quality resulting in a higher proportion of marketable tubers. Other studies have reported addition of NPK to greatly affect both tuber yield and quality (Gunadi 2009; Nina *et al.*, 2015; Regassa *et al.*, 2016). NPK could have contributed to the formation of new potato leaves, enhanced vital processes like plant metabolism and translocation (Burke, 2017), increased leaf area, stimulated radiation interception and plant growth (Rosen and Bierman, 2008), and maintenance of photosynthetically active potato leaves. All contributing to tuber bulking.

Land use efficiency of intercropping arrangements vs. sole crops

All intercropping arrangements had total LERs greater than 1.00, a good indication of efficient resource utilisation between companion crops. The highest TLER of 2.54 was obtained when potato was intercropped with beans at a plant arrangement of 1P:2B. This indicates that an additional land area of 1.54 ha would be required to obtain similar grain and tuber yield when planted as sole crops. The highest land equivalent ratio from plant arrangement 1P:2B could have resulted from the highest proportions of bean plants in this arrangement compared to others with the additional benefits mentioned when legumes are brought into the system. Kidane *et al.* (2017) attributed the increase in crop productivity of intercrops to the increase in the number of plants per unit area. Several studies, notably, Saddam (2009); Wang *et al.* (2014); Raei *et al.* (2015); Asiimwe *et al.* (2016); Kidane *et al.* (2017) and Mugisa *et al.* (2020) have reported intercropping to be a more efficient land use system than sole cropping.

Conclusion

Intercropping of potato and beans at the studied plant densities increased the quantity and quality of potato yield. Whereas the intercrop arrangements of 1P:1B and 1P:2B out yielded sole potato in tuber yield in the favourable highland areas; 1P:1B was at per with sole potato in terms of marketable yield. Intercropping potato with beans in the 1P:2B arrangement did not only increase potato yields by 1.2 t ha^{-1} but also contributed highly to efficient utilisation of land resources (LER = 2.54) compared to sole potato. Addition of NPK increased potato yield, more so at the 75 cm × 30 cm spacing.

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