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Article *in* Field Crops Research · September 2020

DOI: 10.1016/j.fcr.2020.107957

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Field Crops Research 258 (2020) 107957

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Revisiting intercropping indices with respect to potato-legume intercropping systems

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ARTICLE INFO

Keywords:
Intercropping
Biological efficiency of intercropping
Economic efficiency of intercropping
Competition indices

ABSTRACT

Intercropping is gaining popularity in developing countries as a viable strategy for diversifying cropping systems to ease food insecurity, given that arable land is shrinking, and demand for food crops is increasing due to rapid population growth. A field experiment was conducted in 2015 and 2016, to examine the biological and economic viability of two intercropping systems (potato-dolichos and potato-bean planted in two potatoes to legume population density ratios: 1.1:2 and 1: 2.4) and their corresponding pure stands. Intercropping systems were also evaluated based on five competition indices: relative crowding coefficient (K), aggressivity (A), competitive ratio (CR), intercropping advantage (IA) and actual yield loss (AYL). Although biological feasibility revealed that intercropping decreased the yield of intercrops compared with respective monocultures; the economic assessment of different cropping systems indicated that intercropping resulted in a higher remuneration (gross and net income) than pure stands. Intercropping potato with a high population of legume (in 1: 2.4 patterns), resulted in not only higher system productivity but also potato equivalent yield compared to 1.1:2. Intercropping proved to be advantageous with AYL decreasing with increasing proportion of the legumes, whereas IA increased as the population of legumes increased. With regard to competition between the intercrops, the potato was more aggressive (A of potato was positive, and its CR > 1) in all cropping systems, and it dominated over legume (that had negative A values and CR < 1). Aggressivity and dominance capacity was higher in 1: 2.4 than 1.1:2 series. These results suggest that potato-legume intercropping may provide viable intensification options, especially for smallholder farmers.

1. Introduction

Intercropping, which is also referred to as multi-cropping is a centuries-old agricultural practice that involves the growing of multiple crop species in close proximity such that they coexist for a significant part of their life cycle (Vandermeer, 1989; Lithourgidis et al., 2011; Brooker et al., 2014). In tropical areas particularly in Africa, intercropping has been practiced for over a millennium, and it is still gaining popularity among the smallholder farmers (Mucheru-Muna et al., 2010; Gou et al., 2016; Gitari et al., 2018a; and 2019b; Nyawade et al., 2019a; and b). One reason why farmers prefer cultivating crops under intercropping systems, especially in developing nations, dominated by subsistence and resource-constrained agricultural systems, is their ability to over yield compared to monoculture systems. In this

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https://doi.org/10.1016/j.fcr.2020.107957
Received 7 May 2020; Received in revised form 27 July 2020; Accepted 12 September 2020

context, overyielding refers to higher yield achievable when species are intercropped compared to yield under monoculture (Beckage and Gross, 2020). One possible explanation for overyielding phenomenon under intercropping systems is complementarity in use of environmental resources such as land, soil nutrients, light, and water, which results from the reduction of interspecies competition and niche partitioning (Franco et al., 2015; Xue et al., 2016; Gitari et al., 2020; Qian et al., 2018; Evers et al., 2019; Raza et al., 2019). Specifically, complementarity is optimized when there is temporal and spatial exploitation of available resources between the companion species (Brooker et al., 2014; Duchene et al., 2017; Dong et al., 2018; Gitari et al., 2018b, 2020; Nyawade et al., 2019b; Raza et al., 2019). Therefore, niche overlap can help in reducing interspecies competition under intercropping systems resulting in overyielding.

Competition for available resources under intercropping systems can also be offset through facilitation, a phenomenon that occurs when companion plants have beneficial effects on each other (Hauggaard--Nielsen et al., 2006, 2009; Chu et al., 2008). Previous studies on intercropping (not necessarily on potato-based cropping systems) have focused on water use efficiency (Rezig et al., 2013; Wang et al., 2015; Ren et al., 2016; Meixiu et al., 2020), nutrients (such as nitrogen and phosphorus) uptake and use efficiency (Mei et al., 2012; Gao et al., 2014), rhizodeposition transfer (Zhang et al., 2015) and radiation use efficiency (Wang et al., 2015; Raza et al., 2019). However, the interactive competition among the companion crops in potato-legume intercropping systems and economic gains are only partially explored, especially in sub-Saharan Africa.

Potato-legume intercropping is the main potato-based multiple cropping systems in Kenya, and it has received attention (Gitari et al., 2018a; and b, 2019a, and b, 2020; Nyawade, 2019a, b, and c, 2020a; and b). These studies have reported numerous benefits of intercropping, including increased nutrients, water, and radiation use efficiencies, improved soil fertility, and crop productivity besides increased economic returns compared to monoculture systems. Nonetheless, to the best of our understanding, there is a lacuna since no study has focused on the biological and economic efficiency of the potato-legume intercropping system. Besides, until now, the competition intensity of the component crops under such an intercropping system remains unclear.

Various indices have been developed to assess the viability of intercropping systems. For biological evaluation, such indices include land equivalent ratio (LER), land equivalent coefficient (LEC), area time equivalent ratio (ATER), land use efficiency (LUE), system productivity index (SPI), and percentage yield difference (PYD) (Willey, 1979; Mead and Willey, 1980; Adetiloye et al., 1983; Hiebsch and McCollum, 1987; Odo, 1991; Agegnehu et al., 2006; Bedoussac and Justes, 2011; Yaseen et al., 2014; Afe and Atanda, 2015). Economically, intercropping systems have been assessed using income equivalent ratio (IER), monetary advantage index (MAI), relative value total (RVT), replacement value of intercropping (RVI), relative net return index (RNRI) and equivalent yield of main crop (Mead and Willey, 1980; Moseley, 1994; Ghosh, 2004; Alabi and Esobhawan, 2006; Devasenapathy, 2008; Singh et al., 2015; Gitari et al., 2018b). Relative crowding coefficient (K), aggressivity (A), competitive ratio (CR), intercropping advantage (IA) and Actual yield loss (AYL) are among the commonly considered competition indices in the literature (McGilchrist, 1965; Willey and Rao, 1980; Banik et al., 2000; Ghosh, 2004; Dhima et al., 2007; Lithourgidis et al., 2011; Yang et al., 2017; Machiani et al., 2018). Nonetheless, these indices either are scattered in different publications or are expressed in a way that is hard to comprehend. Therefore, the current study aimed at assessing the biological and economic effects of potato-legume intercropping with a focus on competition intensity of the component crops by employing the indices outlined.

2. Materials and methods

2.1. Site description

The experiment was carried out during the 2015 short rains (October–December) and 2016 long rains (March–June) seasons in a research farm located at Upper Kabete Campus, University of Nairobi, Kenya. Kabete lies 1° 25′ S, 36° 74′ E, and 1860 m above sea level. Hereafter, these seasons are referred to as the years 2015 and 2016, respectively. This site is found within the sub-humid agro-ecological zone with well-drained, dark red, very deep (more than 180 cm) clay soils with an argic B-horizon and nitic properties classified as Nitisols (Sombroek et al., 1982; Gachene et al., 1997). Compared to other tropical soils, Nitisols are relatively productive with better chemical properties, hence suitable for potato cultivation (Karuku et al., 2012; Gitari et al., 2018a; Mwendwa et al., 2019). At the beginning of the experiment, the soil was moderately acidic with an average pH of 5.9, organic carbon of 28.3 g kg^{-1}, total nitrogen of 2.5 g kg^{-1}, and available phosphorous of 16.5 mg kg^{-1} in the upper 0.4 m horizons (Table 1). The mean values for exchangeable bases were 1.2, 1.7, 2.8, and 9.6 cmol kg^{-1} for sodium, potassium, calcium and magnesium, respectively. The region receives a mean annual rainfall of 1000 mm distributed in a bimodal pattern with long rains occurring in March to June and the short rains in mid-October to December.

2.2. Experimental design and crop husbandry

The experiment was performed in quadruplicate in experimental units measuring 6 by 4 m arranged in a randomized complete block design with seven treatments comprising three pure stands and four potato-legume intercrops, The tested cultivars of potato (*Solanum tuberosum* L), dolichos (*Lablab purpureus* L), and climbing bean (*Phaseolus vulgaris* L) were 'Shangi', 'KAT/DL-1' and 'Kenya Tamu', respectively, based on farmers' preferences and local agronomic performance. For pure stands, the respective treatments were abbreviated as PS, DS and BS. Planting was done at the onset of rainfall in the third and fourth week of October and March, respectively, in 2015 and 2016. For potato, selected medium-sized pre-sprouted tubers were planted manually in rows 0.1 m deep at an inter-seed spacing of 0.3 m. Under monoculture, the rows were 0.75 m apart, giving a plant density of 4.4 plants m^{-2} (Fig. 1a). Similarly, the legumes were planted in rows at a uniform depth of 0.3 m with two seeds per hill at an inter-hill spacing of 0.25 m. Consequently, under pure stand, with an inter-row spacing of 0.45 m, the achievable plant density was 17.7 plants m^{-2} (Fig. 1b). There were two arrangements for intercrops: conventional (CA) and modified (MA)

Table 1
Soil chemical properties of the experimental site.

Parameter	0 – 20 cm	21 – 40 cm	Method of analysis
pH (water) 1:2.5	5.64	6.07	pH meter (Ryan et al., 2001)
Organic carbon (g kg^{-1})	29.03	27.63	Modified Walkley and Black (Nelson and Sommers, 1996)
Total nitrogen (g kg^{-1})	2.72	2.22	Modified Kjeldahl (Bremner, 1996)
Available phosphorous (mg kg^{-1})	17.09	15.87	UV–vis spectrophotometer (Murphy and Riley, 1962)
Exchangeable bases (cmol kg^{-1})			
Sodium	1.21	1.24	Flame photometry (Jackson, 1967)
Potassium	1.81	1.50	Flame photometry (Jackson, 1967)
Calcium	9.88	9.38	Atomic absorption spectrophotometry (Jackson, 1967)
Magnesium	2.51	3.07	Atomic absorption Spectrophotometry (Jackson, 1967)

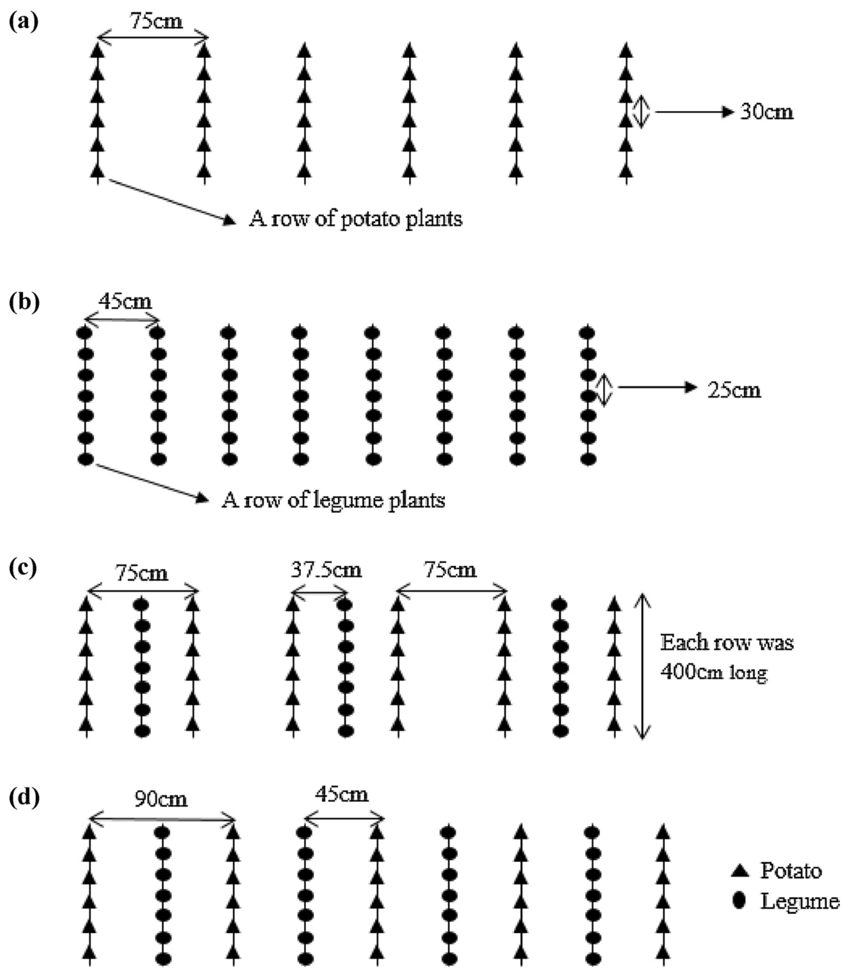

Fig. 1. A schematic representation of different cropping pattern.

arrangement. The former consisted of potato planted at an inter-row spacing of 0.75 m and legumes planted in a single row between every alternate potato rows (Fig. 1c). For the MA, which was proposed by Gitari et al. (2018a), inter-row spacing for potato was increased to 0.9 m with legumes planted on every potato inter-row space (Fig. 1d). Under CA, the final plant density was 4.4 and 5.2 plants m^{-2} (combination ratio of 1:1.2) for potatoes and legumes, respectively. Therefore, the treatments were PD (1:1.2) for potato–dolichos and PB (1:1.2) for potato–bean treatments. For the MA, the respective plant densities were 3.7 and 8.8 plants m^{-2}, with treatments PD (1:2.4) and PB (1:2.4).

Potatoes received 90 kg N ha^{-1} and 55 kg P_2O_5 ha^{-1} From diammonium phosphate at planting and 250 kg ha^{-1} of calcium ammonium nitrate at 28 days after planting (DAP). All the legumes received a one-time basal fertilizer application at the planting of 46 kg P_2O_5 ha^{-1} from triple super phosphate. These were the standard rates for pure stands; hence, adjustments were made accordingly for CA and MA. During the crop cycle, potatoes were sprayed four times in an interval of 14 days starting at 14 DAP with Ridomil Gold MZ 68 W G containing 40 g kg^{-1} of Mefenoxam and 640 g kg^{-1} of Mancozeb as the systemic and contact active ingredients respectively. Weeding was done on all plots at 28 DAP concurrently with hilling-up for potatoes and staking for beans. In CA, hilling up was done by drawing soil from the unplanted inter-row space, whereas for MA, potatoes were ridged with soil scooped gently from both sides of potato rows. Harvesting was done manually at 85 DAP for potato and bean, and 120 DAP for dolichos from the middle four rows per plot.

2.3. Economic analysis

Economic analysis was done to evaluate the economic feasibility of integrating legumes into potato cropping systems. The total variable costs, including cost of fertilizers, pesticides, fungicides, seeds, and labor, were calculated based on the local rates. Gross income was calculated by considering the economic yield based on the prevailing market prices (313.7, 1049.0, and 764.7 US$ Mg^{-1} for potato, dolichos, and bean, respectively). Net income was taken as the difference between gross income and total variable costs. In contrast, the benefit/cost ratio was calculated by dividing gross income by variable costs (Gitari et al., 2018a).

2.4. Evaluation of the performance of intercropping systems

Different indices were used to assess the biological and economic efficiency of the potato-legume intercropping system and the competition intensity of the component crops under such an intercropping system.

2.4.1. Assessment of the biological efficiency of potato-legume intercropping system

The biological efficiency of the potato-legume intercropping system was accessed using the land equivalent ratio, land equivalent coefficient, area time equivalent ratio, land use efficiency, system productivity index and, percentage yield difference. The land equivalent ratio (LER) (Willey, 1979) converts the production of an intercropping system in terms of land acreage as shown in Eqs. (1–3). It is used to indicate the relative area of the pure stand that is required to produce equivalent yield achievable under intercropping (Mead and Willey, 1980). The index, which is sometimes referred to as relative yield total, measures the efficiency at which environmental resources are utilised under intercropping compared with monoculture.

$$LER = (LER_p + LER_l) \tag{1}$$

$$LER_p = \frac{Y_{pi}}{Y_{ps}} \tag{2}$$

$$LER_l = \frac{Y_{li}}{Y_{ls}} \tag{3}$$

Where LER_P and LER_l represent the partial LER of potato and legume, respectively whereas Y_{pi} and Y_{li} depict the corresponding economic yield of potato and legume under the intercropping systems. In contrast, Y_{ps} and Y_{ls} represent the respective yields under pure stands. LER values > 1 are used to indicate intercropping yield advantage while those < 1 denote a disadvantage of intercropping hence, advocating for growing the respective crops as pure stands (Mead and Willey, 1980; Wahla et al., 2009; Machiani et al., 2018).

Land equivalent coefficient (LEC) is a product of LER_P and LER_l and was assessed using Eq. (4), as described by Adetiloye et al. (1983). The area time equivalent ratio (ATER) was proposed by Mead and Willey (1980 (Eq. 5) as a modification for LER. It was used to compare the yield advantage of cultivating potato and legumes under intercropping to the monocropping by taking into consideration the time taken by the component crops under intercropping systems in the field from planting to harvesting (Hiebsch and McCollum, 1987; Doubi et al., 2016)

$$LEC = \frac{Y_{pi} * Y_{li}}{Y_{ps} * Y_{ls}} \tag{4}$$

$$ATER = \frac{(LER_p * t_p) + (LER_l * t_l)}{T} \tag{5}$$

Where t_p and t_l is the growth period in days between planting and maturity for potato and legume, respectively. T is the duration of the component crop with the longest growing period.

On the other hand, land use efficiency (LUE) was computed, as indicated in Eq. (6) (Mead and Willey, 1980; Yaseen et al., 2014). The system productivity index (SPI) (Odo, 1991) was used to assess productivity and stability of the intercropping systems by standardizing the legume yield (the secondary crop) in terms of potato (the primary crop) as elucidated by Agegnehu et al. (2006) and Machiani et al. (2018) (Eq. 7). Percentage yield difference (PYD), by definition, refers to the percentage yield difference between the pure stand and the intercrop (Afe and Atanda, 2015). It assumes the pure stand yield to be 100 % and that reduction in yield of one component crop is typically compensated by an increase in yield of the companion crop. Unlike the other indices, the higher the PYD value, the lower the efficiency of the intercropping system, and vice versa. PYD was computed as shown in Eq. (8) (Afe and Atanda, 2015).

$$LUE = \left(LER + \frac{ATER}{2}\right) * 100 \tag{6}$$

$$SPI = Y_{pi} + \left(\frac{Y_{ps}}{Y_{ls}}\right) * Y_{li} \tag{7}$$

$$PYD = 100 - \left(\frac{Y_{ps} - Y_{pi}}{Y_{ps}} + \frac{Y_{ls} - Y_{li}}{Y_{ls}}\right) * 100 \tag{8}$$

Where Y_{pi} and Y_{li} depict the economic yield of potato and legume under the intercropping, respectively, whereas Y_{ps} and Y_{ls} represent the respective yields under pure stands.

2.4.2. Evaluation of the economic efficiency of intercropping systems

The economic efficiency of the intercropping systems was analyzed using potato equivalent yield, income equivalent ratio, monetary advantage index, relative value total, replacement value of intercropping, and relative net return index. The economic yields (tuber and grain) were converted into potato equivalent yield PEY (Gitari et al., 2019b) (Eq. 9).

$$PEY = Y_{pi} + \left(\frac{Y_{li} * P_l}{P_p}\right) \tag{9}$$

Where P_p and P_l represent the market prices of potato (tuber) and legume (grain), respectively.

Income equivalent ratio (IER) is also referred to as a monetary equivalent ratio. It is defined as the area required under the pure stand to that under intercropping to produce the same gross income under the same management level (Devasenapathy, 2008) (Eqs. 10–12). It applies a similar concept to LER. However, as opposed to LER that measures yield in terms of plant product productivity; instead, IER utilizes gross income.

$$IER = (IER_p + IER_l) \tag{10}$$

$$IER_p = \frac{Y_{pi} * P_p}{Y_{ps} * P_p} \tag{11}$$

$$IER_l = \frac{Y_{li} * P_l}{Y_{ls} * P_l} \tag{12}$$

Where IER_P and IER_l represent the partial IER of potato and legume, respectively. The monetary advantage index (MAI) was determined as indicated in Eq. (13) (Ghosh, 2004). The cropping system with the highest MAI is ranked the most profitable.

$$MAI = \left(\frac{LER - 1}{LER}\right) * VCI \tag{13}$$

Where the value of the combined intercrops (VCI) was computed as shown in Eq. (14) (Finney, 1990).

$$VCI = (Y_{pi} * P_p) + (Y_{li} * P_l) \tag{14}$$

Despite the LER being the most common index in agronomy studies, it does not account for the economic value of the cultivated crops. Relative value total (RVT), proposed by Alabi and Esobhawan (2006) (Eq. 15), offers a solution to such a shortcoming. This is very appropriate, particularly to the farmer who is aiming at getting the economic value out of the intercropping enterprise.

$$RVT = \frac{(Y_{pi} * P_p) + (Y_{li} * P_l)}{Y_{ps} * P_p} \tag{15}$$

Replacement value of intercropping (RVI) is an index that accounts for variable cost of production; hence it is superior to RVT. It was calculated following Eq. (16) (Moseley, 1994; Singh et al., 2015).

$$RVI = \frac{(Y_{pi} * P_p) + (Y_{li} * P_l)}{Y_{ps} * P_p - C_{ps}} \tag{16}$$

Where C_{ps} is the variable cost of potato (the main crop) in a pure stand. The relative net return index (RNRI) was calculated following a formula suggested by Mead and Willey (1980) (Eq. 17).

$$RNRI = \frac{[(Y_{pi} * P_p + Y_{li} * P_l) \pm D_{pl}]}{Y_{ps} * P_p} \tag{17}$$

Where D_{pl} is the difference in the cost of cultivation (variable cost) between potato-legume intercropping system and that of pure potato stand. A RNRI value > 1 is preferred for it indicates that intercropping gives higher returns compared to pure stand.

2.4.3. Competition indices

Relative crowding coefficient, aggressivity, competitive ratio, actual yield loss, and intercropping advantage were used to evaluate the competitive effect of potato-legume intercropping systems. The relative crowding coefficient (K) was used as a competitive power coefficient to measure the relative dominance or aggressiveness of either legume on potato or vice versa in an intercropping system (Ghosh, 2004; Lithourgidis et al., 2011) (Eqs. 18–20).

$$K = K_p * K_l \quad (18)$$

$$K_p = \frac{Y_{pi} * Z_l}{(Y_{ps} - Y_{pi}) * Z_P} \quad (19)$$

$$K_l = \frac{Yli * Z_{Pl}}{(Y_{ls} - Y_{li}) * Z_l} \quad (20)$$

Where K_p and K_l represent the relative crowding coefficient for potato and legume under the intercropping system, respectively. Z_p represents the sown proportion (%) of potato to legume in the mixture whereas Z_l denotes that of legume to potato.

Aggressivity (A) was adopted as a competitive index to measure the extent at which the relative yield of one crop in the mixture was higher than that of the other, as expressed in Eqs. (21–22) (McGilchrist, 1965; Machiani et al., 2018).

$$A_p = \frac{Y_{pi}}{Y_{ps} * Z_p} - \frac{Y_{li}}{Y_{ls} * Z_l} \quad (21)$$

$$A_l = \frac{Y_{li}}{Y_{ls} * Z_l} - \frac{Y_{pi}}{Y_{ps} * Z_p} \quad (22)$$

If A_p or $A_l = 0$, then both crops in the intercropping system are equally competitive. A positive A_p denotes dominance of potato over the legume, whereas when it is negative, it indicates that legume is the dominating species.

Competitive ratio (CR) (Willey and Rao, 1980; Dhima et al., 2007) was used to assess the competitive ability of the component crops in an intercropping system. It was calculated according to Eqs. (23–24).

$$CR_p = \left(\frac{LER_P}{LER_l}\right) * \left(\frac{Z_l}{Z_P}\right) \quad (23)$$

$$CR_l = \left(\frac{LER_l}{LER_p}\right) * \left(\frac{Z_P}{Z_l}\right) \quad (24)$$

When $CR_p < 1$ there is a positive benefit of intercropping, suggesting that potato can be grown in association with legume whereas when $CR_l > 1$, that is an indication of a negative benefit. If the difference between CR_l and CR_p is 0, then potato and the companion legume are equally competitive (Bantie et al., 2014; Raza et al., 2020). On the other hand, if by subtracting CR_l from CR_p gives a positive value, then intercropped potato is dominant. In contrast, a negative value indicates that the companion legume dominates potato.

Actual yield loss (AYL) was used to provide detailed information about competition between intercrops as it indicates the equivalent yield gain or loss of component crops in comparison to the respective pure stands (Banik, 1996) (Eqs. 25–27). As opposed to LER, AYL takes into consideration the actual sown proportion of land occupied by the component crops in the field.

$$AYL = AYL_p + AYL_l \quad (25)$$

$$AYL_p = \left[LER_p * \left(\frac{100}{Z_P}\right) - 1\right] \quad (26)$$

$$AYL_l = \left[LER_l * \left(\frac{100}{Z_l}\right) - 1\right] \quad (27)$$

Where AYL_p and AYL_l represent the proportionate yield loss of potato and legume, respectively, under intercropping relative to the yields in pure stand. The value '100' denotes the sown proportion of the crop under monoculture. A positive AYL value indicates an advantage accrued when crops are grown as intercrops and vice versa applies for a negative value (Dhima et al., 2007; Machiani et al., 2018). Intercropping advantage (IA) was used as a gauge for the economic viability of the potato-legume intercropping system. The index was derived from Eq. (28–30) (Banik, 1996).

$$IA = IA_p + IA_l \quad (28)$$

$$IA_p = AYL_p * P_p \quad (29)$$

$$IA_l = AYL_l * P_l \quad (30)$$

2.5. Statistical analysis

Generalized linear mixed models chosen based on Akaike Information Criterion using the package *lme4* in the R software were used for statistical analyses (Bates et al., 2015; R Core Team, 2015). Whenever the analysis of variance *p*-values was found to be significant, separation of mean was done using the Fisher least's significant difference with a threshold level of significance set at $p \le 0.05$ (Abdi and Williams, 2010).

3. Results

3.1. Rainfall and temperature during the study period

In 2015 short rains, a cumulative 714 mm of rainfall was recorded which was 42 % higher than the 20-year (1994–2013) average value (416 mm) (Fig. 2). The rainfall in 2016 long rains amounted to 840 mm and was 335 mm lower compared to the long-term average (505 mm). The highest rainfall intensity was observed in November (478 mm) and April (437 mm) for 2015 short rains and 2016 long rains, respectively. During the off-season period (January and February), about 200 mm was recorded. Throughout the study period, the mean air temperature was within the long-term record, rising gradually to the peak value (23 °C) in February and March, then decreasing progressively to as low as 20 °C in May and June.

3.2. Effect of potato-legume intercropping on yield and economics

Different potato legume intercropping treatments significantly ($p \le 0.05$) influenced the yields of potato and legumes (Table 2). The highest and lowest potato tuber yield were obtained under treatment PS (33.4 Mg ha^{-1}) and PB (1:2.4) (26.9 Mg ha^{-1}). Additionally, the maximum legume seed yield (5.7 Mg ha^{-1}) was obtained in BS, whereas the lowest value (1.0 Mg ha^{-1}) was recorded in PD (1:1.2). On average, under treatment PB (1:2.4), potato achieved 80 % of PS tuber yield, and legume (bean) achieved 55 % of BS yield. Generally, treatment PD (1:2.4) and PB (1:2.4) significantly improved legume yield by 46 % and 47 %, respectively, as compared to respective yields in PD (1:1.2) and PB (1:1.2).

Gross and net income followed an analogous trend (Table 2). For instance, with respect to dolichos integrated treatments, PD (1:2.4) resulted in higher gross income compared to PD (1:1.2) (US$ 11,014 versus US$ 10,639 ha^{-1}). A similar observation was made in potato-bean treatment with PB (1:2.4) recording 6% higher gross income compared to PB (1:1.2). Of the three pure stands, PS fetched more than double gross income compared to PD and PB, which had a record of 3872 and 4387 US$ ha^{-1}, respectively. Benefit: cost ratio differed substantially between treatments with the highest values noted in PD (1:2.4) (5.0) and PB (1:2.4) (4.8), whereas DS had the least ratio of 1.2.

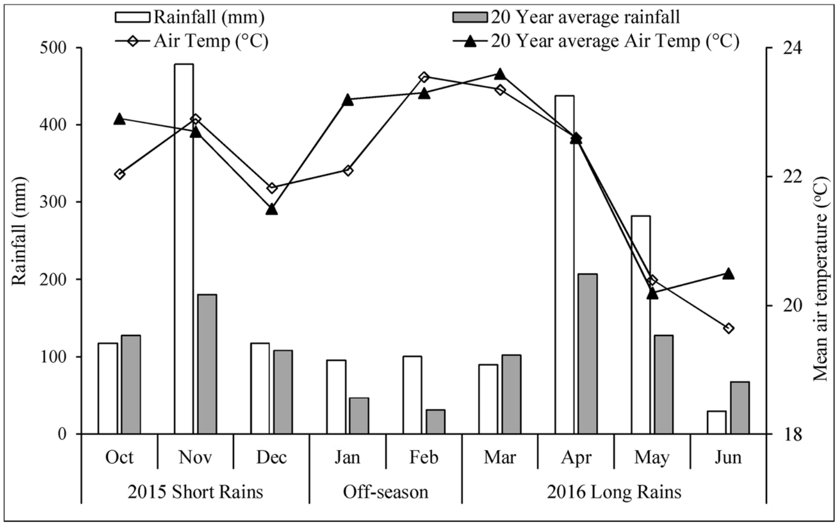

Fig. 2. Monthly total rainfall and mean air temperature in comparison with the 20-year (1994–2013) average values (Modified from Gitari et al., 2019a).

Table 2
Yield and economics of pure stands and potato-legume intercropping systems (mean of 2 years and 4 replicates).

Treatment	Yield (Mg ha^{-1})		Cost and income ($ ha^{-1})			Benefit: cost ratio
	Potato	Legume	Total cost	Gross income	Net income	
PS	33.43^{a}	–	1890.21	10486.60^{c}	8596.39^{c}	4.55^{b}
DS	–	3.69^{b}	1726.01	3872.12^{f}	2146.11^{f}	1.24^{e}
BS	–	5.74^{a}	1770.88	4386.51^{e}	2615.63^{e}	1.48^{d}
PD (1:1.2)	30.59^{b}	1.02^{f}	1920.37	10638.66^{bc}	8718.29^{bc}	4.54^{b}
PB (1:1.2)	28.35^{c}	1.67^{e}	1995.80	10168.31^{d}	8172.51^{d}	4.09^{c}
PD (1:2.4)	28.78^{c}	1.89^{d}	1840.27	11013.65^{a}	9173.38^{a}	4.98^{a}
PB (1:2.4)	26.85^{d}	3.14^{c}	1853.70	10825.52^{ab}	8971.82^{ab}	4.84^{a}
$LSD_{(0.05)}$	0.820	0.137		285.9	285.8	0.150
p value	<0.001	<0.001		<0.001	<0.001	<0.001

PS, pure potato stand; DS, pure dolichos stand; BS, pure bean stand; PD, potato-dolichos; PB, potato-bean; 1:1.2 and 1:2.4 refer to plant density ratio of potato to legume. Means followed by different letters (down the column) differ significantly at $p \leq 0.05$.

3.3. Biological efficiency of potato-legume intercropping system

Partial LER of legume increased significantly ($p \leq 0.05$) as the proportion of potato decreased. Across the years, it was higher in PB (1:2.4) (0.55) and PD (1:2.4) (0.51) than in PB (1:1.2) (0.29) and PD (1:1.2) (0.27) (Fig. 3). Regardless of the year, partial LER value for potato was significantly highest in PD (1:1.2) (0.92), intermediate in PD (1:2.4) (0.87) and PB (1:1.2) (0.85) and least in PB (1:2.4) (0.81). Total LER increased as the proportion of legume increased. For instance, PB (1:2.4) recorded a higher total LER compared to PB (1:1.2) (1.36 versus 1.15).

LEC, ATER, LUE, SPI, and PYD were significantly ($p \leq 0.05$) influenced by potato-legume intercropping systems with growing seasons (years) having only marginal effect (Table 3). Generally, all the indices increased with an increase in the proportion of legumes in the mixture and were higher than in 2016 than 2015. Across the seasons, a mean LEC of 0.42 was obtained in PB (1:2.4) and PD (1:2.4) compared to 0.25 in PB (1:1.2) and PD (1:1.2). Similar differences were obtained for ATER and LUE with respective higher values of 1.13 and 193.13 in treatment with potato: legume ratio of 1:2.4. With respect to SPI, the lowest (38.1 Mg ha^{-1}) value was recorded in PB (1:1.2), the highest in PD (1:2.4) (46.0) and PB (1:1.2) (45.2) with an intermediate value of 39.6 Mg ha^{-1} in PD (1:1.2). PYD showed similar differences, with average values ranging between 15 and 38 %.

3.4. Economic efficiency of the intercropping systems

Income equivalent ratio (IER) values in all treatments (Fig. 4) were greater than unity (> 1), indicating yield advantage over pure stands. Averaged across the years, the treatments with higher legume proportions had significantly higher IER values compared to those with a higher population density of potato. For instance, the highest (1.38) and lowest (1.14) IER were recorded in PD (1:2.4) and PB (1:1.2), respectively. Across the years, the partial IER value for legumes increased as their seeding ratio in the mixtures increased.

Intercropping potato with legumes resulted in a significant ($p \leq 0.05$) effect on PEY, MAI, RVT, RVI and RNRI (Table 4). Across the years, PEY was lowest in PB (1:1.2) (32.4 Mg ha^{-1}), intermediate in PD (1:1.2) (33.9) and highest in PD (1:2.4) (35.1) and PB (1:2.4) (34.5). In both years, the MAI for the 1:2.4 mixtures of potato: legume was significantly greater than that for 1:1.2 mixtures. Irrespective of the year, the RVT noted in PD (1:2.4) (1.06) differed significantly from that in PD (1:1.2) (1.02) and PB (1:1.2) (0.98) but not in PB (1:1.2) (1.04). A similar observation was made for RVI with values decreasing in the order: PD (1:2.4) (1.29) > PB (1:2.4) (1.27) > PD (1:1.2) (1.25) > PB (1:1.2) (1.19). In 2015, RNRI was lowest (0.98) and highest (1.05) in PB (1:1.2) and PD (1:2.4), respectively. Although higher RNRI values were recorded in 2016 than 2015, there were no significant differences between the cropping systems.

3.5. Competition indices under potato-legume intercropping systems

Based on the individual years, only legumes under 1:2.4, planting densities had higher relative crowding coefficients (K) (Table 5). Nonetheless, on pooling the data across the years, the highest (22.0) and lowest (7.4) coefficients for potato were obtained in PD (1:1.2) and PB (1:1.2), respectively. With regard to legume, intercropping resulted in

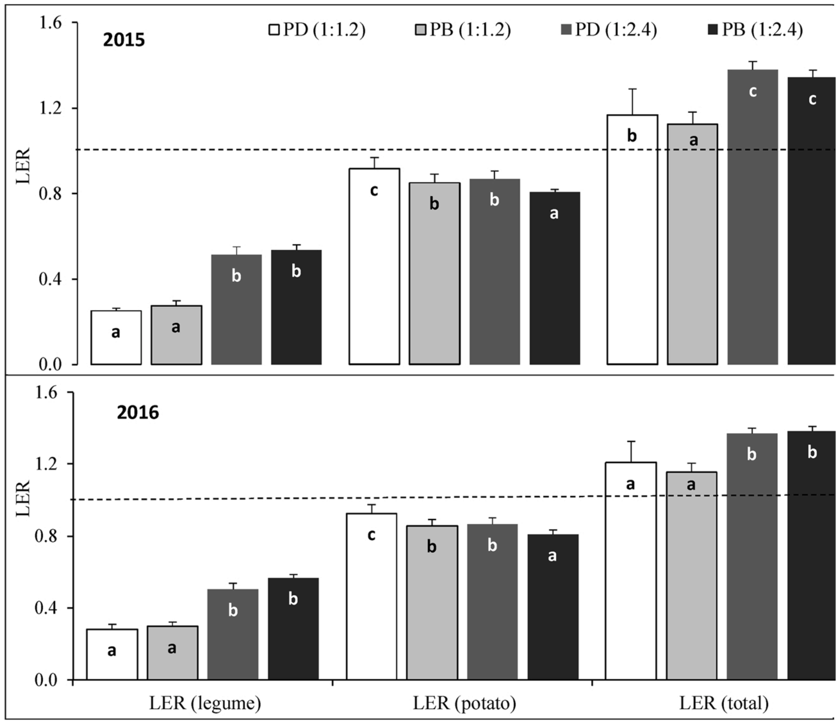

Fig. 3. Land equivalent ratios (LERs) of potato-legume intercropping systems in 2015 and 2016. Bars bearing different letters within the same LER indicate significance at $p \leq 0.05$. Error bars epitomize the standard error of the means. The dashed lines denotes an LER equal to 1.

Table 3
Land equivalent coefficient (LEC), area time equivalent ratio (ATER), land use efficiency (LUE), system productivity index (SPI) and percentage yield difference (PYD) as influenced by potato-legume intercropping systems.

	Treatment	LEC	ATER	LUE (%)	SPI (Mg ha^{-1})	PYD (%)
2015	PD (1:1.2)	0.23^{a}	0.90^{a}	161.85^{a}	38.86^{a}	16.84^{b}
	PB (1:1.2)	0.23^{a}	0.88^{a}	156.42^{a}	37.45^{a}	12.54^{a}
	PD (1:2.4)	0.44^{b}	1.13^{b}	194.41^{b}	46.02^{b}	38.05^{c}
	PB (1:2.4)	0.43^{b}	1.11^{b}	189.74^{b}	44.78^{b}	34.35^{c}
2016	PD (1:1.2)	0.27^{a}	0.94^{a}	168.49^{a}	40.30^{a}	21.34^{a}
	PB (1:1.2)	0.26^{a}	0.92^{a}	162.39^{a}	38.74^{a}	16.60^{a}
	PD (1:2.4)	0.45^{b}	1.13^{b}	194.58^{b}	45.91^{b}	38.14^{b}
	PB (1:2.4)	0.45^{b}	1.13^{b}	193.77^{b}	45.54^{b}	37.06^{b}
p values	Treatment	<0.001	<0.001	<0.001	<0.001	<0.001
	Year	0.024	0.032	0.036	0.068	0.039

PD, potato-dolichos; PB, potato-bean; 1:1.2 and 1:2.4 refer to plant density ratio of potato to legume. Down the column and within the same year, means followed by different letters differ significantly at $p \leq 0.05$.

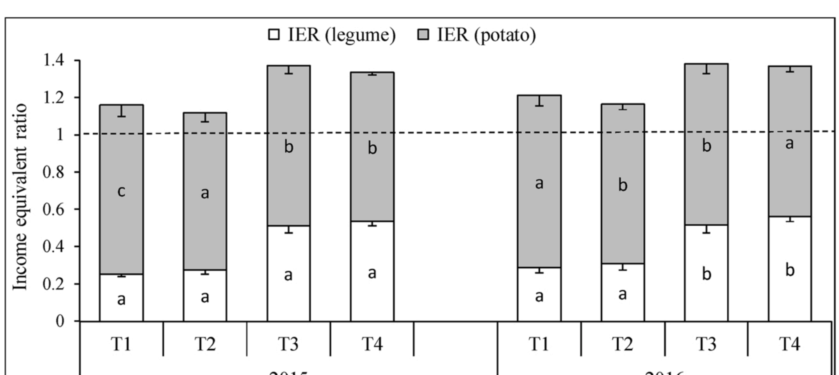

Fig. 4. Income equivalent ratios (IERs) for potato-legume intercropping systems denoted by T1, T2, T3, and T4 for PD (1:1.2), PB (1:1.2), PD (1:2.4), and PB (1:2.4), respectively in 2015 and 2016. Within a year, bars bearing the same letter are not significantly different at $p \leq 0.05$. Error bars exemplify the standard error of means. The dashed line represents an IER equal to 1.

Table 4
Potato equivalent yield (PEY), monetary advantage index (MAI), relative value total (RVT), replacement value of intercropping (RVI) and relative net return index (RNRI) as affected by potato-legume intercropping systems.

	Treatment	PEY	MAI	RVT	RVI	RNRI
2015	PD (1:1.2)	33.48^{b}	1512.65^{b}	1.01^{b}	1.23^{b}	1.01^{ab}
	PB (1:1.2)	32.11^{a}	1120.95^{a}	0.97^{a}	1.18^{a}	0.98^{a}
	PD (1:2.4)	35.05^{c}	3029.56^{c}	1.06^{c}	1.29^{c}	1.05^{c}
	PB (1:2.4)	34.38^{bc}	2755.68^{c}	1.04^{bc}	1.27^{bc}	1.03^{bc}
	$LSD_{(0.05)}$	1.254	359.2	0.038	0.461	0.038
	p value	0.003	<0.001	0.003	0.003	0.009
2016	PD (1:1.2)	34.35^{ab}	1893.61^{a}	1.03^{ab}	1.26^{ab}	1.04^{a}
	PB (1:1.2)	32.72^{a}	1457.51^{a}	0.99^{a}	1.20^{a}	1.00^{a}
	PD (1:2.4)	35.17^{b}	3044.54^{b}	1.06^{b}	1.29^{b}	1.05^{a}
	PB (1:2.4)	34.64^{b}	2937.94^{b}	1.04^{b}	1.28^{b}	1.04^{a}
	$LSD_{(0.05)}$	1.687	586.8	0.051	0.062	0.051
	p value	0.046	<0.001	0.046	0.046	0.123

PD, potato-dolichos; PB, potato-bean; 1:1.2 and 1:2.4 refer to plant density ratio of potato to legume. Down the column and within the same year, means followed by different letters differ significantly at $p \leq 0.05$.

Table 5
Relative crowding coefficient (K) of potato-legume intercropping systems.

	2015			2016		
Treatment	K_p	K_l	K	K_p	K_l	K
PD (1:1.2)	20.87^{a}	0.29^{a}	6.05^{a}	23.16^{a}	0.36^{a}	8.34^{a}
PB (1:1.2)	7.20^{a}	0.32^{a}	2.30^{a}	7.55^{a}	0.39^{a}	2.94^{a}
PD (1:2.4)	17.03^{a}	0.44^{b}	7.49^{a}	16.73^{a}	0.45^{ab}	7.53^{a}
PB (1:2.4)	10.12^{a}	0.48^{b}	4.86^{a}	10.43^{a}	0.53^{b}	5.53^{a}
$LSD_{(0.05)}$	14.401	0.075	3.982	14.68	0.105	0.291
p value	0.195	<0.001	0.091	0.147	0.017	7.33

PD, potato-dolichos; PB, potato-bean; 1:1.2 and 1:2.4 refer to plant density ratio of potato to legume. Down the column, means followed by different letters differ significantly at $p \leq 0.05$.

37, 31, and 14 % lower K_l in PD (1:1.2), PB (1:2.4) and PD (1:2.4), respectively compared to the average value of 0.51 recorded in PB (1:2.4). The overall K for the intercropping systems indicated that PB (1:1.2) had a significantly lower value of 2.6 compared to 7.6, 7.4 and 5.2 recorded for PD (1:1.2), PD (1:2.4) and PB (1:2.4), respectively.

In all treatments, aggressivity values for potato (A_p) under intercropping systems were positive (0.014–0.022), whereas those of legumes (A_l) had negative values ranging from −0.22 to −0.013 (Fig. 5). Across the years, a consistent observation was made where A_p increased significantly ($p \leq 0.05$) as the proportion of potato increased. In contrast, A_l was higher in PD (1:1.2), PD (1:2.4), with a lower proportion of legumes. The results of competitive ratio (CR) were similar to those of K (Fig. 6). In all intercropping systems, the competitive ability of potato was significantly improved, as indicated by greater values of CR_p compared to the corresponding values of CR_l (Fig. 6). Potatoes were more competitive when intercropped with dolichos than with bean, whereas for legumes, beans were observed to show greater competitiveness when intercropped with poatoes.

Across the years, potato was the dominant species as indicated by positive values of AYL_p that differed significantly between treatments in a decreasing order: PB (1:1.2) (0.88) < PD (1:1.2) (1.03) < PB (1:2.4) (1.75) < PD (1:2.4) (1.95). On the other hand, the dominated species, legume had negative AYL_l values with PB (1:1.2) and PD (1:2.4) recording the lowest (−0.52) and highest (−0.22) values, respectively. The intercropping advantage (IA) indicated that only potato-legume intercropping systems with potato to legume ratio of 1.2.4 were advantageous, whereas those with 1.1.2 ratio were not remunerative (Table 6). With respect to 1.2.4 treatments, PB (1:2.4) was 14 % more remunerative than PD (1:2.4). Although results signposted both 1.1.2 treatments to be disadvantageous, PB (1:1.2), which had significantly higher IA value (−88), was relatively lucrative compared to PD (1:1.2) (IA = −219).

4. Discussion

4.1. Yield and economics under potato-legume intercropping systems

The yield results shows superiority of crops (potato/legumes) under pure stand over the intercropping systems. This could be attributed to minimal interactional competition (Banik et al., 2000). The decrease in the yield of the intercropped potato may be ascribed to the intense interplant competition. However, when taking into consideration the production of the whole intercropping entity, there was higher yield production by integrating legumes in potato cropping systems relative to pure-stands. The higher economic returns obtained over different potato-legume intercropping systems were a clear indication of gain from intercropping. This may be attributed to niche complementarities brought about by the spatial and temporal differences in the utilization of the available resources among crops (Dahmardeh et al., 2010; Zhang et al., 2010; Li et al., 2014; Gitari et al., 2020). For instance, niche complementarity is due mainly to contrasting root architecture of the companion crops, and it determines how plants access nutrients and water (Zhang et al., 2014). For example, dolichos roots have been

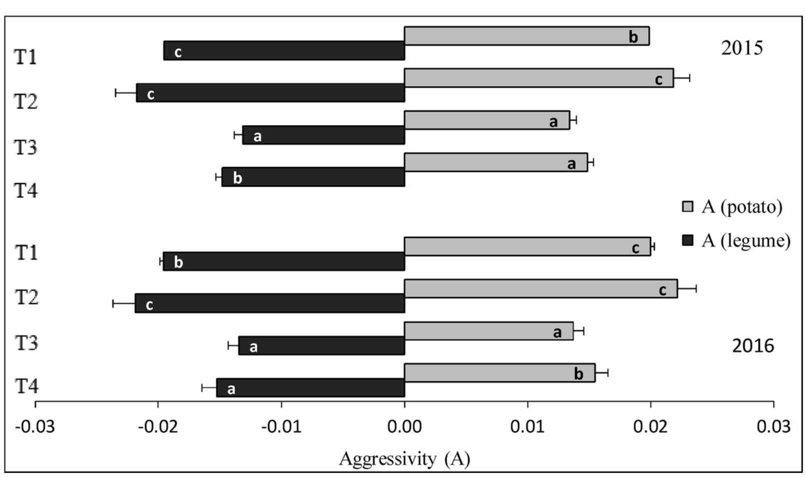

Fig. 5. Aggressivity between potato and legume over 2015 and 2016 under intercropping systems denoted by T1, T2, T3, and T4 for PD (1:1.2), PB (1:1.2), PD (1:2.4), and PB (1:2.4), respectively. Within a year, per companion crop, bars bearing the same letter are not significantly different at $p \leq 0.05$. Error bars represent the standard error of means.

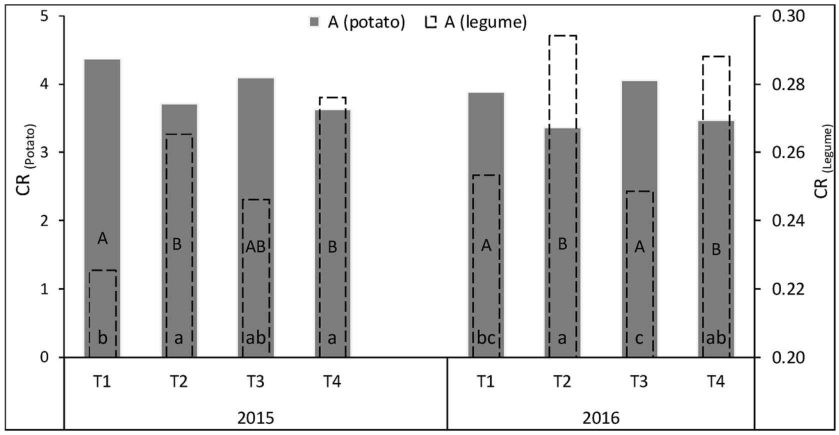

Fig. 6. Competitive ratio (CR) for potato (wide grey bars) and legume (narrow clear bars) under intercropping systems denoted by T1, T2, T3, and T4 for PD (1:1.2), PB (1:1.2), PD (1:2.4), and PB (1:2.4), respectively. Bars bearing different letters (upper case for potato and lower case for legume) across the treatments and within the same year indicate means that differ significantly at $p \leq 0.05$.

Table 6
Actual yield loss (AYL) and intercropping advantage (IA) of potato-legume intercropping systems.

		Actual yield loss			Intercropping advantage		
	Treatment	AYL_p	AYL_l	AYL	IA_p	IA_l	IA
2015	PD (1:1.2)	1.01[b]	−0.55[b]	0.47[b]	318.21[b]	−573.57[a]	−255.36[a]
	PB (1:1.2)	0.87[a]	−0.50[a]	0.36[a]	272.51[a]	−385.54[b]	−113.03[b]
	PD (1:2.4)	1.95[d]	−0.27[c]	1.68[d]	612.82[d]	−288.00[c]	324.82[c]
	PB (1:2.4)	1.75[c]	−0.24[d]	1.51[c]	548.12[c]	−184.39[d]	363.73[c]
	$LSD_{(0.05)}$	0.098	0.076	0.038	30.84	61.51	49.54
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2016	PD (1:1.2)	1.04[b]	−0.48[a]	0.55[b]	325.12[b]	−506.91[a]	−181.79[a]
	PB (1:1.2)	0.89[a]	−0.44[b]	0.44[a]	277.75[a]	−340.16[b]	−62.41[b]
	PD (1:2.4)	1.94[d]	−0.27[d]	1.68[c]	610.01[d]	−282.76[c]	327.25[c]
	PB (1:2.4)	1.76[c]	−0.21[c]	1.55[b]	550.77[c]	−157.71[d]	393.07[d]
	$LSD_{(0.05)}$	0.057	0.053	0.073	17.78	49.06	50.89
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.123

PD, potato-dolichos; PB, potato-bean; 1:1.2 and 1:2.4 refer to plant density ratio of potato to legume. Down the column and within the same year, means followed by different letters differ significantly at $p \leq 0.05$.

reported to go beyond 1 m deep (Gitari et al., 2020). Perhaps this may have enabled it to exploit nutrients from different soil domains by spreading its roots underneath those of neighboring potato hence sparing nutrients on the surface horizon for potato uptake.

The higher-yielding of the dolichos integrated treatments over those with bean, as noted in Table 4 for PEY, RVT, RVI, and RNRI, may be attributed to the phenological differences between these crops. For example, the potato was harvested within three months when dolichos was at flowering stage. This may have allowed dolichos to utilize the water remaining in the soil and nutrients mineralized from residues of the harvested potato resulting in optimum yield. Such findings were reported by Hinsinger et al. (2011) under maize and faba bean intercropping system. Besides, the higher than unity values for RVT recorded in PD (1:1.2), PD (1:2.4), and PB (1:2.4) treatments were an indication of the economic feasibility of growing potato and legume in association (Nyawade and Gitari, 2020). Similarly, the higher than unity ATER values in 1:2.4 treatments indicated the efficiency of the intercrops with respect to use of crop area in a given growing season (Maitra et al., 2000).

In contrast, PB (1:1.2) recorded RVT that was less than one, an indication that potato was disadvantaged when grown in association with bean at close inter-row spacing. Darabad et al. (2011) reported similar results under potato-Safflower (*Carthamus tinctorius* L.) intercropping systems. From our previous studies (Gitari et al., 2018a; and b), it was observed that climbing bean tend to amass a dense canopy that has a shading effect on the companion potato crop. Such canopy decreases light transmission to the leaves of intercropped potato, which consequently affects water and nutrients uptake resulting in reduced tuber yield (Nyawade et al., 2019b; Raza et al., 2019).

4.2. Competition indices

The LER values recorded under intercropping systems were greater than one, an indication that integration of legumes into potato-based cropping systems favored growth and yield of the companion crops grown in mixtures. This is an indication that the interspecific facilitation was greater than interspecific competition, which implies that intercropping resulted in greater land-use efficiency (Wahla et al., 2009; Machiani et al., 2018). The lower LER observed in 1:1.2 series than those of 1:2.4 suggested that intercropped potato suppressed legumes when they are planted in close association. Higher LER under wider inter-row spacing could be attributed to optimum growing space which enhanced the interception of more light (Wang et al., 2015). These results concur with those findings reported by Ghanbari et al. (2010) and Gitari et al. (2018a; and b) that under intercropping, there is increased light interception and improved utilization of moisture and nutrients resulting in higher crop production compared with pure cropping.

Assessment of intercropping based on relative crowding coefficient (K) indicated lesser interspecific competition of the intercrops compared to the intraspecific competition under pure stands. According to Ghosh (2004) and Lithourgidis et al. (2011), species in the mixture have their own K values within the intercropping system. With regard to the present study, intercropped potatoes always recorded higher K values than those of intercrops, an indication that they were more predominant over legumes, which exhibited lower coefficient values. It can further be deduced that intercropping resulted in a yield advantage given that the product of K_p and K_l was greater than 1. Otherwise, a K value that equals to 1 depicts no yield advantage whereas when the value is less than one, it indicates a yield disadvantage (Banik, 1996).

Under all treatments, the differences between the competitive ratios of potato and those of legumes were positive, an indication that potato was the dominant intercrop. Such results were observed by Dua et al. (2017) under potato-French bean (*Phaseolus vulgaris* L) intercropping systems. The competition ratio for legumes in all intercrops (CR_l) was positive but lower than unity, an indication of positive interaction; hence, the tested legumes can feasibly be intercropped with potato. On the other hand, the CR_p was significantly higher than unity indicating a negative effect of potato on the companion legume (Willey and Rao, 1980; Dhima et al., 2007; Raza et al., 2019).

The positive values for partial AYL_p of potato revealed that potato dominated over the legume, which exhibited lower partial AYL_l values. This was an indication of yield gain, probably due to the positive effect of legumes on potato when grown in association (Banik, 1996; Banik et al., 2000; Yang et al., 2017). On the other hand, the negative values for partial AYL_l were an indication of yield loss for legume when intercropped with potato. For instance, the mean AYL_l of −0.22 in PB (1:2.4) indicated a 22 % loss for beans yield when grown in association with potato as compared to its pure stand. Nonetheless, in all treatments the yield gains for potato (AYL_p = positive) were sufficient enough to compensate for the yield loss of legume (AYL_p = negative) when grown in association. This was an indication of the advantage of intercropping as shown by positive AYL values. The lower AYL_l values in 1:2.4 than those in 1: 1.2 treatments conform with findings by Banik et al. (2000) and Yang et al. (2017). They reported a decrease in partial yield loss for the dominant species as its population density increases. The monetary advantage indices obtained from all intercropping systems showed a definite gain from intercropping. Thus, if the ultimate goal of growing crops under intercropping is economic advantages, then the system with potato: legume ratio of 1: 2.4 would be preferred based on the results of this experiment.

5. Conclusion

The present study evaluated the biological and economic feasibility of potato-legume intercropping systems in two potatoes to legume population ratios (1:1.2 and 1: 2.4) against the corresponding pure stands. Following the assessment of these intercropping systems using 17 indices, the study indicated that potato-legume intercropping is beneficial in increasing yield of the components crops resulting in higher land-use efficiency. It also revealed higher economic gain from intercropping compared to pure stands with returns increasing with increasing population density of legumes. When grown in association, the potato was more aggressive and it dominated over legume hence the need to consider spacing and population density of companion crops. Increasing the population density of legumes resulted in minimal yield loss of the intercropping systems. The study shows that potato-legume intercropping is feasible farming practice, especially for smallholder farmers.

Authors statement

This manuscript has solely been submitted to Field Crop Research

Declaration of Competing Interest

The authors declare that there is no conflict of interest with regard to the present manuscript.

Acknowledgments

We are grateful to the International Potato Center (sub-Saharan Africa) for supporting this study through grants from the German Federal Ministry for Economic Cooperation and Development (BMZ) (GIZ: 13.1432.7-001.00), Consultative Group for International Agricultural Research(CGIAR) Fund Donors for Research Programs namely Climate Change, Agriculture and Food Security (CCAFS), and Roots, Tubers, and Bananas (RTB).

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