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Optimizing yield and economic returns of rain-fed potato (*Solanum tuberosum* L.) through water conservation under potato-legume intercropping systems

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ABSTRACT

Even though potato (Solanum tuberosum L.)-based intercropping systems are widely practised in developing countries, only a few studies have focused on legumes as the companion intercrops. This study was conducted to assess the effect of incorporating legumes into the potato production system on ground cover, soil moisture content (SMC), tuber and legume yield, potato equivalent yield (PEY), gross and net income and benefit: cost ratio (BCR). The treatments comprised of pure potato stand (PS), potato-dolichos (Lablab purpureus L.) (PD), potato-garden pea (Pisum sativum L.) (PG) and potato-bean (Phaseolus vulgaris L.) (PB). Results indicated a significantly higher (69%) ground cover at tuber initiation stage in PD compared to 66% in PG and PB and 56% in PS. Similarly, the highest SMC values were recorded at tuber initiation stage: 230, 207, 201 and 188 mm m − 1 in PD, PG, PB and PS, respectively. Fresh tuber yield was highest in PS (36 t ha − 1) and PD (35 t ha − 1) and lowest in PG (29 t ha − 1). PEY was higher under intercropping than monocropping systems. Potato-dolichos was the most profitable intercropping system with a net income of US$ 9174 ha − 1 and a BCR of 5.7 compared to PS (US$ 7436 ha − 1) with a BCR of 5.1. The study showed that dolichos is a promising legume crop that could be integrated into potato cropping systems to improve CWP without compromising the tuber yield.

1. Introduction

Potato (*Solanum tuberosum* L.) is an important food security crop and a major source of household income for smallholder farmers in Kenya. The country's area under potato production is 145,967 ha with an annual production of approximately 1.3 Tg (FAOSTAT, 2017). Nevertheless, potato sector in Kenya is still underdeveloped and is faced with low productivity of $8 - 15\,t\,ha^{-1}$, against the attainable yield of $30 - 40\,t\,ha^{-1}$ under normal field conditions (Muthoni et al., 2013; Gitari et al., 2018). The low productivity is mainly ascribed to the erratic rainfall patterns (Mugo et al., 2016). Potato is mainly affected due to its superficial and fibrous root system of which about 85% is concentrated in the upper 0.3 m of the soil profile making the crop very susceptible to drought (Reyes-Cabrera et al., 2016; Burke, 2017; Aliche et al., 2018).

Potato production under rain-fed agriculture thus requires a focus on water use efficiency (Pereira et al., 2012). Various interventions that have been promoted to increase water use efficiency in rain-fed agriculture, include increasing the amount of fertilizer applied to crops, supplemental irrigation, use of plastic film and use of crop residues as mulch (Kumar et al., 2000; Essah et al., 2012; Carli et al., 2014; Zhang et al., 2016, 2017). Nevertheless, the first three interventions are far beyond the financial ability of most resource-constrained farmers in Kenya. On the other hand, one challenge of using crop residues as a moisture conservation strategy in potato production is their availability in adequate quantities coupled with their competitive uses as fuel and fodder (Karuku et al., 2014; Gachene et al., 2015). In addition, under tropical conditions, organic mulches decompose rapidly besides being susceptible to termite infestation (Gachene et al., 2015; Kamau et al., 2017). Systematic integration of legume crops into potato production systems could be a viable option for addressing these challenges. These crops can enhance soil moisture conservation by covering the soil surface, which significantly reduces water loss through run-off and evaporation (Ogindo and Walker, 2005; Karuma et al., 2011; Chepkemoi

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et al., 2014; Namoi et al., 2014; Gitari et al., 2017; Singh et al., 2017). Various crops such as maize, sulla, spinach, radish and beans have been intercropped with potato, resulting in increased water use efficiency (Sharaiha and Hadidi, 2008; Rezig et al., 2013; Fan et al., 2016; Singh et al., 2016; Zhang et al., 2016). However, most of these studies focused on potato under non-legume intercropping systems. Sharaiha and Hadidi (2008) reported higher water use efficiency under potato-bean intercropping under irrigation, and Singh et al. (2016) observed higher potato equivalent yield when potato was intercropped with radish. In Kenya, intercropping of potato with legumes (dolichos, garden peas and beans) has been reported to reduce run-off and soil loss compared with the pure stand of potato (Nyawade, 2015). However, the author did not monitor the soil moisture dynamics under those intercropping systems.

Lower soil moisture occurring during tuber formation and bulking stages is very critical and can reduce yield more than when it occurs at any other growth stage of the potato (Steduto et al., 2012). To attain the potential potato yield, adequate soil moisture should be available in the rooting zone, particularly during tuber formation stage (Reyes-Cabrera et al., 2016). Depending on the soil type, climatic conditions and growth period, potato requires about 500 − 700 mm of cumulative water in a growing season (Sood and Singh, 2003; Ierna and Mauromicale, 2012).

Given the importance of potato as a food security crop in the most sub-Saharan farming system, there is a need to understand how the integration of different legumes into potato production system affects the tuber yield. Therefore, the objective of this study was to assess ground cover and soil moisture content under potato-legume intercropping systems, and the effects of these systems on economic yield and returns.

2. Materials and methods

2.1. Experimental site description

The experiment was conducted at Kabete Field Station, College of Agriculture and Veterinary Sciences, University of Nairobi. The site falls in the sub-humid agro-ecological zone (Jaetzold et al., 2006), and lies at 1° 25' S, 36° 74' E, and at 1860 m above sea level. Rainfall occurs in a bimodal pattern, from October to December and March to June, and locally referred to as short and long rains, respectively.

2.2. Soil physico-chemical properties of the experimental site

The soil is classified as a Humic Nitisol, which is well-drained, dark red to dark reddish-brown, clay, very deep (more than 1.8 m) with low to moderate inherent soil fertility (Gachene et al., 1997; Karuku et al., 2012; Gitari, 2013, Gitari et al., 2015; IUSS Working Group WRB, 2015). Before establishing this experiment, twelve soil samples were taken as described by Pennock and Yates (2008) at 0 − 0.3 m depth, and they were composited, air-dried, ground to pass through a 2 mm sieve. Soil pH (soil: water ratio of 1: 2.5) was measured using a pH meter (Ryan et al., 2001), total N by modified Kjeldahl method (Bremner, 1996) and organic carbon by modified Walkley and Black method (Nelson and Sommers, 1996). Phosphorus was extracted by Mehlich-1 method (Mehlich, 1978) then measured using a UV–vis spectrophotometer (Murphy and Riley, 1962). Cation exchange capacity was analysed following procedures provided by Rhoades and Polemio (1977). Flame photometry method was used to analyse K and Na while Atomic Absorption Spectrophotometry was used for Ca and Mg analyses (Jackson, 1967). Soil texture was measured using the hydrometer method (Gee and Bauder, 1979). Undisturbed soil samples were also collected in core rings for bulk density determination as described by Doran and Mielke (1984). Saturated hydraulic conductivity was determined following Reynolds et al., 2002 method. The total available water, saturation, field capacity, permanent wilting point and matric potential were estimated using the hydraulic properties' calculator (Saxton and Rawls, 2006). The soil physico-chemical properties of the experimental site are presented in Table 1.

Table 1
Soil physico-chemical properties of the experimental site at 0–0.3 m depth.

Physical Properties		Chemical Properties	
Sand (g kg^{-1})	306.12	pH (water) 1:2.5	5.64
Clay (g kg^{-1})	422.80	Exchangeable Na ($cmol_c$ kg^{-1})	1.21
Silt (g kg^{-1})	271.08	Exchangeable K ($cmol_c$ kg^{-1})	1.81
Bulk density (g cm^{-3})	1.03	Exchangeable Ca ($cmol_c$ kg^{-1})	8.98
Matric potential (bar)	14.92	Exchangeable Mg ($cmol_c$ kg^{-1})	2.51
Hydraulic conductivity (mm hr^{-1})	20.81	Cation exchange capacity ($cmol_c$ kg^{-1})	30.78
Total available water (mm m^{-1})	130.5	Base saturation (%)	47.14
Field capacity (mm m^{-1})	386.2	Organic C (g kg^{-1})	29.02
Permanent wilting point (mm m^{-1})	256.3	Total N (g kg^{-1})	2.71
Saturation (mm m^{-1})	480.7	Available P (mg kg^{-1})	17.09

2.3. Experimental design

The experiment was laid out using a randomized complete block design with four replications in 4 m x 6 m plots (Fig. 1). Treatments consisted of four cropping systems, namely, pure potato stand (var. Shangi) (PS), and potato intercropped with dolichos (*Lablab purpureus* L. var. Uncinatus) (PD), garden pea (*Pisum sativum* L. var. Green feast) (PG) and climbing bean (*Phaseolus vulgaris* L. var. Kenya tamu) (PB). Shangi is the most common potato cultivar in Kenya with an early maturity of 3 − 4 months and an attainable yield of 30 − 40 t ha^{-1} (Gitari et al., 2018). The experiment was conducted for four consecutive seasons, from the short rains season in 2014 to long rains season in 2016. Planting was done manually at the onset of each rainy season with pre-sprouted seed tubers planted at a spacing of 0.3 m within rows and 0.9 m between rows at a depth of 0.1 m to give a plant density of 36,400 plants ha^{-1}. Legumes were planted between the rows of potato with two seeds per hill spaced at 0.25 m to give a plant density of 88,000 plants ha^{-1}. The seed rates were 1.8 t ha^{-1} and 20 kg ha^{-1} for potato and legumes, respectively. Fertilizer application was done twice only on potato, at planting with 200 kg ha^{-1} of NPK (17:17:17) fertilizer and 28 days after planting (DAP) with 200 kg ha^{-1} of calcium ammonium nitrate (27% N) fertilizer to supply the crop with 88 kg N ha^{-1}, 34 kg P_2O_5 ha^{-1} and 34 kg K_2O ha^{-1}.

Potato was sprayed to control blight with Ridomil Gold MZ 68 W G (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) alternated with Daconil 720 SC (Chlorothalonil 720 g L^{-1}) four times in a fortnight interval starting at 14 DAP. Dolichos were sprayed with Duduthrin 1.7 EC (Lambda-cyhalothrin 17.5 g L^{-1}) alternating with Bestox 100 EC (Alpha-cypermethrin 50 g L^{-1}) to control aphids. Weeding was done by hand hoeing at 28 and 56 DAP. At 28 DAP, beans were staked using wooden sticks whereas, potatoes were ridged with soil that was drawn gently from up to 0.35 m from each side of the potato rows.

2.4. Data collection

Soil moisture and ground cover were measured on a weekly basis starting from the planting date and 7 DAP, respectively, up to 84th DAP when potato had attained the physiological tuber maturation. The data were taken from three different points per plot and subsequently grouped into four potato development stages based on Biologische Bundesanstalt Bundessortenamt and Chemical Industrie scale (BBCH) (Hack et al., 2001). The stages were stolon development, tuber initiation, tuber bulking, and tuber maturation with BBCH of 21 − 29, 41 − 49, 60 − 73 and 93 − 95, respectively. Percentage ground cover

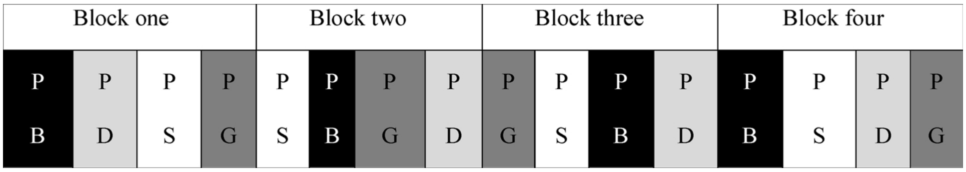

Fig. 1. Schematic illustration of how treatment's randomization was done in the four blocks. The plots measured 4 by 6 m with an inter-plot spacing of 0.5 m. PS, PD, PG and PB represent potato pure stand, and potato-dolichos, potato-garden peas and potato-bean intercropping system, respectively.

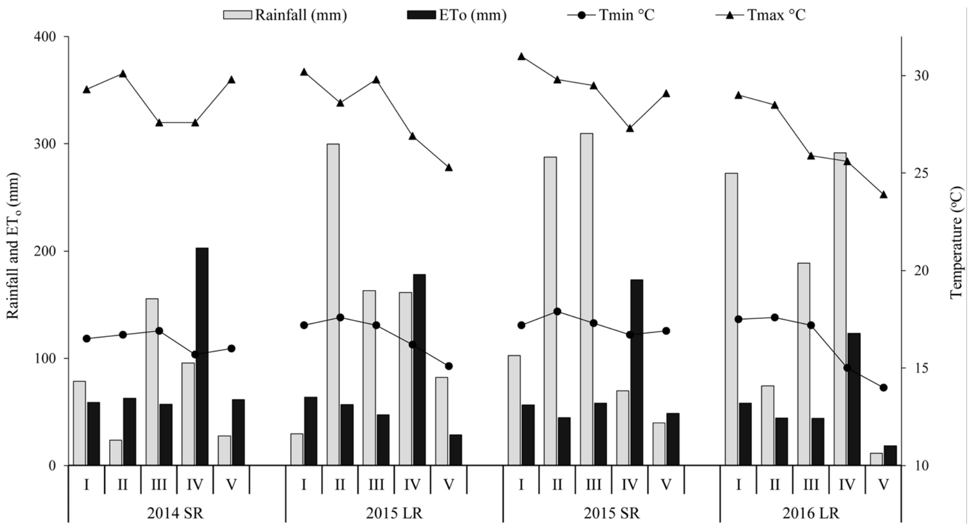

Fig. 2. Rainfall, reference evapotranspiration (ET_o)minimum (Tmin) and maximum (Tmax) temperature recorded for different potatodevelopment stages namely, sprout development (I), stolon development (II), tuber initiation (III), tuberbulking (IV) and tuber maturation (V) from 2014 short rains (SR) to 2016 longrains (LR).

(PGC) was measured using a sighting frame and expressed in percentage as described by Elwell and Wendelaar (1977) (Eq. (1)).

$$\text{PGC}(\%) = \frac{\text{No. of tubes in which vegetation cover is sighted} \times 100}{\text{Total no. of sighted tubes}} \quad (1)$$

Soil moisture content was measured using a digital handheld moisture sensor meter-HSM50 (Omega®). Moisture readings (volumetric soil water contents - θ_v) were taken from between and within the crop rows by inserting the sensor to a depth of 0.2 m, and then they were converted to mm using Eq. (2).

$$\text{Soil moisture content (mm)} = \theta_v \times \text{SD} \quad (2)$$

Where θ_v is the volumetric soil water content (%) and SD = the sampling depth (300 mm).

The tuber and legume yield were estimated from the central 3 m by 2 m area of each plot. Harvesting was carried out manually at 85 DAP for potato and bean, and 120 DAP for dolichos. Potato plants were dehaulmed by cutting at 0.1 m above the ground level, and then tubers were dug out using a fork hoe. Dolichos and beans were harvested when 80% of the pods had turned brown. The whole plant was uprooted, sun-dried for three days and threshed to obtain the grains. Peas were harvested twice between 65 and 75 DAP when the pods were filled but still green.

The yield (tubers and legumes) was expressed in t ha^{-1} then converted into potato equivalent yield (PEY) terms using Eq. (3) (Gitari et al., 2018).

$$\text{PEY} = (\text{kg ha}^{-1}) + \text{PY}(\text{kg ha}^{-1}) + \frac{\text{LY}(\text{kg ha}^{-1}) \times \text{LP}(\text{US\$ Kg}^{-1})}{\text{PP}(\text{US\$ Kg}^{-1})} \quad (3)$$

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

For economic analysis, net income for each cropping system was estimated using Eq. (4).

$$\text{Net income} = \text{Gross income} - \text{Total cost of cultivation} \quad (4)$$

Where total cost of cultivation included the cost of inputs and labour. The cost of inputs (seed, fertilizers, fungicides and pesticides) was estimated based on the local market prices. Labour was valued by recording the time taken to carry out various cultural activities (land preparation, planting, weeding, earthing up, staking and harvesting) and paid at the rate of US\$ 4.85 man-day^{-1} of 8 h. Gross income was taken as the total value of economic yield (tubers and grains) per cropping systems.

2.5. Data analysis

Generalized linear models (GLM) were used to determine the effects of cropping systems on ground cover, soil moisture content, yield and economic returns. The 2.2.3 version of R software (R Core Team, 2015) was used for statistical analyses using the package lme4 (Bates et al., 2015). Several models were fitted by sequentially adding the explanatory variables into the base model. The choice of the best model was based on the lowest Akaike Information Criterion (AIC). Means were separated using Tukey's Honest Significant Difference at $p \leq 0.05$ (Abdi and Williams, 2010).

3. Results

3.1. Rainfall, reference evapotranspiration and temperature during the study period

Rainfall was above 500 mm in all the seasons except 2014 short rains, which had a cumulative amount of 381 mm (Fig. 2). The average seasonal rainfall was 547 mm for short rains and 788 mm for long rains, respectively. Higher rainfall was received during tuber initiation and bulking potato development stages compared to sprout development, stolon development and tuber maturation stages. Similarly, reference evapotranspiration was relatively higher especially during bulking potato development stage with an average of 170 mm compared to 40 mm

Table 2
Groundcover (means ± standard error) as influenced by cropping systems (CS) at different potato development stages (PDS) and seasons (S).

Potato development stage	Cropping System	Groundcover (%) 2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Stolon development (BBCH 21–29)	PS[1]	29.2 ± 5.6^{b}[2]	36.7 ± 6.6^{b}	35.0 ± 8.0^{b}	30.8 ± 4.7^{c}
	PD	34.6 ± 8.6^{ab}	37.1 ± 6.9^{b}	43.3 ± 8.1^{ab}	34.2 ± 3.3^{bc}
	PG	39.2 ± 4.2^{a}	47.1 ± 4.5^{a}	44.6 ± 6.6^{a}	40.8 ± 4.2^{a}
	PB	37.5 ± 7.8^{a}	45.0 ± 9.3^{a}	51.3 ± 9.3^{a}	38.3 ± 6.9^{ab}
Tuber initiation (BBCH 41–49)	PS	54.6 ± 3.3^{c}	65.0 ± 4.3^{b}	54.6 ± 3.3^{b}	49.6 ± 7.2^{b}
	PD	70.0 ± 6.7^{a}	75.8 ± 5.6^{a}	65.0 ± 4.8^{a}	65.4 ± 6.2^{a}
	PG	67.9 ± 5.4^{ab}	74.6 ± 5.4^{a}	61.7 ± 6.2^{a}	59.2 ± 6.3^{a}
	PB	64.2 ± 4.2^{bc}	73.8 ± 4.3^{a}	64.6 ± 3.3	62.5 ± 8.7^{a}
Tuber bulking (BBCH 60–73)	PS	48.8 ± 4.8^{b}	58.3 ± 8.9^{b}	40.8 ± 7.9^{b}	40.8 ± 7.9^{b}
	PD	67.1 ± 5.8^{a}	75.4 ± 7.5^{a}	60.0 ± 8.3	60.0 ± 8.0^{a}
	PG	59.2 ± 9.3^{a}	71.3 ± 4.3^{a}	52.5 ± 5.1^{a}	52.5 ± 5.4^{a}
	PB	64.2 ± 4.2^{a}	72.1 ± 4.5^{a}	54.2 ± 7.2^{a}	54.2 ± 7.2^{a}
Tuber maturation (BBCH 93–95)	PS	13.3 ± 2.5^{c}	28.3 ± 6.2^{b}	13.3 ± 2.5^{c}	27.9 ± 4.5^{c}
	PD	48.3 ± 6.2^{a}	65.4 ± 7.8^{a}	48.3 ± 6.2^{a}	52.1 ± 5.4^{a}
	PG	31.7 ± 7.8^{b}	37.5 ± 5.8^{b}	31.7 ± 7.8^{b}	38.8 ± 4.3^{b}
	PB	20.0 ± 6.4^{bc}	31.3 ± 6.8^{b}	20.0 ± 6.4^{bc}	41.7 ± 2.5^{b}

Summary of analyses of variance	CS	PDS	S	CS x PDS	CS x PDS x S
Degrees of freedom	3	3	3	9	27
F value	237.1	974.4	99.5	42.7	2.7
p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[1] PS, pure potato stand; PD, potato-dolichos; PG, potato-garden; PB, potato-bean.
[2] Means followed by the same superscript letter (within a column and a potato development stage) are not significantly different ($p \le 0.05$) by Tukey's HSD test.

recorded in tuber maturation stage. Temperature ranged from 20 to 25 °C across the seasons with the warmest (23.3 °C) season being 2015 short rains and the coolest (21.4 °C) was 2016 long rains.

3.2. Effect of cropping systems on ground cover and soil moisture content at different potato development stages and seasons

There were significant ($p < 0.001$) effects of cropping systems (CS) on ground cover and soil moisture content at different potato development stages (PDS) and seasons (S) (Table 2). The effect of these factors on ground cover was in the decreasing order of PDS (F = 974) > CS (F = 237) > S (F = 100). Across the potato development stages and seasons, ground cover was significantly highest and lowest under PD (56%) and PS (39%), respectively, while intermediate values were recorded in PG (51%) and PB (50%) cropping systems. Regardless of the season, ground cover at the stolon development stage (BBCH: 21 − 29) was significantly higher in PG and PB than PD and PS. At tuber initiation stage (BBCH: 21 − 29), PS had significantly less ground cover compared to the intercropping systems whereas, at tuber bulking stage (BBCH: 60 − 73), PD had the highest ground cover, although the difference between PD and PB was not significant. At the tuber maturation stage (BBCH: 93 − 95), PS and PG had the lowest percentage ground cover while PB and PD had an intermediate and highest cover, respectively.

Interaction of CS by PDS and CS by S were significant ($p < 0.001$) for soil moisture content (SMC), but there was no three-way interaction (Table 3). The effects of these factors on soil moisture content was in a decreasing order of PDS (F = 893) > S (F = 319) > CS (F = 132). Across the potato development stages and seasons, SMC varied significantly between cropping systems with the highest value in PD (207 mm m^{-1}), lowest in PS (168 mm m^{-1}) and intermediate in PG (183 mm m^{-1}) and PB (179 mm m^{-1}) (Table 4). Depending on potato development stages, at stolon development, SMC was significantly higher in PD than PS but the differences between PD and either PG or PB were not significant. At tuber initiation stage, SMC recorded in PD was 10, 13 and 18% higher than in PG, PB and PS, respectively. Soil moisture content value recorded in PD at tuber bulking stage was significantly higher than those in PS and PB by 18 and 17%, respectively. At tuber maturation, PG and PB resulted in intermediate SMC values, which were 25% lower than in PD and 12% higher than in PS.

3.3. Effect of potato-legume intercropping systems on yield and economic returns

Cropping systems significantly influenced tuber yield, potato equivalent yield, gross and net income variables, and they varied with growing seasons (Table 4). Across the seasons, fresh tuber yield was highest in PS (36 t ha^{-1}) and PD (35 t ha^{-1}) and lowest in PB (30 t ha^{-1}) and PG (29 t ha^{-1}) (Fig. 3a). When intercropped with potato, dolichos grain yield was lowest compared to the other legumes ranging from 1.8 to 1.9 t ha^{-1} whereas beans and peas recorded yield ranging from 2.5 to 2.7 t ha^{-1} and 3.1 to 3.5 t ha^{-1}, respectively (Fig. 3b).

When all economic yields (grain and tubers) were expressed in potato equivalent yield terms, the highest values were observed in PD and PB (43 and 40 t ha^{-1}, respectively) whereas PG and PS had the lowest (38 and 36 t ha^{-1}, respectively) (Table 4). The highest cost of production was incurred under potato-legume intercropping systems ranging from US$ 1550 ha^{-1} in PG to US$ 1600 ha^{-1} in PD, compared to US$ 1450 ha^{-1} in PS. Nevertheless, these potato-legume intercropping systems were the most profitable with net income of US$ 9174, 8496, 7884 ha^{-1} for PD, PB and PG, respectively compared to PS (US$ 7436 ha^{-1}). This resulted in higher benefit: cost ratios in PD and PB (5.7 and 5.4, respectively) compared to 5.1 in PS and PG.

4. Discussion

4.1. Effect of cropping systems on ground cover and soil moisture

The observed trends of ground cover indicate the potential role of legumes in promoting water conservation in these cropping systems. The high ground cover in potato-dolichos could be attributed to the ability of dolichos to accumulate more biomass than other legumes. For instance, in the 2014 short rains season, the amount of rainfall received was 9% below seasonal average and unevenly distributed with October recording the highest rainfall (148 mm) of which 76% only occurred in 2 days. The crop might have used the available soil water effectively

Table 3
Soil moisture content (means ± standard error) as influenced by cropping systems (CS) at different potato development stages (PDS) and seasons (S).

Potato development stage	Cropping system	Soil moisture content (mm m^{-1})			
		2014 Short Rains	2015 Long Rains	2015 Short Rains	2016 Long Rains
Stolon development (BBCH 21–29)	PS[1]	191.8 ± 14[b][2]	162.6 ± 8[d]	197.5 ± 44[b]	242.4 ± 16[b]
	PD	199.3 ± 14[a]	192.6 ± 22[a]	245.9 ± 29[a]	294.4 ± 15[a]
	PG	170.9 ± 19[c]	173.8 ± 6[c]	221.6 ± 42[a]	278.7 ± 20[ab]
	PB	186.5 ± 6[bc]	183.5 ± 12[b]	200.0 ± 35[ab]	267.8 ± 15[ab]
Tuber initiation (BBCH 41–49)	PS	156.7 ± 13[b]	205.6 ± 17[b]	206.0 ± 17[b]	184.5 ± 11[b]
	PD	190.9 ± 19[a]	250.3 ± 19[a]	253.0 ± 33[a]	225.0 ± 10[a]
	PG	165.2 ± 16[b]	228.6 ± 11[a]	244.6 ± 41[a]	190.6 ± 27[b]
	PB	150.9 ± 7[b]	230.7 ± 13[a]	221.8 ± 22[ab]	201.3 ± 20[ab]
Tuber bulking (BBCH 60–73)	PS	117.9 ± 24[b]	201.0 ± 14[b]	225.1 ± 19[b]	176.2 ± 13[b]
	PD	155.3 ± 14[a]	233.3 ± 20[a]	270.3 ± 29[a]	217.3 ± 13[a]
	PG	124.2 ± 9[b]	227.9 ± 11[a]	253.0 ± 32[ab]	183.8 ± 44[b]
	PB	121.3 ± 9[b]	216.9 ± 12[ab]	228.3 ± 20[b]	191.8 ± 24[ab]
Tuber maturation (BBCH 93–95)	PS	91.3 ± 13[b]	133.4 ± 15[c]	100.7 ± 20[b]	88.1 ± 4[c]
	PD	126.4 ± 5[a]	166.9 ± 12[a]	149.8 ± 33[a]	141.2 ± 17[a]
	PG	99.1 ± 4[b]	149.0 ± 6[b]	120.2 ± 21[ab]	102.3 ± 17[b]
	PB	96.0 ± 5[b]	149.6 ± 6[b]	110.5 ± 18[b]	109.3 ± 10[b]

Summary of analyses of variance

	CS	PDS	S	CS x S	PDS x S
Degrees of freedom	3	3	3	9	9
F value	132.2	893.3	318.6	5.6	117.5
p value	< 0.001	< 0.001	< 0.001	< 0.001	0.043

[1] PS, pure potato stand; PD, potato-dolichos; PG, potato-garden; PB, potato-bean.
[2] Within a column for each potato development stage, means followed by different superscript letters differ significantly at $p \leq 0.05$ by Tukey's HSD test.

resulting in the high canopy cover and eventually more biomass production. Nyawade (2015) reported that dolichos usually maintain a high ground cover of up to 40% beyond the physiological maturity period of potato. This probably was the reason for the high ground cover especially at early stages of potato development, which could help in intercepting rainfall, thus reducing raindrop impact on the soil surface (Ogindo and Walker, 2005; Karuma et al., 2011; Nyawade, 2015; Singh et al., 2017; Zhang et al., 2017; Aliche et al., 2018). This may have increased the infiltration resulting in higher soil moisture content in potato-legume intercropping as compared to pure potato stand.

Increased ground cover, especially in the potato-dolichos intercropping system, might have created a microclimatic zone by shielding the moist and cool air close to the soil surface, thereby reducing water loss through evaporation. Higher soil moisture contents have also been reported under other intercropping systems such as potato-maize (Mushagalusa et al., 2008; Fan et al., 2016), dolichos-cassava (Namoi et al., 2014) and dolichos-sweet potato (Chepkemoi et al., 2014). On the contrary, potato-pea and potato-bean intercropping systems, which had relatively less dense canopy cover than potato-dolichos probably experienced a higher water loss through direct evaporation from the soil surface resulting in lower soil moisture content.

Table 4
Potato equivalent yield (PEY), gross and net income and benefit: cost ratio means as influenced by cropping systems (CS) at different seasons (S).

Season	Cropping System	PEY (t ha^{-1})	Cultivation Cost (US$ ha^{-1})	Gross Income (US$ ha^{-1})	Net Income (US$ ha^{-1})	Benefit: Cost Ratio
2014 Short Rains	PS[1]	31.9[d][2]	1449	7968[d]	6519[d]	4.5[c]
	PD	38.9[a]	1600	9730[a]	8130[a]	5.1[a]
	PG	34.1[c]	1551	8521[c]	6970[c]	4.5[c]
	PB	36.2[b]	1596	9053[b]	7456[b]	4.7[b]
2015 Long Rains	PS	38.2[c]	1449	9557[c]	8108[c]	5.6[b]
	PD	46.4[a]	1600	11601[a]	10001[a]	6.3[a]
	PG	40.4[b]	1551	10100[b]	8550[b]	5.5[bc]
	PB	41.1[b]	1596	10268[b]	8672[b]	5.4[c]
2015 Short Rains	PS	39.0[c]	1449	9752[c]	8303[c]	5.7[b]
	PD	46.5[a]	1600	11636[a]	10036[a]	6.3[a]
	PG	41.0[b]	1551	10247[b]	8696[b]	5.6[b]
	PB	45.2[a]	1596	11307[a]	9710[a]	6.1[a]
2016 Long Rains	PS	33.1[c]	1449	8263[c]	6814[c]	4.7[b]
	PD	40.5[a]	1600	10128[a]	8528[a]	5.3[a]
	PG	35.5[b]	1551	8872[b]	7321[b]	4.7[b]
	PB	39.8[a]	1596	9938[a]	8342[a]	5.2[a]
CS		< 0.001	–	< 0.001	< 0.001	< 0.001
S		< 0.001	–	< 0.001	< 0.001	< 0.001
CS x S		< 0.001	–	< 0.001	< 0.001	< 0.001

[1] PS, pure potato stand; PD, potato-dolichos; PG, potato-garden; PB, potato-bean.
[2] Within a column, means followed by the same superscript letter are not significantly different at $p \leq 0.05$ by Tukey's HSD test.

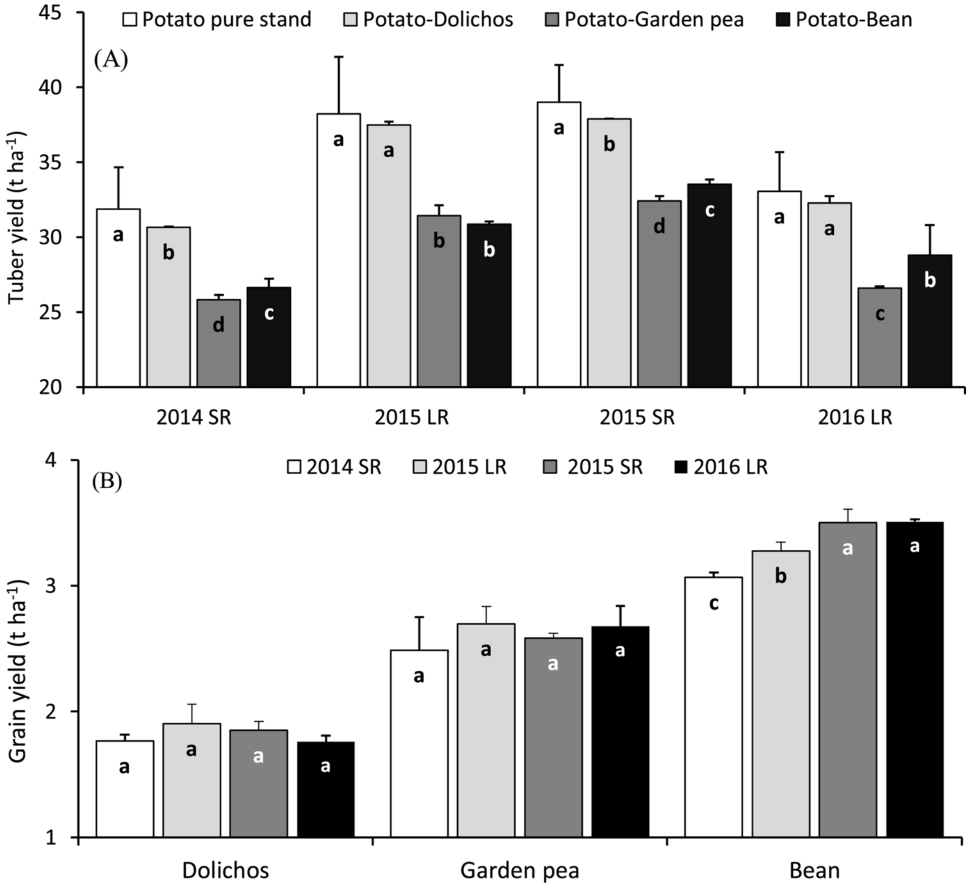

Fig. 3. Potato tuber yield (A) and legume grain yield (B) as influenced by cropping systems at different seasons. SR and LR denote short and long rains seasons, respectively. Bars bearing the same letter across the treatments and within the same season for tuber yield, and across the season and within the same treatments for grain yield are not significantly different at $p \leq 0.05$. Error bars signify standard error of the means.

4.2. Effect of cropping systems on yield and economic returns

The almost similar potato yield in PD compared to PS would suggest a positive interaction between the two crops, which could be explained by temporal shoot architectural differences. In this case, during the stolon development stage of potato, dolichos had a lower-lying canopy than that of potato. This could have enabled potato to obtain enough solar radiation for photosynthesis, resulting in higher tuber yield. At later stages of potato development, increased ground cover due to relatively higher dolichos biomass could have further benefited potato by reducing water loss through evaporation and lowering the temperature within the canopy (Ogindo and Walker, 2005; Borowy, 2012). These results corroborate earlier findings by Liao et al. (2016) and Burke (2017) that lower temperatures promote translocation of photo-assimilates to the developing tubers leading to higher tuber yield, which was comparable to that in pure stand.

On the other hand, in potato-bean intercropping, higher-lying canopy of bean at very early potato growth stages could have resulted in a decreased light interception by the potato plants, thus reducing their photosynthetic capacity hence the low tuber yield. This concurs with the findings by Fan et al. (2016) and Gitari et al. (2017) who reported that tuber yield is highly dependent on the amount of intercepted solar radiation. In a potato-maize intercropping system, Mushagalusa et al. (2008) reported a 4–26% decrease in potato yield, which they attributed to the shading effect of maize crops.

Apart from the shading effects on potato, the observed variations in potato tuber yield across different cropping systems may be attributed to the differences in root architecture of these legume crops. The root system of dolichos can grow up to a depth of about 2 m (Gitari et al., 2018). This might have reduced the competition for available water. In contrast, beans and peas have shallow roots (0.2–0.4 m), which could have increased competition with potato for resources such as water and nutrients, resulting in lower tuber yield. Similar results were obtained when potato was intercropped with maize (Mushagalusa et al., 2008). Similarly, Singh et al. (2016) and Zhang et al. (2016) reported a decrease in tuber yield when potato was intercropped with radish and faba bean, respectively.

In 2014 short rains, there was generally a lower potato tuber yield in all the treatments, which could be attributed to the low rainfall amount received during that season. Given that potato cultivation under monoculture requires 500 – 700 mm of water in a growing season (Sood and Singh, 2003; Ierna and Mauromicale, 2012), the rainfall amount recorded in this season was inadequate to meet the crop's seasonal water requirement. This might have resulted in water stress condition, which might have resulted in reduced nutrient uptake and translocation of assimilates into the tubers leading to low yield (Fleisher et al., 2008; Gitari et al., 2016, 2018). This argument is further reinforced by the findings by Ramirez et al. (2016) who reported that tuber yield decreases in response to an increase in water stress. Under water stress conditions, crops close their stomata resulting in decreased transpiration (Ierna and Mauromicale, 2012; Liao et al., 2016).

The higher potato equivalent yield under intercropping systems compared to pure potato cropping system could mainly be attributed to the additional legume grain yield. Another possible explanation for this observation could be increased nutrient uptake and translocation of assimilates into potato tubers and legume seeds as observed by Fleisher et al. (2008) and Gitari et al. (2016, 2018). Higher potato equivalent yields have been reported by Singh et al. (2016) under radish intercropping compared to pure potato stand. Notwithstanding the lower grain yield recorded in potato-dolichos plots, the potato equivalent yield was still high due to the high market price of dolichos (US$ 1.17 kg^{-1}) compared to beans and peas whose market prices are less than a dollar per kg. In addition, dolichos has high socio-economic value to many African communities (Maass et al., 2010) as it is consumed by lactating mothers. Higher gross income has also been reported under potato-bean (Zhang et al., 2016) and maize-okra-cowpea (Sharma et al., 2017) intercropping systems compared to the respective pure stands.

The higher productivity observed under intercropping systems especially in potato-dolichos relative to a pure stand of potato could imply that there was an effective use of water as a higher proportion of soil moisture was taken up by the plants and used for transpiration rather than being lost through direct evaporation from the soil surface (Blum, 2012). High canopy cover under potato-dolichos may have reduced evaporative water loss while promoting productive water use. With a high density of roots under the intercropping system, then it is expected that water uptake is accelerated resulting in high transpiration and consequently high yield (Mabhaudhi et al., 2013; Chimonyo et al., 2016). Zhang et al. (2016) reported a better water utilization under potato-legume intercropping systems compared to monocropping systems. Sharaiha and Hadidi (2008) and Rezig et al. (2013) reported higher productivity when potato was intercropped with bean and sulla (*Hedysarum coronarium* L.), respectively compared to the pure stand of potato. The current study, therefore, emphasizes the great potential of potato-legume intercrops that can easily be adopted, especially by smallholder farmers to increase their incomes. Moreover, dolichos shows the potential of being successfully incorporated into the potato production systems without necessarily compromising the tuber yield.

5. Conclusion

This study has shown that increased ground cover under intercropping systems could be a potential water conservation strategy. Therefore, the findings from this study have demonstrated the economic feasibility of intercropping potato with legumes. In this regard, dolichos was the most effective legume that could be integrated into potato cropping systems to improve crop water productivity without compromising potato yield. Increased crop water productivity is vital, especially for resource-constrained smallholder farmers who are reliant on rain-fed agriculture for their livelihood. However, given that this was a four-season study and thus is subject to seasonal variations, it will be important to look at the effects of these intercropping systems on crop water productivity, yield and economic returns on a long-term basis.

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References

Abdi, H., Williams, L.J., 2010. Honestly significant difference (HSD) test. In: Salkind, N.J., Dougherty, D.M., Frey, B. (Eds.), Encyclopedia of Research Design. Sage, Thousand Oaks, CA, USA, pp. 583–585.

Aliche, E.B., Oortwijn, M., Theeuwen, T.P.J.M., Bachem, C.W.B., Visser, R.G.F., Linden, C.G., 2018. Drought response in field grown potatoes and the interactions between canopy growth and yield. Agric. Water Manage. 206, 20–30.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.

Blum, A., 2012. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res. 112, 119–123.

Borowy, A., 2012. Growth and yield of stake tomato under no-tillage cultivation using hairy vetch as living mulch. Acta Sci. Pol. Hortorum. Cultus. 11, 229–252.

Bremner, J.M., 1996. Nitrogen total. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis, Part 3: Chemical Methods. Soil Sci. Soc. Am., Inc. Am. Soc. Agron., Inc., Madison, WI, pp. 1085–1121.

Burke, J.J., 2017. Growing the Potato Crop. Vita, Equity House, Upper Ormond Quay, Dublin 7, Ireland.

Carli, C., Yuldashev, F., Khalikov, D., Condori, B., Mares, V., Monneveux, P., 2014. Effect of different irrigation regimes on yield, water use efficiency and quality of potato (*Solanum tuberosum* L.) in the lowlands of Tashkent, Uzbekistan: a field and modelling perspective. Field Crops Res. 163, 90–99.

Chepkemoi, J., Onwonga, R.N., Karuku, G.N., Kathumo, V.M., 2014. Efficiency and interactive effects of tillage practices, cropping systems and organic inputs on soil moisture retention in semi-arid Yatta sub-county, Kenya. J. Agric. Environ. Sci. 3, 145–156.

Chimonyo, V.G.P., Modi, A.T., Mabhaudhi, T., 2016. Water use and productivity of a sorghum-cowpea-bottle gourd intercrop system. Agric. Water Manage. 165, 82–96.

Doran, J.W., Mielke, L.N., 1984. A rapid, low-cost method for determination of soil bulk density. Soil Sci. Soc. Am. J. 48, 717–719.

Elwell, H.A., Wendelaar, F.E., 1977. To Initiate a Vegetal Cover Data Bank for Soil Loss Estimation. Department of Conservation and Extension (now Agritex), Harare Research Bulletin No. 23.

Essah, S.Y.C., Delgado, J.A., Dillon, M., Sparks, R., 2012. Cover crops can improve potato tuber yield and quality. Hort. Technol. 22, 185–190.

Fan, Z., An, T., Wu, K., Zhou, F., Zhou, F., Zi, S., Yang, Y., Xue, G., Wu, B., 2016. Effects of intercropping of maize and potato on sloping land on the water balance and surface runoff. Agric. Water Manage. 166, 9–16.

FAOSTAT, 2017. Online Database, Food and Agriculture Organization of the United Nations. (Accessed March 6 2017). http://www.fao.org.

Fleisher, D.H., Timlin, D.J., Reddy, V.R., 2008. Elevated carbon dioxide and water stress effects on potato canopy gas exchange, water use, and productivity. Agric. For. Meteorol. 148, 1109–1122.

Gachene, C.K.K., Jarvis, N.J., Linner, H., Mbuvi, J.P., 1997. Soil erosion effects on soil properties in a highland area of Central Kenya. Soil Sci. Soc. Am. J. 61, 559–564.

Gachene, C.K.K., Baaru, M.W., Gathaara, V., Onwonga, R., Mbuvi, J.V., 2015. Factors that influence adoption of soil and water conservation technologies at Kathekakai location, Machakos County. In: Khalif, Z., Gachene, C.K.K., Gicheru, P., Mburu, D.M., Gakahu, C.G. (Eds.), Sustainable Land Management in Dry Land Management. United Nations Development, Nairobi, Kenya, pp. 85–105.

Gee, G.W., Bauder, J.W., 1979. Particle size analysis by hydrometer: a simplified method for routine textural analysis and a sensitivity test of measured parameters. Soil Sci. Soc. Am. J. 43, 1004–1007.

Gitari, H.I., 2013. Lime and Manure Application to Acid Soils and their Effects on Biochemical Soil Properties and Maize Performance at Kavutiri - Embu County. MSc. Thesis. Kenyatta University, Kenya.

Gitari, H.I., Mochoge, B.E., Danga, B.O., 2015. Effect of lime and goat manure on soil acidity and maize (*Zea mays*) growth parameters at Kavutiri, Embu County - Central Kenya. J. Soil Sci. Environ. Manage. 6, 275–283.

Gitari, H., Gachene, C., Karanja, N., Schulte-Geldermann, E., 2016. Evaluation of potato (Solanum tuberosum L.) nutrient use efficiency under legume intercropping systems. Annual conference proceedings of Tropical and Subtropical Agricultural and Natural Resource Management (TROPENTAG), organised by the University of Natural Resources and Life Sciences. (BOKU Vienna), Austria, September 18–21, 2016.

Gitari, H., Gachene, C., Karanja, N., Schulte-Geldermann, E., 2017. Water use efficiency and yield of potato in potato-legume based intercropping systems in a semi-humid region, Kenya Versailles, France. Twentieth European Association for Potato Research (EAPR) Conference July 9–14, 2017.

Gitari, H.I., Karanja, N.N., Gachene, C.K.K., Kamau, S., Sharma, K., Schulte-Geldermann, E., 2018. Nitrogen and phosphorous uptake by potato (*Solanum tuberosum* L.) and their use efficiency under potato-legume intercropping systems. Field Crops Res. 222, 78–84.

Hack, H., Gall, H., Klemke, T., Klose, R., Meier, U., Stauss, R., Witzenberger, A., 2001. The BBCH scale for phonological growth stages of potato (*Solanum tuberosum* L.). In: Meier, U. (Ed.), Growth Stages of Mono and Dicotyledonous Plants, BBCH Monograph. Federal Biological Research Centre for Agriculture and Forestry.

Ierna, A., Mauromicale, G., 2012. Tuber yield and irrigation water productivity in early potatoes as affected by irrigation regime. Agric. Water Manage. 115, 276–284.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, Updates 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. FAO, Rome.

Jackson, M.L., 1967. Soil Chemical Analysis. Prentice Hall of India Private Limited, New Delhi.

Jaetzold, R., Schmidt, H., Hornetz, B., Shisanya, C.A., 2006. 2nd ed. Farm Management Handbook of Kenya. Natural Conditions and Farm Information, vol. II Ministry of Agriculture/GTZ, Nairobi, Kenya part 2/B2.

Kamau, S., Barrios, E., Karanja, N.K., Ayuke, F., Lehmann, J., 2017. Spatial variation of soil macrofauna and nutrients in tropical agricultural systems influenced by historical charcoal production in South Nandi, Kenya. Appl. Soil Ecol. 119, 286–293.

Karuku, G.N., Gachene, C.K.K., Karanja, N., Cornelis, W., Kironchi, G., 2012. Soil hydraulic properties of a Nitisol in Kabete, Kenya. Trop. Subtrop. Agroecosyst. 15, 595–609.

Karuku, G.N., Gachene, C.K.K., Karanja, N., Cornelis, W., Verplacke, H., 2014. Effect of different cover crop residue management practices on soil moisture content under a tomato crop (*Lycopersicon esculentum*). Trop. Subtrop. Agroecosyst. 17, 509–523.

Karuma, A., Gachene, C.K.K., Gicheru, P.T., Mwang'ombe, A.W., Mwangi, H.W., Clavel, D., Verhagen, J., Von-Kaufmann, R., Francis, J., Ekaya, W., 2011. Effects of legume cover crop and sub-soiling on soil properties and maize (*Zea Mays* L.) growth in semi-arid area of Machakos District, Kenya. Trop. Subtrop. Agroecosyst. 14, 237–243.

Kumar, V., Ghosh, B.C., Bhat, R., Karmakar, S., 2000. Effect of irrigation and fertilizer on yield, water use efficiency and nutrient uptake of summer groundnut (*Arachis* *hypogaea*). Indian J. Agron. 45, 756–760.

Liao, X., Su, Z., Liu, G., Zotarelli, L., Cui, Y., Snodgrass, C., 2016. Horticultural impact of soil moisture and temperature on potato production using seepage and center pivot irrigation. Agric. Water Manage. 165, 230–236.

Maass, B.L., Knox, M.R., Venkatesha, S.C., Angessa, T.T., Ramme, S., Pengelly, B.C., 2010. Lablab purpureus (L.) Sweet – a crop lost for Africa? Trop. Plant Biol. 3, 123–135.

Mabhaudhi, T., Modi, A.T., Beletse, Y.G., 2013. Response of taro (*Colocasia esculenta* L. Schott) landraces to varying water regimes under a rainshelter. Agric. Water Manage. 121, 102–112.

Mehlich, A., 1978. New extractant for soil test evaluation of phosphorus, potassium, magnesium, calcium, sodium, manganese and zinc. Com. Soil Sci. Plant Anal. 9, 477–492.

Mugo, R.M., Ininda, J.M., Okoola, R.E., 2016. Inter annual variability of onset and cessation of the long rains in Kenya. J. Meteorol. Relat. Sci. 9, 30–47.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.

Mushagalusa, G.N., Ledent, J.F., Draye, X., 2008. Shoot and root competition in potato/maize intercropping: effects on growth and yield. Environ. Exp. Bot. 64, 180–188.

Muthoni, J., Shimelis, H., Melis, R., 2013. Potato production in Kenya: farming systems and production constraints. J. Agric. Sci. 5, 182–197.

Namoi, N.L., Onwonga, R.N., Karuku, G.N., Onyango, C.M., Kathumo, V.M., 2014. Influence of selected ecological farming practices on soil moisture retention and yield of sorghum (*Sorghum bicolor* L.) Moench) and cassava (*Manihot esculanta* Crantz) in semi-arid Yatta sub-county, Kenya. J. Agric. Sci. 6, 214–231.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon and organic matter. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis, Part 3: Chemical Methods. Soil Sci. Soc. Am., Inc. Am. Soc. Agron., Inc., Madison, WI, pp. 61–1010.

Nyawade, O.S., 2015. Effect of Potato (*Solanum Tuberosum* L.) Cropping Systems on Soil and Nutrient Losses Through Run-off in a Humic Nitisol. MSc. Thesis. University of Nairobi, Kenya.

Ogindo, H.O., Walker, S., 2005. Comparison of measured changes in seasonal soil moisture content by rained maize-bean intercrop and component cropping in semi-arid region of southern Africa. Phys. Chem. Earth 30, 799–808.

Pennock, D., Yates, T., 2008. Soil sampling designs. In: Carter, M.R., Gregorich, E.G. (Eds.), Soil Sampling and Methods of Analysis, 2nd ed. Taylor and Francis Group, USA, pp. 25–38.

Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manage. 108, 39–51.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Ramirez, D.A., Yactayo, W., Rens, L.R., Rolando, J.L., Palacios, A., Mendiburu, F.D., Mares, V., Barreda, C., Loayza, H., Monneveux, P., Zotarelli, L., Khan, A., Quiroz, A., 2016. Defining biological thresholds associated to plant water status for monitoring water restriction effects: stomatal conductance and photosynthesis recovery as key indicators in potato. Agric. Water Manage. 177, 369–378.

Reyes-Cabrera, J., Zotarelli, L., Dukes, M.D., Rowland, D.L., Sargent, S.A., 2016. Soil moisture distribution under drip irrigation and seepage for potato production. Agric. Water Manage. 169, 183–192.

Reynolds, W.D., Elrick, D.E., Youngs, E.G., 2002. Rings or cylinder infiltrometers (Vadose zone). In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis Part 4. Physical Methods: Soil Science Society of America Book Series. No. 5. Soil Sci. Soc. Am. pp. 818–820.

Rezig, M., Sahli, A., Ben, F., Harbaoui, Y., 2013. Potato (*Solanum tuberosum* L.) and sulla (*Hedysarum coronarium* L.) intercropping in Tunisia: effects in water consumption and water use efficiency. J. Agric. Sci. 5, 123–134.

Rhoades, J.D., Polemio, M., 1977. Determining cation exchange capacity: a new procedure for calcareous and gypsiferous soils. Soil Sci. Soc. Am. J. 41, 524–528.

Ryan, J., George, E., Rashid, A., 2001. Soil and Plant Analysis Laboratory Manual, 2nd ed. Jointly published by the International Center for Agricultural Research in the Dry Areas (ICARDA) and the National Agricultural Research Centre (NARC), pp. 46–48.

Saxton, K.E., Rawls, W., 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. (Accessed April 1 2017). http://hydrolab.arsusda.gov/soilwater/Index.htm.

Sharaiha, R.K., Hadidi, N.A., 2008. Micro-Environmental Effects on Potato and Bean Yields Grown Under Intercropping System. Agronomy Series University of Agricultural Sciences and Veterinary Medicine No. 51.

Sharma, N.K., Singh, R.J., Mandal, D., Kumar, A., Alam, N.M., Keesstra, S., 2017. Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. Agric. Ecosyst. Environ. 247, 43–53.

Singh, R.J., Pande, K.K., Sachan, V.K., Singh, N.K., Sahu, R.P., Singh, M.P., 2016. Productivity, profitability, and energy consumption of potato-based intercropping systems. Int. J. Veg. Sci. 22, 190–199.

Singh, R.J., Ghosh, B.N., Sharma, N.K., Patra, S., Dadhwal, K.S., Meena, V.S., Deshwal, J.S., Mishra, P.K., 2017. Effect of seven years of nutrient supplementation through organic and inorganic sources on productivity, soil and water conservation, and soil fertility changes of maize-wheat rotation in north-western Indian Himalayas. Agric. Ecosyst. Environ. 249, 177–186.

Sood, M.C., Singh, N., 2003. Water management. In: Khurana, S.M.P., Minhas, J.S., Pandey, S.K. (Eds.), The Potato: Production and Utilization in Sub-tropics. Mehta Publishers, New Dehli, pp. 111–112.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop yield response to water. FAO. Irrig. Drain. Pap. 66, 184–188.

Zhang, X., Wang, H., Yu, X., Hou, H., Fang, Y., Ma, Y., 2016. The study on the effect of potato and beans intercropping with whole field plastics mulching and ridge-furrow planting on soil thermal-moisture status and crop yield on semi-arid area. Sci. Agric. Sin. 49, 468–481.

Zhang, Y.L., Wanga, F., Shock, C.C., Yang, K., Kang, S., Qin, S., Li, S., 2017. Influence of different plastic film mulches and wetted soil percentages on potato grown under drip irrigation. Agric. Water Manage. 180, 160–171.