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Abstract

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A B S T R A C T

An accurate estimation of crop evapotranspiration and soil water balance under potato-legume intercropping is important for improving the crop water productivity of rainfed potato. This study quantified the evapotranspiration, yield, and soil water balance of potato (*Solanum tuberosum* L.) intercropped with lima bean (*Phaseolus lunatus* L.) or dolichos (*Lablab purpureus* L.) in comparison to the same crops under monocropping. The experiment was set up in three agroecological zones of Kenya: upper midland (with an altitude range of 1500–1653 m above sea level (masl)), lower highland (1892–1923 masl) and upper highland (2502–2594 masl). The dual crop coefficient approach was adopted with the SIMDualKc model to estimate crop evapotranspiration and compute the soil water balance. The dual crop coefficient partitions crop evapotranspiration into crop transpiration and soil evaporation by applying both soil evaporation and basal crop coefficient. The model was calibrated and validated using field data observed along four crop growth seasons. The basal crop coefficients, the ratios of soil evaporation to evapotranspiration, and that of transpiration to evapotranspiration were determined. The yields of different intercrops were converted into equivalent yield of potato based on price of the produce. Good agreement between the observed and simulated data for available soil water and crop evapotranspiration was found with modeling efficiency > 0.8. The residual mean square error was low and ranged from 0.01−0.08 m^3 m^{-3} for available soil water and 0.03−0.09 mm d^{-1} for crop evapotranspiration. The transpiration to actual evapotranspiration ratio of potato-legume intercropping was 6−28% greater than that of the sole potato because legume intercrops fully covered the ground by mid-season, thus limiting the energy available for soil evaporation. Crop yields were significantly greater under intercropping as transpiration occurred near its potential rate, thus not limiting yields. These results support the dual crop coefficient method as an appropriate tool to estimate and accurately partition crop evapotranspiration under potato-legume intercropping.

1. Introduction

The current climate change scenarios of decreasing precipitation and increasing temperatures in most tropical countries (IPCC, 2019, 2021; Christensen et al., 2007; Meehl et al., 2007) may hinder potato production in these zones. This is because potatoes have a shallow rooting system, thus requiring frequent wetting by rain or irrigation, particularly in areas with high evaporative demand (Ahmadi et al., 2011;

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Quiroz et al., 2012). Where seasonal rainfall amounts fall below the range of 500–700 mm, tuber formation and filling are suppressed (Sood and Singh, 2003; Pavlista, 2015). In extreme cases of water deficit, potatoes respond by curling their leaves to lower transpiration rates, a mechanism that lowers water use and in turn negatively impacts tuber yield (Struik et al., 1989).

The adverse effects of elevated water deficit on potato growth can be reduced by properly designed legume intercropping systems and improved water-saving policies and practices (Gitari et al., 2020; Burke, 2017; Muthoni et al., 2013). Better use of soil water under intercropping systems has been observed when the component crops have different rooting architecture, enabling the deep-rooted intercrop to extract water below the roots of the companion crop (Yang et al., 2011). An improved use efficiency of water may be achieved when one of the component crops has a reduced water demand (Brooker et al., 2015). Legume intercrops may also create shade that lowers the soil temperatures and increase the soil moisture content (Nyawade et al., 2019). Policies that recommend integrative use of heat-tolerant potato cultivars and legume intercropping have shown improved capacity to adapt potato production to warmer midlands and therefore have a greater potential to expand the area under potato production (Nyawade et al., 2020a).

In the tropical highlands, however, only about 5–12% of the farmers practice potato-legume intercropping, mainly with the common bean (*Phaseolus vulgaris* L.) and garden pea (*Pisum sativum* L.) (Muthoni et al., 2013; Gitari et al., 2018a, 2018b; Nyawade et al., 2020a, 2020b; Gebru et al., 2017). This low rate of adoption is largely attributed to limited farmer sensitization as most legume intercropping studies have been conducted in research stations with very little or no involvement of farmers and policy actors (Matusso et al., 2014; Gebru et al., 2017; Lal et al., 2011; Totin et al., 2020). According to Nyawade et al. (2020c), farmers will only adopt potato-legume intercropping if the system is properly designed to guarantee yield and income increase. From an empirical perspective however, an effective intercropping system must address the complexity of computing the crop evapotranspiration and soil water balance (Miao et al., 2016). It is only then that it can be established with high accuracy whether the system improves yields or positively impacts the crop water productivity.

The use of properly calibrated models to compute the crop evapotranspiration and soil water balance has subsequently been proposed (Allen et al., 1998; Rosa et al., 2012a, 2012b; Pereira et al., 2021a, 2021b). The models adopted should aim at providing accurate standard and updated crop coefficient (K_c) values (Pereira et al., 2021a, 2021b). Besides, the models must be devoid of biases caused by flaws in experimental design, measurement equipment, vegetation management, data handling, model parameterization, and interpretation of results (Allen et al., 2011; Pereira et al., 2021a, 2021b). In this regard, the use of weighed crop coefficient (single K_c approach) proposed by Allen et al. (1998) and dual K_c models described in Pereira et al. (2021a, 2021b) and Rosa et al. (2012a, 2012b) have been adopted.

The single K_c model approach is simple to apply (Allen et al., 1998). The model uses crop height and the fraction of soil surface cropped with each of the crops to obtain K_c for the intercrop. This approach was successfully adopted when performing the soil water balance of wheat–maize and wheat–sunflower systems (Pereira et al., 2007; Miao et al., 2016; Zhu et al., 2012). However, the single K_c model exhibits low accuracy and cannot partition evapotranspiration into actual crop transpiration ($T_{c\ act}$) and soil evaporation (E_s) (Allen and Pereira, 2009; Allen et al., 2011; Rosa et al., 2012a, 2012b; Zhang et al., 2013).

The dual K_c method therefore becomes necessary as it can partition $ET_{c\ act}$ into $T_{c\ act}$ and E_s with high accuracy (Rosa et al., 2012a). The model achieves this by applying a basal crop coefficient (K_{cb}) and a soil evaporation coefficient, K_e (Allen et al.,1998; Rosa et al., 2012a, 2012b). The basal crop coefficient describes the plant transpiration while the soil water evaporation coefficient describes evaporation from the soil surface. Wetting of the soil due to rain or irrigation event may result in a large value of K_e. As the soil surface dries up, the K_e value reduces and falls to zero when no water becomes available for evaporation (Allen et al., 1998). Summation of K_{cb} and K_e can never exceed a maximum value, $K_{c\ max}$, a value determined by the energy available for evapotranspiration at the soil surface.

The SIMDualKc model (Rosa et al., 2012a, 2012b), is one of the models that adopt the Food and Agriculture (FAO) dual K_c approach to partition ET_{act} into $T_{c\ act}$ and E_s using a daily time step. The model has been applied with high accuracy in numerous studies for various open-field crops grown in different climates and conditions e.g., wheat–maize crop sequence (Zhang et al., 2013) and monocultures of maize (Martins et al., 2013), hop (*Humulus lupulus*) (Fandĩno et al., 2015), potato (Paredes et al., 2018), wheat (Gao et al., 2014), pea (*Pisum sativum* L.) (Paredes et al., 2017), soybean (Wei et al., 2015), cotton (Rosa et al., 2012b), and peach orchard (Paco et al., 2012). Qiu et al. (2015) tested with good accuracy the application of the SIMDualKc model for hot pepper grown under greenhouse conditions. In addition, the model has been applied over a range of cultural practices that may affect ET_c, such as crop density and height, canopy architecture, irrigation methods, and use of mulches or active (green) ground cover in water management (Paco et al., 2012; Rosa et al., 2012b). Moreover, the SIMDualKc has been applied for wheat–maize and wheat–sunflower intercropping to simulate soil water balance and crop yield with great success (Miao et al., 2016). A combination of the SIMDualKc (Rosa et al., 2012a) with the phasic Stewart's water yield model (Stewart et al., 1977) was tested with a high accuracy using maize transpiration as a driving variable (Paredes et al., 2014).

The applicability of the SIMDualKc model for potato-legume intercropping has however not been described. This study examined the applicability of the SIMDualKc model to partition evaporation and transpiration under potato-legume intercropping in a tropical condition. Specifically, the study aimed at (i) calibrating and validating the SIMDualKc model for potato, lima bean and dolichos as single crops and intercrops, with potato as the main crop (ii) deriving the basal crop coefficients (K_{cb}) for the single crops and intercrops (iii) and quantifying the evapotranspiration and yield of the potato-legume intercropping systems.

2. Materials and methods

2.1. Study site

The trials were carried out in the long and short rains of 2017 and 2018 in three agroecological zones of Kenya; upper midland (0°29'35.71''S, 37°20'55.29''E; 1500–1653 m above sea level (masl)), lower highland (1°14'45.00''S, 36°44'19.51''E; 1892–1923 masl) and upper highland (0°14'39.08''S, 36°17'18.99''E; 2502–2594 masl) (Fig. 1). All the three sites fall along the Mount Kenya Belt that exhibits bimodal distribution of rainfall, with the long rains occurring from early

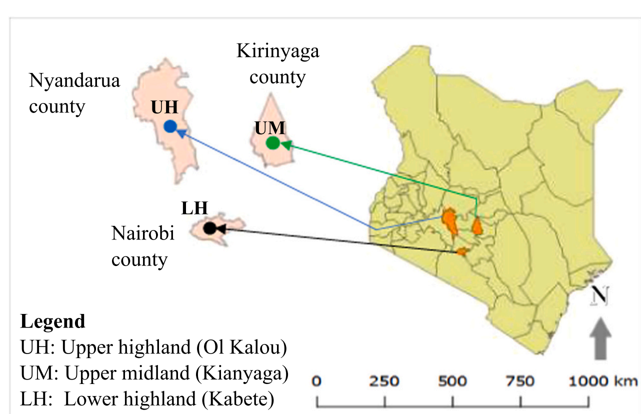

Fig. 1. Map of Kenya showing sites selected for establishment of the trials.

March to late May, and the short rains from mid-October to late December. The specific sites however, exhibit differences in agro-climatic factors, mainly the temperatures and rainfall, and are differentiated by different soil types (Jaetzold et al., 2012). Based on the long-term averages (> 30 years), the upper highland site receives a mean annual temperature of 18.2 °C with an annual rainfall amount of 1500 mm. The lower highland site receives an average temperature of 21.2 °C and annual rainfall of 1100 mm, while the upper midland site exhibits a relatively lower annual rainfall amount averaging 800 mm and a mean annual temperature of 24.4 °C. The amounts of rainfall and temperatures recorded in the study sites during the study period are presented in Fig. 3. The rainfall amounts were generally higher in the upper highland, moderate in the lower highland and lowest in the upper midland while air temperatures were highest in the upper midland, moderate in the lower highland and lowest in the upper highland.

The soils in the upper midland are well-drained, shallow to very deep, dark reddish-brown silty loam classified as Rhodic Ferralsol. The soils in the lower highland are dark red friable clay, with clear, smooth boundaries classified as Humic Nitisol (Jaetzold et al., 2012). The soils in the upper highland are dark brown to very dark red-brown firm clay to silt loam clay classified as Ferric Luvisol. Details of the measured soil properties (0–1.2 m depth) before the experiment are provided in Table 1.

2.2. Experimental layout and crop husbandry

The trials were laid out in a randomized complete block design with four replications on slopes averaging 12–15%. The plots measured 4.25 m wide by 3 m long and were separated by a 1 m path. The treatments comprised of sole potato (*Solanum tuberosum* L.), sole lima bean (*Phaseolus lunatus* L.), sole dolichos (*Lablab purpureus* L.) and intercrop of potato with either lima bean or dolichos. Unica (CIP 392797.22) which is a medium-tall potato cultivar with early maturity (2.5–3.5 months) and characterized by good yield potential and high tolerance to water and heat stress (NPCK, 2019) was adopted in this study. Intercropping was done in 2 rows of potato alternating with 2 rows of legumes. Sole potato rows were spaced 0.75 m, while sole legume rows were spaced 0.5 m. In intercropping, rows were 0.75 m from potato to potato, 0.75 m from potato to legume, and 0.5 m from legume to legume (Fig. 2). Pre-sprouted tubers were planted at a uniform depth of 0.1 m. Two legume bean seeds per hole were planted at a within row space of 0.3 m.

Fertilization was based on soil test results and crop nutrient requirements and on average consisted of basal application of 50 kg ha^{-1} N, 90 kg ha^{-1} P_2O_5, 100 kg ha^{-1} K_2O and topdress of 40 kg ha^{-1} calcium ammonium nitrate at 14–21 days after potato emergence. Legumes received only basal phosphorus (46% triple super phosphate) at a constant rate of 20 kg ha^{-1} across the three agroecological zones. Weeding was performed at 14–21 days after potato emergence by hand hoeing and entailed earthing up the soil around potato vines and slight tamping of the soil around legumes' stem base. The legumes 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 and other insect pests, while potato crops were sprayed with Ridomil Gold MZ 68WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) to control the late blight disease. Potatoes were harvested at maturity (3–3.5 months after planting) by digging out tubers using hand hoes while legumes were harvested by manually removing pods and retaining crop residues for incorporation into the soil.

2.3. Data collection

2.3.1. Meteorological data

Rainfall (R), solar radiation (R_s), air temperature (T), wind speed (u_2) and relative humidity (RH) during the experimental period, were obtained from the agro-meteorological stations located at about 200–500 m from the study sites. These data were used to compute the reference crop evapotranspiration (ET_o) using the FAO Penman-Monteith method (Allen et al., 1998).

2.3.2. Field observations and measurements

The data collection required for modeling and yield assessment were performed along both crop seasons. The dates of each crop growth stage (crop development, mid growth, and maturity) were assumed when 80% of plants attained that stage and are summarized in Supplementary Table 1. A point frame consisting of a single row of 10 pins spaced 10 mm with tripods measuring 2 m in height was used to quantify the maximum crop cover at 2 weeks intervals (Coxson and Looney, 1986). Crop height (h, m) was measured in 10 random plants using a graduated tape measure. The leaf area index (LAI) was measured along the crop season using a Sunfleck Ceptometer-LP-80 (Decagon Devices, Pullman, WA, USA). Measurements were taken only under sky-blue conditions with no or minimum clouds between 1130 and 0130 h (local time) and during a period of constant incident solar radiation. The LAI values were converted into a fraction of ground cover (f_c, dimensionless) using the approximation proposed by Allen and Pereira (2009) and were used in the SIMDualKc simulations.

Measurements of the soil water content (SWC, m^3 m^{-3}) were derived from a calibrated tensiometer installed at the inter-rows at every 0.30 m depth increments to a depth of 1.2 m. Additional measurements were taken after heavy rainfall events and the values averaged to the effective

Table 1
Soil properties measured at start of the experiment.

Agroecological zone	Soil depth(m)	Clay	Silt	Sand	Textural class	pb	θs	$θ_{FC}$	$θ_{WP}$	ASW	pH	SOC	N	P
			%			Mg m^{-3}		m^3 m^{-3}				%	%	ppm
Upper midland	0–0.3	29.5	33.3	37.2	CL	1.32	0.48	0.29	0.17	0.12	4.99	1.82	0.13	33.30
	0.3–0.6	29.2	36.9	33.9	CL	1.34	0.49	0.31	0.18	0.13	4.99	1.04	0.23	23.40
	0.6–0.9	32.9	29.8	37.3	CL	1.35	0.50	0.31	0.18	0.13	4.93	0.88	0.11	24.40
	0.9–1.2	33.8	32.4	33.8	CL	1.36	0.50	0.33	0.19	0.14	4.92	0.33	0.09	20.20
Lower highland	0–0.3	49.7	22.5	27.8	C	1.19	0.53	0.40	0.33	0.07	5.11	2.06	0.19	24.40
	0.3–0.6	49.2	24.2	26.6	C	1.22	0.54	0.43	0.35	0.08	5.14	1.56	0.11	18.20
	0.6–0.9	50.1	24.2	25.7	C	1.22	0.55	0.48	0.35	0.13	5.16	0.98	0.06	17.70
	0.9–1.2	51.3	24.8	23.9	C	1.25	0.56	0.48	0.37	0.11	5.20	0.42	0.02	16.60
Upper highland	0–0.3	48.3	46.1	5.6	SC	1.22	0.51	0.43	0.31	0.12	5.21	3.09	0.22	16.60
	0.3–0.6	46.9	48.4	4.7	SC	1.22	0.53	0.45	0.34	0.11	5.22	2.34	0.24	17.90
	0.6–0.9	34.6	59.5	5.9	SCL	1.26	0.51	0.38	0.22	0.16	5.26	1.92	0.11	15.50
	0.9–1.2	33.9	57.9	8.2	SCL	1.29	0.52	0.39	0.23	0.16	5.28	0.98	0.09	14.90

pb, soil bulk density; θs, soil water content at saturation; $θ_{FC}$, soil water content at field capacity; $θ_{WP}$, soil water content at permanent wilting point; ASW, total available soil water content; SOC, soil organic carbon; N, total nitrogen; P, available phosphorus (P). C, CL, SC, SCL denote clay, clay loam, silt clay and silt clay loam, respectively.

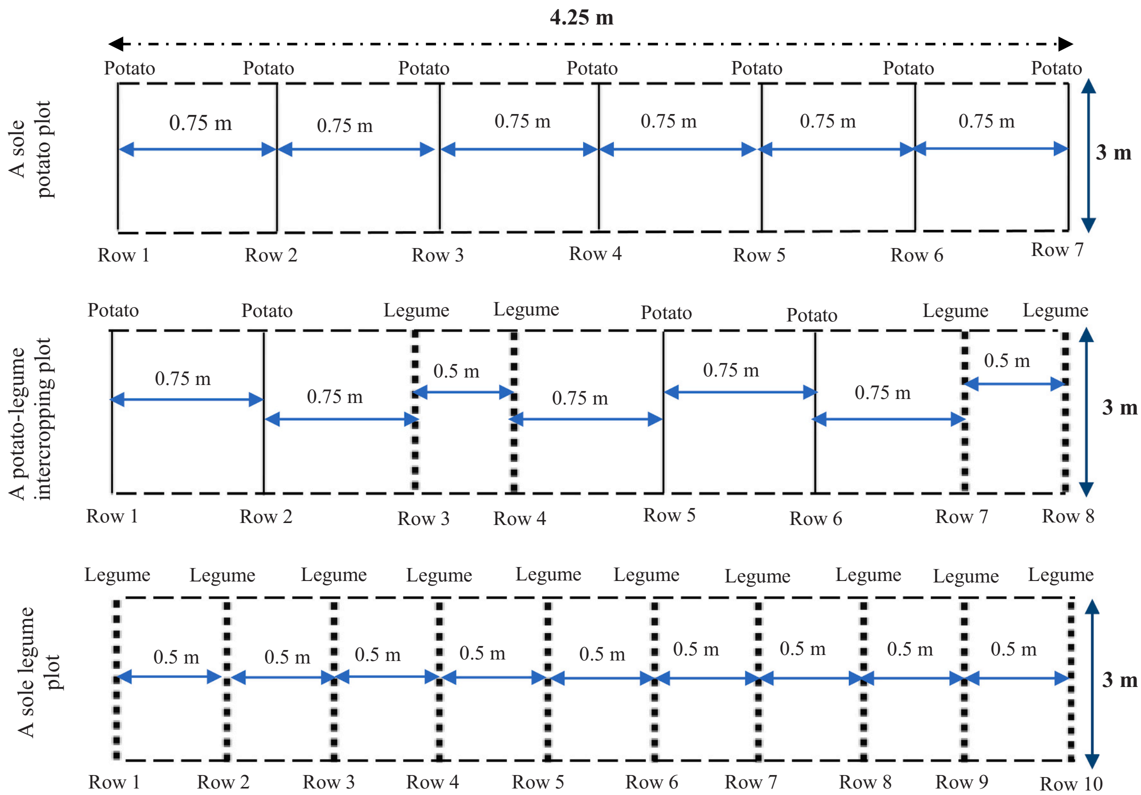

Fig. 2. Schematic illustration of inter row spacing deployed for sole cropping and intercropping systems.

root depth and used for model simulations. The effective root depth (Z_r, m) was observed using soil samples taken at 0.10 m layer increment to the depth of 1.2 m. The soil samples were sieved through 2 mm mesh placed in a shallow tub of water to wash away the fine soil particles and enable the root material to be observed. Results showed that most roots were concentrated in the upper 0.40 m layer of soil, but a significant volume of legume roots was found to a depth of 1.2 m. Thus, the soil water balance was performed for a depth of 1.2 m under both single and intercropping systems. Three undisturbed soil samples of 100 cm^3 were taken at 0.3 m depth and used to determine the soil water retention curve using a pressure plate apparatus for suctions of − 10, − 33, − 100 and − 1500 kPa (Ramos et al., 2011).

Micro-lysimeters (PVC) with a length of 150 mm, an internal diameter of 110 mm, and an external diameter of 115 mm, were used to measure the soil evaporation (E_s). The base of the tubes was sealed with waterproof tape. The soil in the micro-lysimeters was replaced every two days or after significant precipitation events to keep the soil moisture coinciding with that of the field conditions. For sole cropping, the micro-lysimeters were placed only in the central rows between plants. For intercropping, they were placed in the internal row of potato strips, in the adjacent row between potato and legume strips, and at the internal row of the legume strips. The weight of the micro-lysimeters was taken (using a portable balance with the precision of ± 0.01 g) at about 1800 h (local time) each day, thus when energy available for evaporation and transpiration was reduced. The soil evaporation for a plot was represented by the mean value of three lysimeters' readings using Eq. (1).

$$E_s = 10\frac{\Delta M_i}{A_e} \tag{1}$$

where E_s is the mean soil evaporation depth (mm d^{-1}), ΔM_i is the mean daily weight changes of the micro-lysimeter (g d^{-1}), and A_e is the cross-sectional area of the lysimeters (cm^2). Reference crop evapotranspiration, ET_o was computed with the FAO Penman-Monteith equation (Allen et al., 1998). Seasonal evapotranspiration rates (ET_{act}) from each plot were estimated using a water balance equation (Eq. (2); Allen et al., 1998) based on measured changes in soil water content, rainfall, and runoff, including data from emergence to physiological maturity in the different cropping systems.

$$ET_a = P + I - RO - DP + \Delta S \tag{2}$$

where P is the precipitation/rainfall amount, I the net irrigation depth, RO the runoff (mm), DP the deep percolation (mm), and ΔS the change of soil water stored in soil layer of the 0–1.2 m depth, i.e., the difference in the available soil water content at the start and end of the season. Deep percolation was computed using the parametric equation developed by Liu et al. (2006), which is a component of the SIMDualKc model. The current meter containing a revolving wheel turned by the movement of water was used to measure the runoff. The meters were inserted to a flow depth of 0.6 m in each plot. The number of rotations (rpm) was recorded, and the velocity of flow was calculated from a calibrated chart. Groundwater depths were measured using an electronic water level sensor (KGU9901, Chongqin Shanlan, China) with a 4–7 days interval during all the sampling periods in each season. In each site, the observation well was located within the experimental area. The capillary rise was not considered in this equation since the water tables across the study sites were deeper than 10 m (Karuku et al., 2014). The daily $T_{c\ act}$ was calculated by subtracting E_s from $ET_{c\ act}$.

Final yields were obtained after harvesting the entire plots. The yields (potato tubers and legume grains or legume forage) were converted into potato equivalents (PEY) using Eq. (3). For dolichos, the estimations considered grain and shoot biomass separately for this legume is used both as pulse and forage.

$$PEY(t\ \ ha^{-1}) = PY(kg\ \ ha^{-1}) + \frac{LY(kg\ \ ha^{-1}) * LP(US\$\ \ kg^{-1})}{PP(US\$\ \ kg^{-1})} \tag{3}$$

Where PEY = potato equivalent yield, i.e., the yields of different intercrops converted into equivalent yield of potato based on price of the produce. PY = potato yield, LY = legume yield, PP = market price of potato (0.38 US\$ kg^{-1}) and LP = market price of legumes (0.21, 0.05 and 1.15 US\$ kg^{-1} for lima bean grain, dolichos forage and dolichos grain respectively).

Replacement series was employed to hold the total density of the intercrop constant and vary the ratio among the intercrop species, thus allowing for yield comparison between the crops grown in biculture and monoculture.

2.4. The SIMDualKc model

The SIMDualKc model (Rosa et al., 2012a, 2012b) was used to compute the potential (ET_c) and actual $ET_{c\ act}$, as well as simulate the soil water balance of single cropped potato/legumes, and potato-legume intercropping. The model adopts the FAO dual crop coefficient approach (Allen et al., 1998; Allen and Pereira, 2009) to compute and partition the daily crop evapotranspiration (ET_c, mm d^{-1}) into crop transpiration (T_c, mm d^{-1}) and soil evaporation (E_s, mm d^{-1}).

2.4.1. The SIMDualKc model inputs

The model input data in the present application are summarized in Table 3. The model calibration was performed using the data observed along the four crop growth seasons of the study. A trial-and-error procedure was used as detailed by Pereira et al. (2015a, 2015b). The initial values of parameters were: the basal crop coefficient (K_{cb}, dimensionless), depletion fractions for no stress (p, dimensionless), thickness of the evaporation soil layer (Z_e, m), total evaporable water (TEW, mm), readily evaporable soil water (REW, mm) estimated according to Allen et al. (1998, 2005a), runoff curve number (CN) algorithm as tabled by Allen et al. (2007), deep percolation (DP, mm), and capillary rise from the shallow groundwater table (CR, mm) as proposed by Liu et al. (2006). As there were no reference K_c values for lima bean and dolichos, the initial K_c values of these crops were determined as the ratio of crop evapotranspiration to reference evapotranspiration (ET_c/ET_o) when the soil surface is dry. For intercropping, the initial K_c was derived using Eq. (4).

$$K_c = \frac{f_1 h_1 kc_1 + f_2 h_2 kc_2}{f_1 h_1 + f_2 h_2} \tag{4}$$

where f_1 and f_2 are fractions of the soil surface planted by potatoes and legumes in an intercropping i.e., 0.5, h_1 and h_2 are the height of potatoes and legumes, respectively; and K_{c1} and K_{c2} are crop coefficients for potatoes and legumes in monoculture.

2.4.2. The SIMDualKc model calibration

The SIMDualKc model calibration entailed adjusting significant model inputs to minimize differences between observed and simulated values for the available soil water content (ASW) and crop evapotranspiration (ET_c). The data collected along the four crop growth seasons was used and these include (1) the crop parameters K_{cb} and p, the initial values of which were those tabulated by Allen et al. (1998); (2) the soil evaporation parameters Z_e, TEW and REW, also initialized from estimations proposed by Allen et al. (1998, 2005a); (3) the deep percolation parameters, a_D and b_D with the initial values proposed by Liu et al. (2006). The initial soil water conditions assumed that the soil was fully wetted at both the evaporable layer and the root zone, i.e., the initial depletion was zero.

2.4.3. The SIMDualKc model validation

Validation entailed evaluating accuracy of the model for available soil water (ASW) and crop evapotranspiration (ET_c) computations performed using the calibrated parameter values. Parameters were adjusted using a trial-and-error procedure as described by Pereira et al. (2015a, 2015b). The process was initiated by focusing on the crop parameters, K_{cb} and p until estimation errors were small and varied little from one iteration to the next. In the first iteration, the initial values of soil parameters (Z_e, TEW, REW) were kept unchanged while adjusting the crop parameters (K_{cb}, p). In the second iteration, the revised crop parameters were kept unchanged while adjusting the soil parameters until the error was minimal and stable. Later, the deep percolation (DP) and runoff curve number (CN) parameters were optimized, and finally, all the parameters were adjusted again. The trial-and-error procedure was ended when differences between the simulated and observed ASW and ET_c values were minimized and did not change from one iteration to the next. The initial and final calibration parameters are shown in Table 4.

2.4.4. The SIMDualKc model performance

Various statistical indicators were used to assess the SIMDualKc model performance. These indicators are detailed in Pereira et al. (2015a, 2015b) and Rosa et al. (2012a, 2012b), and consist of linear regression with 0 interceptions (i.e., Y = bx) between observed and simulated values, which regression coefficient is given in Eq. (5). This indicator was performed to evaluate the accuracy of the model predictions.

$$b_0 = \frac{\sum_{i=1}^{n} O_i P_i}{\sum_{i=1}^{n} O_i^2} \tag{5}$$

When b_0 is close to 1.0, the covariance is close to the variance of the observed values indicating that the predicted and observed values are statistically similar.

In addition, the determination coefficient (R^2), root mean square error (RMSE), mean absolute error (MAE) (Moriasi et al., 2007) and the Willmott (1981) index of agreement (d_{IA}, non-dimensional) that represents the ratio between the mean square error and the "potential error'' were computed (see Eqs. (6–9)).

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \overline{O}) \left(P_i - \overline{P}\right)}{\left[\sum_{i=1}^{n} (O_i - \overline{O})^2\right]^{0.5} \left[\sum_{i=1}^{n} (P_i - \overline{P})^2\right]^{0.5}} \right)^2 \tag{6}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N} (Q_i - P_i)^{20.5}}{N} \right] \tag{7}$$

$$MAE = \frac{\sum_{i=1}^{N} |Q_i - P_i|}{N} \tag{8}$$

$$d_{IA} = 1 - \frac{\sum_{i=1}^{N} (Q_i - P_i)^2}{\sum_{i=1}^{N} (|P_i - \bar{Q}| + Q_i - \bar{Q}} |)x^2 \tag{9}$$

When $d_{IA} = 1$, a perfect agreement between the observed and predicted values are attained and when $d_{IA} = 0$, there is no agreement (Legates and McCabe, 1999; Moriasi et al., 2007).

Other statistical indicators used as defined by Moriasi et al. (2007) and Pereira et al. (2015a, 2015b) are given in Eqs. (10–13) and include (i) ratio of the RMSE to the standard deviation of observed data (RSR) that standardizes RMSE using the standard deviation of observations; with RSR values close to zero indicating a good simulation performance; (ii) the average relative error (ARE, %), which expresses the relative size of estimated errors, (iii) the percent bias (PBIAS) that measures the average tendency of the simulated data to be larger or smaller than their corresponding observations, with low values indicating an accurate model simulation; positive or negative values refer to the occurrence of an under-or over-estimation bias, (iv) modeling efficiency (EF) defined by Nash and Sutcliffe (1970) as a measure of the relative magnitude of the mean square error compared to the measured data variance. The target value for EF is 1.0 while a null or negative value indicates that the mean square error is larger than the observed data variance. A perfect model fit will have $R^2 = d_{IA} \approx 1.0$ and MAE = RMSE≈ 0 (Fandĩno et al., 2015).

$$RSR = \frac{\left[\sum_{i=1}^{n} O_i - P_i)^2\right]^{0.5}}{\left[\sum_{i=1}^{n} O_i - \overline{P})^2\right]^{0.5}} \tag{10}$$

$$ARE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{O_i - P_i}{O_i}\right| \tag{11}$$

$$PBIAS = 100\frac{\sum_{1}^{n}(O_i - P_i)}{\sum_{1}^{n}(O_i)} \tag{12}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2} \tag{13}$$

where O_i and P_i (i = 1, 2,. n) represent pairs of observed and predicted values for a given variable, and $\bar{O}$ and $\overline{P}$ are the respective mean values.

2.4.5. The SIMDualKc modeling of crop evapotranspiration

Using the dual K_c approach under non-stressed and non-limited conditions, the SIMDualKc computes potential daily ET_c using Eq. (14).

$$ET_c = (K_{cb} + K_e)ET_o \tag{14}$$

where K_{cb} is the basal crop coefficient and K_e is the soil evaporation coefficient (dimensionless) computed using Eq. (20). When the crop is water-stressed, a water stress coefficient (K_s) [0 – 1] is introduced on K_{cb}, thus the actual crop evapotranspiration ($ET_{c\ act}$) is computed using Eq. (15) as:

$$ET_{c\ \ act} = (K_s K_{cb} + K_e)ET_o \tag{15}$$

where K_s is the water stress coefficient computed using Eq. (16).

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \qquad K_s = \frac{TAW - D_r}{(1-p)TAW - RAW}\ for\ D_r > RAW \tag{16}$$

$K_s = 1\ for\ D_r \le RAW$, i.e., $K_s = 1$ when D_r is below the readily available water (RAW, mm), and $K_s < 1$ when $D_r >$ RAW (Allen et al., 1998, 2005a).

$$TAW = 1000(\theta_{F,r} - \theta_{W,r})Z_r \tag{17}$$

In the equation, TAW is the total available soil water (mm) computed using Eq. (17) and defined as the soil water storage in the root zone between field capacity and the wilting point, RAW is the readily available soil water (mm), i.e., RAW = pTAW, and p is the soil water depletion fraction for no stress. Z_r is the rooting depth (m).

Further, the SIMDualKc model partitions daily crop evapotranspiration (ET_c, mm d^{-1}) into crop transpiration (T_c, mm d^{-1}) and soil evaporation (E_s, mm d^{-1}) using Eqs. (18) and (19), respectively.

$$T_c = K_{cb}ET_o \tag{18}$$

$$E_s = K_e ET_o \tag{19}$$

where ET_o is the crop reference evapotranspiration (mm), K_{cb} is the basal potential crop coefficient, K_e is the evaporation coefficient measured using Eq. (20). Both K_{cb} and K_e are dimensionless.

2.4.6. Computation of the soil evaporation coefficient (K_e)

Whenever the soil is wet and exposed to radiation, evaporation from the soil is estimated to occur at a maximum rate, thus K_e is also at maximum, subject to the sum $K_c = K_{cb} + K_e$ being limited to a maximum value of crop coefficient ($K_{c\ max}$) that represents an upper limit on the evaporation and transpiration from any cropped surface. Therefore, the SIMDualKc computes evaporation coefficient, K_e using Eq. (20).

$$K_e = K_r(K_{c\ \ max} - K_{cb}) \le f_{ew}K_{c\ \ max} \tag{20}$$

Where summary of the equations (Eqs. (21–28)) used for the K_e calculation (from Allen et al., 1998, 2005a) is given in Table 2.

Table 2
Summary of the equations used for the soil evaporation coefficient (K_e) calculation (from Allen et al., 1998, 2005b).

$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW}\ for\ D_{e,i-1}$ [Kr = 1.0 when D_e < REW, mm). Differently, $K_r < 1$ when De > REW] (21)
$TEW = 1000(\theta)_{FC} - 0.5\theta_{WP})Z_e$ (22)
$K_{c\ \ max} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.04(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, K_{cb} + 0.05\right)$ (23)
$f_c = \left(\frac{K_{cb} - K_{c\ \ min}}{K_{c\ \ max} - K_{c\ \ min}}\right)^{(1+0.5h)}$ (24)
$K_{cb} = K_{cb(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}$ [this eq. applies when RH_{min} differs from 45% and/or where the average u_2 is different from 2 m s^{-1}] (25)
$K_{cb} = K_{c\ \ min} + K_d(K_{cb\ \ full} - K_{c\ \ min})$ [this eq. is used for K_{cb} adjustment to crop density and height. The value for K_c declines when plant density or leaf area falls below full ground cover] (26)
$K_d = \min\left(1, M_{Lfc,fc}^{\left(\frac{1}{1+h}\right)}\right)$ (27)
$few = \min\boxed{f_0}(1 - f_c f_w)$ (28)

where TEW (mm) and REW (mm) are respectively the total and readily evaporable water in the soil surface layer of thickness Z_e (m), $D_{e\ i-1}$ is the cumulative depth of water depleted from the soil surface layer at the end of the previous day, θ_{FC} is soil water content at field capacity [m^3 m^{-3}], θ_{WP} is soil water content at wilting point [m^3 m^{-3}], f_c is the effective fraction of soil surface covered by vegetation [0–0.99], K_{cb} is the value for the basal crop coefficient for the particular day or period, $K_{cb\ (Tab)}$ is the value tabled by Allen et al. (1998, 2007) and Allen and Pereira (2009) for $K_{cb\ mid}$ (and for $K_{cb\ end}$ when $K_{cb\ end} > 0.45$), $K_{c\ min}$ is the minimum K_c for dry bare soil with no ground cover [0.15–0.20], $K_{c\ max}$ is the maximum K_c immediately following wetting, h is the mean maximum plant height during the period of calculation (initial, development, mid-season, or late-season) [m], the exponent '1 + 0.5 h' represents the effect of plant height on shading the soil and increasing the K_{cb} given a specific value for $f_c(K_{cb} - K_{c\ min}) \ge 0.01$ for numerical stability. RH_{min} is the mean value for minimum daily relative humidity during the mid or late season [%], and is $\le 80\%$ when adjusting K_{cb}, K_d is the density coefficient, $K_{cb\ full}$ is the estimated K_{cb} for peak plant growth conditions having nearly full ground cover (or LAI > 3), f_w is the fraction of the soil surface wetted by irrigation or precipitation.

2.4.7. Application of the SIMDualKc for intercropping

Computing a weighed averaged K_c for intercrops as proposed by Allen et al. (1998) does not apply to the dual K_c approach. This is because K_{cb} and K_e, which are the K_c components vary daily and independently from each other for the different crop components (Miao et al., 2016). For this reason, the SIMDualKc model pays particular attention to the fraction of ground cover (f_c), crops height (h), and to the K_{cb} daily evolution through considering the time variation of the density coefficient, K_d (Eq. (29)).

$$K_d = \min\left(1, M_{Lfc,fc}^{\left(\frac{1}{1+h}\right)}\right) \tag{29}$$

where ML [1.5–2.0] is a multiplier on f_c describing the effect of canopy density on shading and maximum relative evapotranspiration per fraction of ground shaded (Allen and Pereira, 2009). For intercropping, it is

Table 3
Model input parameters for the SIMDualKc.

Data input	Parameter
Meteorological data	• Precipitation (mm) • Reference crop evapotranspiration, ET_o (mm) • Wind speed (m s^{-1}) • Minimum relative humidity (%) • Maximum and minimum air temperature (T_{max} and T_{min}, C)
Soil data	• Number of soil layers and soil layer depths, d (m) • Soil water content at field capacity (θ_{FC}, m^3m^{-3}) • Soil water content at the permanent wilting point (θ_{WP}, m^3m^{-3}) • The total available water in the root zone (TAW, mm) • The soil water content at planting in the root zone and the evaporation layer expressed as a % of TAW and TEW, respectively.
Evaporation soil layer	• Thickness of the evaporation soil layer (Z_e, m) • Values of θ_{FC} and θ_{WP} used to compute the total evaporable water (TEW) • Percentage of the textural fractions of sand and clay used for estimating the readily evaporable water (REW)
Deep percolation	• Data taken relative to the soil at saturation and to its draineability as defined by Liu et al. (2006) and Miao et al. (2016).
Crop data	• Dates of the crop growth stages • Crop height (h, m) • Multiplier on ground cover (f_c) describing the effect of canopy density () • Fractions of ground wetted by irrigation (f_w) • Fractions of ground wetted and exposed to radiation (few) for the same crop stages • Basal crop coefficient at initial, mid and end of growth season ($K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$) • The soil water depletion fraction for non-stress, p, at the various growth stages (p_{ini}, p_{mid}, p_{end}) • The rooting depth (m) • The fraction of ground cover by the crop (f_c, %) throughout the crop season.
Intercropping data	• Identification of both crops and their respective fractions, f_r

important to consider the interaction between a dominant and a subordinated crop (Miao et al., 2016). It thus results that one may compute K_{cb} of the intercrop ($K_{cb\ inter}$) using Eq. (30).

$$K_{cb\ inter} = \max[K_{cb\ sub} + K_{d\ dom}(K_{cb\ dom} - K_{cb\ sub}); K_{cb\ dom} + K_{d\ sub}(K_{cb\ sub} - K_{cb\ dom})] \tag{30}$$

where $K_{cb\ dom}$ and $K_{cb\ sub}$ are the K_{cb} values of the dominant and subordinated crops, respectively, and $K_{d\ dom}$ and $K_{d\ sub}$ are the density coefficients for the dominant and subordinated crops. The latter is given by Eqs. (31) and (32), respectively.

$$K_{d\ \ dom} = f_{r\ \ dom}\left(\frac{1}{1+\max(h_{dom} - h_{sub^0})}\right) \tag{31}$$

$$K_{d\ \ sub} = f_{r\ \ sub}\left(\frac{1}{1+\max(h_{sub} - h_{dom^0})}\right) \tag{32}$$

where $f_{r\ dom}$ and $f_{r\ sub}$ are the fractions of the soil surface cropped with the dominant and the subordinated crops, respectively, and h_{dom} and h_{sub} are the heights of the dominant and subordinated crops, respectively (data given in Supplementary Table 2).

The estimation of the depletion fraction for the intercrop (p_{inter}, dimensionless) for no stress is performed as follows: (i) when only one component crop is available in the field, then p_{inter} is that of the considered crop; (ii) during the co-growth period, p_{inter} is estimated as a weighted mean of the p values of both crops. The respective weights consist of the f_r multiplied by the respective K_{cb} value. Thus, p_{inter} is computed using Eqs. (33–35) as:

$$p_{inter} = p_{dom} \quad if \quad Date_{act} < Date_{plant\ \ sub} \tag{33}$$

Table 4
Basal crop coefficients (K_{cb}), depletion fraction for no stress (p), soil evaporation (TEW, REW and Z_e) and deep percolation parameters (a_D, b_D).

		Initial			Calibrated		
		P	LB	DL	P	LB	DL
Crop parameters	$K_{cb\ ini}$	0.48	0.5	0.48	0.41	0.47	0.46
	$K_{cb\ mid}$	1.15	0.9	1.11	1.11	0.88	1.10
	$K_{cb\ end}$	0.4	0.56	0.62	0.40	0.53	0.60
Depletion fractions							
	p_{ini}	0.33			0.33		
	p_{mid}	0.33			0.33		
	p_{end}	0.33			0.33		

		Initial			Calibrated														
					Upper midland					Lower highland					Upper highland				
					P	LB	DL	P-LB	P-DL	P	LB	DL	P-LB	P-DL	P	LB	DL	P-LB	P-DL
	Z_e	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Soil evaporation	TEW (mm)	37	37	37	38	36	36	36	35	38	38	37	36	37	40	38	39	39	41
	REW (mm)	7	7	7	10	9	8	9	8	11	9	10	9	9	10	8	9	9	8
Deep percolation	a_D	390	390	390	360	360	350	350	340	370	360	350	350	360	380	360	380	360	380
	b_D	-0.017	-0.017	-0.017	-0.021	-0.018	-0.017	-0.019	-0.020	-0.018	-0.017	-0.016	-0.016	-0.017	-0.019	-0.017	-0.021	-0.018	-0.017

$K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ refer to the basal crop coefficients for the initial, mid and end season crop growth stages; p_{ini}, p_{mid} and p_{end} – depletion fraction for no stress relative to the initial, mid and end season crop growth stages; Z_e – evaporation layer depth (m), TEW – total evaporable water (mm), REW– readily evaporable water (mm); a_D (mm) and b_D are the parameters of the deep percolation equation (Liu et al., 2006). P– sole potato, LB– sole lima bean, DL – sole dolichos, P–LB – potato–lima bean, P–DL – potato–dolichos.

$$p_{inter} = \frac{p_{dom} f_{c\ dom} K_{cb\ dom} + p_{sub} f_{c\ sub} K_{c\ sub}}{f_{c\ dom} K_{cb\ dom} + f_{c\ sub} K_{c\ sub}} \quad (34)$$

$$p_{inter} = p_{sub} \ \ if \ \ Date_{act} > Date_{harv\ \ dom} \quad (35)$$

where p_{dom} and p_{sub} are the p values of the dominant and subordinated crops, $Date_{act}$ is the current date during the model run, and $Date_{plant\ sub}$ and $Date_{harv\ dom}$ are the planting and harvest dates of the subordinated and dominant crops, respectively. The K_{cb} values are considered as part of the weights to express the possible higher sensitivity to water deficits of one of the crops, particularly during the mid-season.

2.4.8. Soil water balance estimation using the SIMDualKc

The SIMDualKc model computes the daily soil water balance in the crop root zone using Eq. (36).

$$D_{r\ i} = D_{r\ i-1} - R_i - I_{n,i} - CR_i + ET_{c\ act,i} + DP_i + RO_i \quad (36)$$

where $D_{r,i}$ and $D_{r,i-1}$ are the root zone depletion (mm) at the end of days i and $i-1$, respectively, R is rainfall, I is net irrigation, CR is the capillary rise from a shallow water table, $ET_{c\ act}$ is the actual crop evapotranspiration, DP is deep percolation through the bottom of the root zone, and RO is the surface runoff of the non-infiltrated precipitation, all variables expressed in mm and referring to day i. RO is computed using the curve number (CN) method associated with the daily water balance in the soil surface layer. The CR and DP terms are computed using the parametric approaches proposed by Liu et al. (2006), and as described in Rosa et al. (2012a). Model applications involving the computation of both CR and DP are presented in Rosa et al. (2012b), Wu et al. (2015) and Fandĩno et al. (2015). In the present application, the water table was greater than 10 m deep across the sites and CR was null.

2.5. Statistical analyses

The effects of intercropping on tuber and legume grain yield, root length density and soil water balance components (transpiration, evaporation, evapotranspiration, deep percolation, runoff, and soil water storage), were tested using generalized linear models using R software, version 3.5.2 (R Core Team, 2017; Bates et al., 2015). Tukey's honest significant difference (HSD) test was used for treatment mean separations with a threshold probability level set at $p \leq 0.05$. Evaluation of the SIMDualKc performance was done using the statistical indicators described in Section 2.4.4.

3. Results

3.1. Crop cover development

Maximum crop cover differed among the cropping systems and between the agroecological zones (Fig. 4). In the upper midland and lower highland, maximum crop cover was significantly greater in intercropping (62–95%) compared with sole potato stands (48–83%). In the upper highland, maximum crop cover was greater in sole potato (89%) than in potato-dolichos intercropping (74%) and sole dolichos (58%). On average, plots with dolichos recorded remarkably higher crop cover in the upper midland (16–94%) and lower highland (11–95%), and those with lima bean recorded the highest crop cover (12–96%) in the upper highland.

3.2. Root length density

Root length density (RLD) at 0–0.3 m depth was higher in the sole potato stands than in the intercropping stands (Table 5). At 0.3–0.6 m depth, the highest RLD (1854–4146 m m^{-3}) was recorded under potato-lima bean intercropping. This is compared with the sole potato that showed RLD ranging between 246 and 930 m m^{-3}. At 0.6–0.9 m depth in the upper midland, potato-dolichos intercropping showed the highest RLD of 10,326 m m^{-3}. At 90–120 cm depth, RLD ranged between 906 and 972 m m^{-3} for potato-lima bean intercropping compared to 2286–2460 m m^{-3} in potato-dolichos intercropping. Generally, dolichos established higher RLD in the lower highland and upper midland agroecological zones while lima bean showed higher RLD in the upper highland agroecological zone.

3.3. Model calibration

The "goodness-of-fit" indicators used for assessing calibration of the SIMDualKc model against the available soil water content and crop evapotranspiration showed a high level of accuracy with R^2 ranging from 0.85 to 0.93. The calibrated values relative to crop parameters (initial $K_{cb\ in}$, $K_{cb\ mid}$ and $K_{cb\ end}$) were close to the initial/default values irrespective of the agroecological zone and cropping systems (Table 4). Similarly, the initial soil evaporation parameters ($Z_e = 0.15$ m, TEW $= 37$ mm, and REW $= 7$ mm) and those relative to the deep percolation($a_D = 390$ and $b_D = -0.017$) were close to the calibrated values across the cropping systems and agroecological zones.

3.4. Model validation

A good agreement was found between predicted and measured available soil water (ASW) using the SIMDualKc model (Table 6; Fig. 5), with the slope of linear regression ranging from 0.94−1.03 and R^2 of 0.72−0.93. Low estimation errors were obtained for validation with the root mean square error (RMSE) ranging from 0.01 to 0.08 mm d^{-1}, and small RSR ranging from 0.06 to 0.12, and average relative error (ARE) of 3.8–7.8%. The modeling efficiency (EF) was high ranging from 0.80 to 0.94 across the cropping systems and agroecological zones. The values of the index of agreement (d_{IA}) were generally closer to 1, varying from 0.94 to 0.98 across the cropping systems and agroecological zones (Table 7). The percent bias (PBIAS) was very small across the cropping systems and agroecological zones, ranging from − 1.8 to − 5.8%.

The averages of measured and predicted $ET_{c\ act}$ ranged from 1.5−4.3 mm d^{-1} vs 1.3−4.1 mm d^{-1} for sole potato, 1.6−4.6 mm d^{-1} vs 1.5−4.5 mm d^{-1} for sole legumes and 1.9−4.7 mm d^{-1} vs 1.7−4.7 mm d^{-1} for intercrops across the three agroecological zones with goodness-of-fit" of simulated to the observed values close to 1.0 (Fig. 5). Similarly, the "goodness-of-fit" indicators relative to measured crop transpiration and evaporation and the simulated values were close to 1.0 for monocultures and intercrops (Fig. 5). The estimation errors obtained for validation were low with RMSE ranging from 0.02 to 0.09 mm d^{-1}, and small RSR ranging from 0.06 to 0.14, and ARE of 3.2–7.2% (Table 7). The modeling efficiency (EF) was high ranging from 0.82 to 0.97 across the cropping systems and agroecological zones. The d_{IA} values were generally closer to 1, varying from 0.93 to 0.98 across the cropping systems and agroecological zones. The PBIAS was very small across the cropping systems and agroecological zones, ranging from − 2.3 to 1.7%.

3.5. Basal crop coefficients, evaporation, and transpiration components

The K_e, K_{cb} and $K_{cb\ act}$ curves of single cropping and intercropping, as well as evapotranspiration and its components (transpiration, $T_{c\ act}$ and soil evaporation, E_s) are shown in Fig. 6. Across the cropping systems and agroecological zones, the evaporation coefficient (K_e) showed high peaks during the initial, crop development and at the end of the growing season. During the mid-stage, K_e peaks were smaller and quite few and decreased to minimum values during the late-season stages. The K_{cb} and $K_{cb\ act}$ curves were generally coincident across the different cropping systems and agroecological zones. However, for the potato crop grown in the upper midland and lower highland, the $K_{cb\ act}$ curve was more often below the K_{cb} curve. Intercropping tended to have the $K_{cb\ act}$ curves more coincident compared to sole stands of the crops irrespective

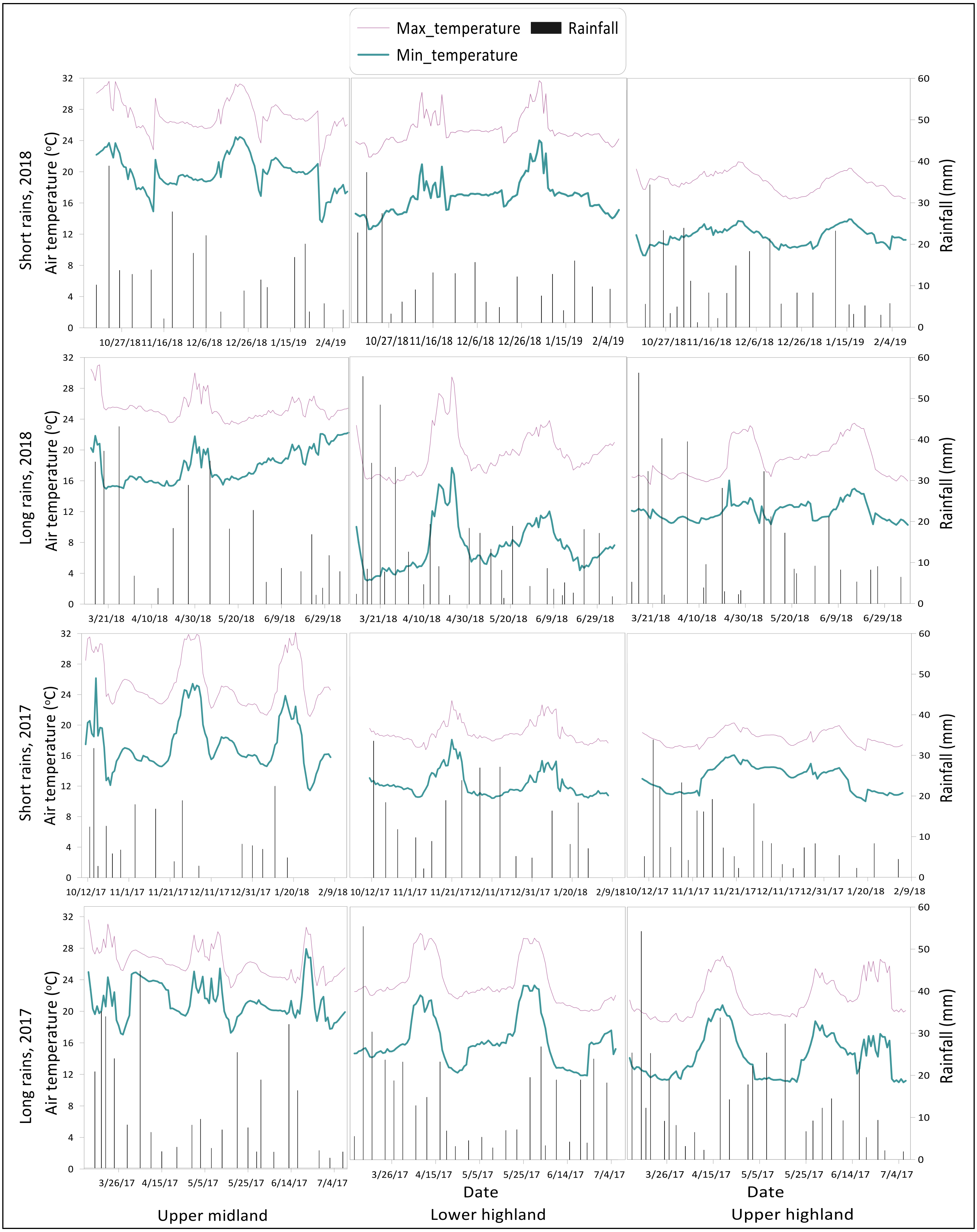

Fig. 3. Daily weather data recorded in the study sites during the crop growth seasons of 2017 and 2018 relative to maximum and minimum temperatures (^{o}C) and rainfall (mm).

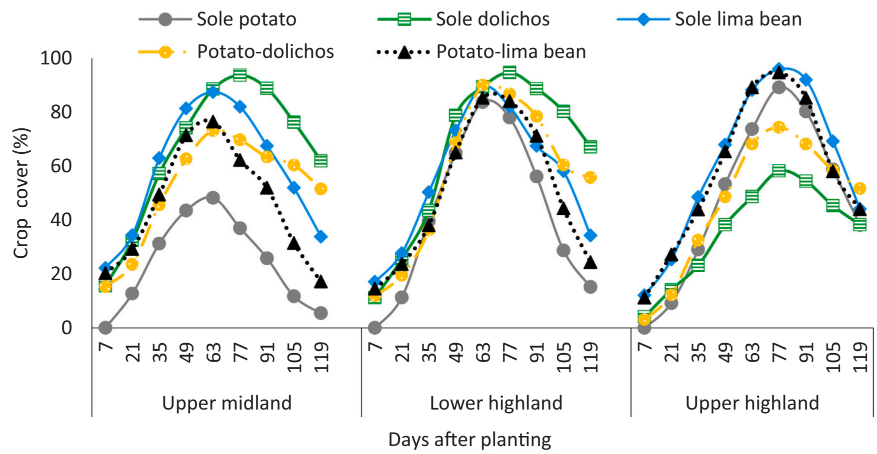

Fig. 4. Changes in vegetal cover by different treatments in the upper midland, lower highland and upper highland agroecological zones. Values are 4 replicates expressed as averages over the four seasons.

Table 5
Changes in crop root length density (m m^{-3}) at tuber bulking stage in different layers of a 1.2 m profile under different cropping systems and agroecological zones.

Agroecological zone	Cropping system	Soil depth (m)			
		0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
		Root length density (m m^{-3})			
Upper midland	Sole potato	5490_B^c	930_A^a	ǂ	ǂ
	Sole lima bean	1950_B^a	9564_C^d	846_A^a	1032_A^a
	Sole dolichos	1470_{AB}^a	1890_B^b	$10{,}326_C^d$	1332_A^b
	Potato-lima bean	2526_C^b	4146_D^c	1566_B^b	906_A^a
	Potato-dolichos	2652_A^b	3870_B^c	5346_C^c	2460_A^c
Lower highland	Sole potato	5886_B^c	606_A^a	ǂ	ǂ
	Sole lima bean	1824_B^a	8706_C^e	660_Aa	906_A^a
	Sole dolichos	1290_A^a	1206_A^b	9804_B^d	1830_A^b
	Potato-lima bean	2886_Cb	3786_D^d	1626_Bb	972_A^a
	Potato-dolichos	2670_Ab	2892_A^c	4206_Bc	2286_A^b
Upper highland	Sole potato	9270_B^d	246_A^a	ǂ	ǂ
	Sole lima bean	5646_C^a	1854_B^c	216_A^a	ǂ
	Sole dolichos	3570_C^b	1230_B^b	192_A^a	ǂ
	Potato-lima bean	6486_C^c	2412_B^d	192_A^a	ǂ
	Potato-dolichos	1950_C^a	1194_B^b	234_A^a	ǂ

Lower and uppercase letters indicate comparisons for means between the cropping systems and soil depths, respectively at $p \leq 0.05$ by Tukey's HSD test. ǂ denotes data not observed. Values are 4 replicates expressed as averages over the four seasons.

of the agroecological zones.

The transpiration rates progressively increased from crop initiation to the mid-season, when the maximum transpiration rate of 2.54–2.96 mm d^{-1} was attained in the sole potato crop compared to 2.86–3.96 mm d^{-1} in the intercrops across the agroecological zones. The maximum E_s ranged from 0.98–1.4 mm d^{-1}, and 0.83–1.34 mm d^{-1} for sole potato and intercropping, respectively, and occurred at about 60–80 days after sowing (DAS) in sole potato and 60–100 DAS for intercrops. Across the agroecological zones, the seasonal $ET_{c\ act}$ for sole potato ranged from 219–283 mm compared to 301–348 mm for intercrops and 329–432 mm for sole legumes (Table 4). The corresponding seasonal transpiration was 100–256 mm, 288–332 mm, and 249–362 mm respectively, while E_s was 26–119 mm, 11–41 mm, and 13–53 mm, respectively. In the upper highland, the seasonal transpiration accounted for a greater component of the $ET_{c\ act}$; 91% of $ET_{c\ act}$ for sole potato, 93–96% for sole legumes and 95–96% for intercropping (Table 8). In the upper midland and lower highland, soil evaporation was an important component of the $ET_{c\ act}$ ranging from 28% to 54% in sole potato, 2–13% in sole legumes and 5–18% in intercrops. Soil evaporation constituted a greater proportion of $ET_{c\ act}$ at the initial stage of crop growth and at the end of the crop growth regardless of the cropping system. Generally, soil evaporation was markedly greater in sole potato relative to intercropping systems. Transpiration constituted a major component of the $ET_{c\ act}$ at the crop development phase. Intercrops showed an increase in crop duration when compared with the same crops grown in sole stands irrespective of the agroecological zone, with potato-dolichos intercropping showing markedly longer duration compared to potato-lima bean intercropping.

3.6. Simulation of the available soil water

In the upper midland and lower highland, the soil water content (SWC) was significantly greater under potato-dolichos intercropping (0.27–0.38 m m^{-3}) than under sole potato (0.24–0.33 m m^{-3}) (Fig. 7). However, in the upper highland, potato-lima bean intercropping exhibited the highest SWC (0.33–0.38 m m^{-3}). Further, in the upper highland, no significant differences were observed for SWC recorded under sole potato (0.28–0.37 m m^{-3}) compared with those under potato-dolichos intercropping (0.3–0.37 m m^{-3}). The observed available SWC falling below the soil water depletion fraction (θ_p) threshold was more frequent in sole potato relative to potato-legume intercropping and was much greater in the upper midland and lower highland than in the upper highland. The regression coefficient for the available SWC varied from 0.91 to 1.03 with a determination coefficient ranging from 0.67 to 0.81.

3.7. Soil water balance

The seasonal soil water balance components of the different cropping systems are presented in Table 9. Evapotranspiration was the main component of soil water balance across the cropping systems and agroecological zones and varied from 219–283 mm in sole potato stands, 301–348 mm in intercropping and 329–432 mm in sole legumes. Rainfall contributed 299 mm, 411 and 470 mm of the soil water input in the upper midland, lower highland, and upper highland, respectively. Soil water storage was significantly greater under intercropping (2.3–10.9 mm) compared with the sole potato (−18 to 5.6 mm). Runoff contributed significantly to the soil water balance in the lower highland

Table 6
"Goodness-of-fit" indicators relative to available soil water of sole crops and potato–legume intercropping.

Agroecological zone	Cropping system	b_0	R^2	RMSE (m^3 m^{-3})	RSR	d_{IA}	PBIAS (%)	ARE (%)	EF
Upper midland	Sole potato	1.01	0.82	0.02	0.07	0.94	-2.1	5.6	0.87
	Sole lima bean	1.02	0.93	0.01	0.06	0.92	-2.0	4.7	0.94
	Sole dolichos	0.98	0.91	0.03	0.08	0.90	-1.8	3.8	0.81
	Potato-lima bean	0.95	0.79	0.05	0.09	0.98	-3.8	7.8	0.83
	Potato-dolichos	0.99	0.82	0.05	0.06	0.97	-3.5	6.6	0.85
Lower highland	Sole potato	1.00	0.81	0.05	0.06	0.95	-2.5	6.6	0.84
	Sole lima bean	1.00	0.85	0.08	0.09	0.97	-1.9	6.8	0.91
	Sole dolichos	0.96	0.82	0.02	0.11	0.98	-2.3	7.3	0.83
	Potato-lima bean	0.94	0.74	0.07	0.12	0.96	-4.3	4.2	0.86
	Potato-dolichos	1.02	0.79	0.05	0.08	0.95	-5.8	5.9	0.82
Upper highland	Sole potato	1.03	0.83	0.11	0.07	0.96	-4.5	4.7	0.81
	Sole lima bean	1.00	0.91	0.04	0.10	0.95	-3.6	5.9	0.90
	Sole dolichos	1.01	0.82	0.06	0.08	0.97	-1.6	6.9	0.80
	Potato-lima bean	0.98	0.72	0.07	0.09	0.98	-4.9	4.8	0.82
	Potato-dolichos	0.94	0.79	0.03	0.08	0.94	-3.9	6.0	0.84

b_0 and R^2 are the coefficients of regression and determination, respectively; RMSE is the root mean square error; RSR is ratio of the RMSE to the standard deviation of measured data; d_{IA} is an index of agreement; PBIAS is the percent bias; ARE is the average relative error; and EF is the model efficiency.

(9.8–55.5 mm) and in the upper highland (38.6–60.2 mm), but was negligible in the upper midland. Similarly, deep percolation contributed significantly to the soil water balance in the upper highland and was significantly greater under sole potato than under potato-lima bean intercropping. Soil evaporation was generally low, not exceeding 13% of $ET_{c\ act}$ under sole legume and intercropping systems (Table 8), but higher for sole potato, with E_s ranging from 9% to 54% of $ET_{c\ act}$. Transpiration was high across the different cropping systems and agroecological zones, ranging from 45% to 96% of the sum of the $ET_{c\ act}$. The variation of the groundwater depths for the period 2017–2018 (Fig. 8) ranged from 10 m during the peak rainfall to 32 m during the critical dry season period. Generally, the water table fluctuated in response to the amount of rainfall received in the study sites.

3.8. Intercropping effect on yield of potato

In the upper midland, sole potato (with 100% potato plants per ha) attained potato yield of 11.4 t ha^{-1}, while potato intercropped with dolichos and lima bean (with 50% potato plants per ha) attained potato equivalent yield of 23.9 and 18.9 t ha^{-1}, respectively (Fig. 9). Similarly, in the lower highland, sole potato attained potato yield of 23.2 t ha^{-1} compared to potato intercropped with dolichos or lima bean that attained potato equivalent yields of 29 and 28.3 t ha^{-1}, respectively. In the upper highland, tuber equivalent yields were significantly greater for potato-lima bean intercropping (34.2 t ha^{-1}) than for potato-dolichos intercropping (28.8 t ha^{-1}). This compared with the 30 t ha^{-1} tuber yield recorded in sole potato.

4. Discussions

4.1. Model performance

The "goodness-of-fit" indicators showed a very good agreement between the measured and simulated available soil water (ASW) and crop evapotranspiration (ET_c) suggesting that the variability of ASW and ET_c were well captured by the model. The low estimation errors obtained for calibration and validation with a small ratio of the RMSE to the standard deviation of observed data (RSR) for ASW and ET_c showed a high accuracy of the model performance. The high modeling efficiency (EF) values across the cropping systems and agroecological zones for ASW and ET_c indicated that the residual variances were much smaller than the measured data variances. The d_{IA} values for AWS and ET_c close to 1.0 across the cropping systems and agroecological zones showed that a nearly perfect agreement between the observed and predicted values was attained. The very small PBIAS values for ASW and ET_c across the cropping systems and agroecological zones demonstrated that no significant under- or over-estimation bias for ASW and ET_c was detected. The small average relative error (ARE) values showed low errors of estimation for the ASW and ET_c. Similarly, the "goodness-of-fit" indicators relative to crop transpiration and evaporation, as well as the observed values close to 1.0 for all simulated sole and intercrops showed that the predicted values were close to those observed, and thus high accuracy of estimation.

The calibrated K_{cb} and p parameters for potato (Table 4) were generally close to those observed in other studies (Allen et al., 1998; Pereira et al., 2021a; Paredes et al., 2018; Zairi et al., 2003; Tasumi and Allen, 2007) suggesting that the dual K_c approach can improve the accuracy of the ET_c estimation when appropriately calibrated base data are used. The $K_{cb\ end}$ values for potatoes were however lower than those reported by Sousa and Pereira (1999) where the very low $K_{c\ end}$ (0.10) was attributed to the natural haulm kill. This is opposed to the present study in which harvesting of potatoes was performed before crop senescence was fully attained. Similarly, the $K_{cb\ end}$ values for potato in this present study (0.4) differed from those reported in Pereira et al. (2021a) for the short season potato, i.e 0.65 but were comparable to that reported for the long season potato (0.35). We were however unable to compare the derived K_{cb} values of dolichos, lima bean and of the intercrops as no studies were reporting the K_{cb} values of these crops. Generally, the authors could obtain only a few papers reporting with high accuracy the derivation of single and basal crop coefficients of legume intercrops for use with the PM-ET_o reference evapotranspiration equation. Most of these studies refer to soybean, chickpea, cowpea, common bean (*Phaseolus vulgaris* L.) and faba bean. Black gram, groundnut, lentil, and pea are mainly the object of single papers while studies on K_c and K_{cb} for dolichos and lima bean are completely unavailable. Nevertheless, the fact that the initial calculated values of dolichos, lima bean and that of potato intercropped with either of the two legumes compared very well with the calibrated values justified the high accuracy of simulations.

The calibrated soil evaporation parameters were close to those given by Allen et al. (1998) for medium-textured soils. Similarly, the calibrated values for the deep percolation parameters a_D and b_D agreed with values proposed by Liu et al. (2006) suggesting high accuracy of estimation. The depletion fraction for no-stress (p) when ET_c is of 5 mm d^{-1} for potato (0.33) also compared well with the values proposed in Allen et al. (1998), i.e., 0.35, but slightly differed from the 0.40 updated by Pereira et al. (2021a) and 0.47 reported by Zairi et al. (2003). These deviations were probably due to the differences in soil water holding characteristics between different soils.

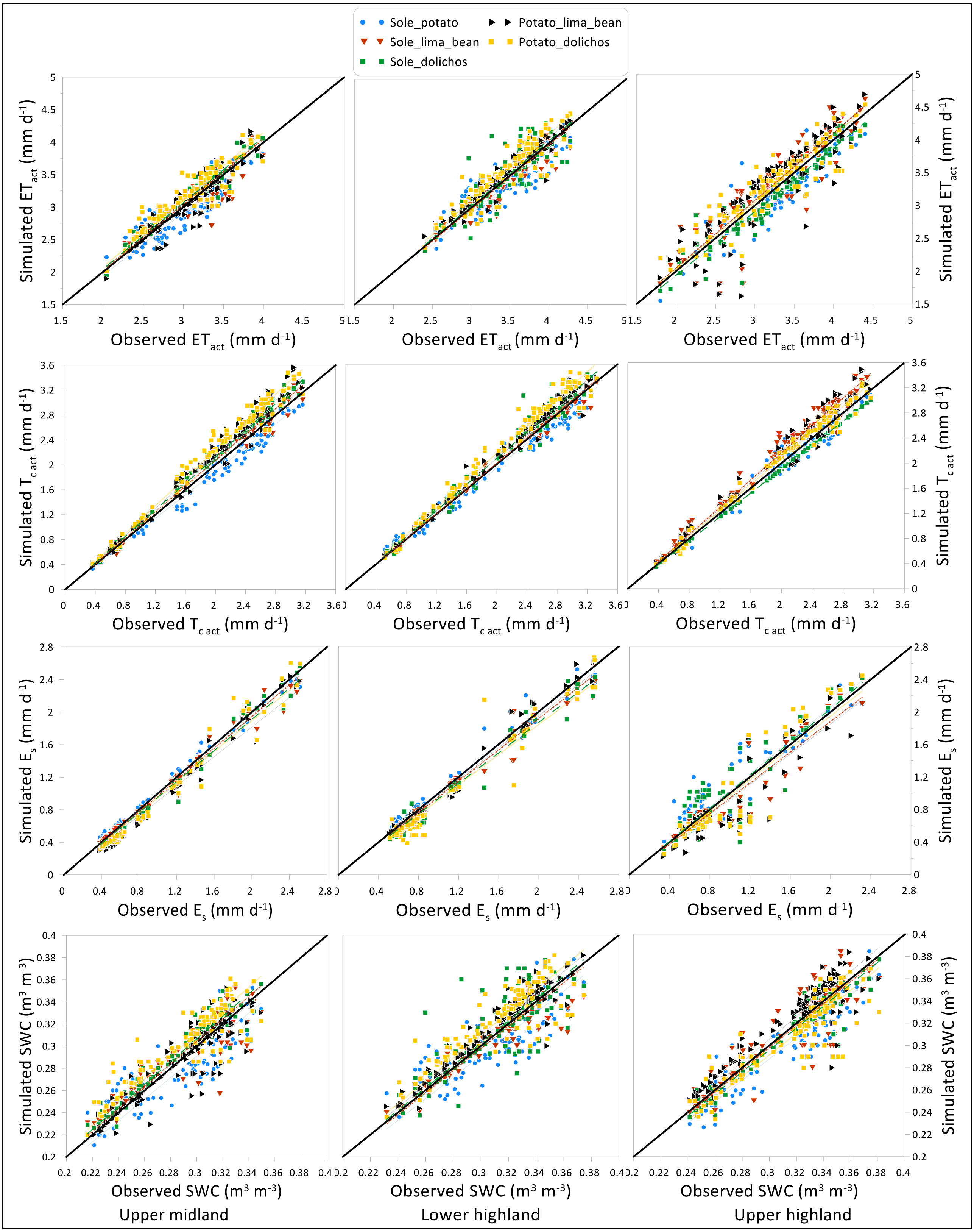

Fig. 5. Observed vs simulated soil water content (SWC), soil evaporation (E_s), actual crop transpiration ($T_{c\ act}$), and actual crop evapotranspiration ($ET_{c\ act}$) for the study sites.

Table 7
"Goodness-of-fit" indicators relative to crop evapotranspiration of sole crops and potato–legume intercropping.

Agroecological zone	Cropping system	b_0	R^2	RMSE (mm d^{-1})	RSR	d_{IA}	PBIAS (%)	ARE (%)	EF
Upper midland	Sole potato	0.98	0.81	0.02	0.12	0.96	-1.1	4.5	0.97
	Sole lima bean	1.01	0.85	0.04	0.09	0.98	1.0	4.7	0.91
	Sole dolichos	0.97	0.92	0.03	0.12	0.97	-1.2	3.2	0.92
	Potato-lima bean	0.89	0.90	0.08	0.08	0.97	-2.2	5.3	0.84
	Potato-dolichos	0.86	0.83	0.07	0.12	0.98	1.2	5.2	0.87
Lower highland	Sole potato	0.95	0.83	0.05	0.07	0.94	-1.3	5.0	0.87
	Sole lima bean	0.99	0.89	0.04	0.12	0.98	-1.7	6.6	0.92
	Sole dolichos	1.00	0.84	0.06	0.10	0.96	1.1	7.2	0.91
	Potato-lima bean	0.89	0.78	0.09	0.14	0.97	-2.3	5.3	0.82
	Potato-dolichos	0.87	0.81	0.08	0.07	0.93	1.4	5.7	0.87
Upper highland	Sole potato	0.98	0.89	0.08	0.08	0.94	-2.1	5.6	0.82
	Sole lima bean	0.97	0.82	0.07	0.13	0.98	-1.6	4.7	0.92
	Sole dolichos	1.01	0.93	0.05	0.06	0.95	1.7	6.9	0.91
	Potato-lima bean	0.95	0.77	0.08	0.08	0.94	-2.0	4.8	0.82
	Potato-dolichos	0.87	0.78	0.08	0.12	0.98	-1.2	5.9	0.85

b_0 and R^2 are the coefficients of regression and determination, respectively; RMSE is the root mean square error; RSR is ratio of the RMSE to the standard deviation of measured data; d_{IA} is an index of agreement; PBIAS is the percent bias; ARE is the average relative error; and EF is the model efficiency.

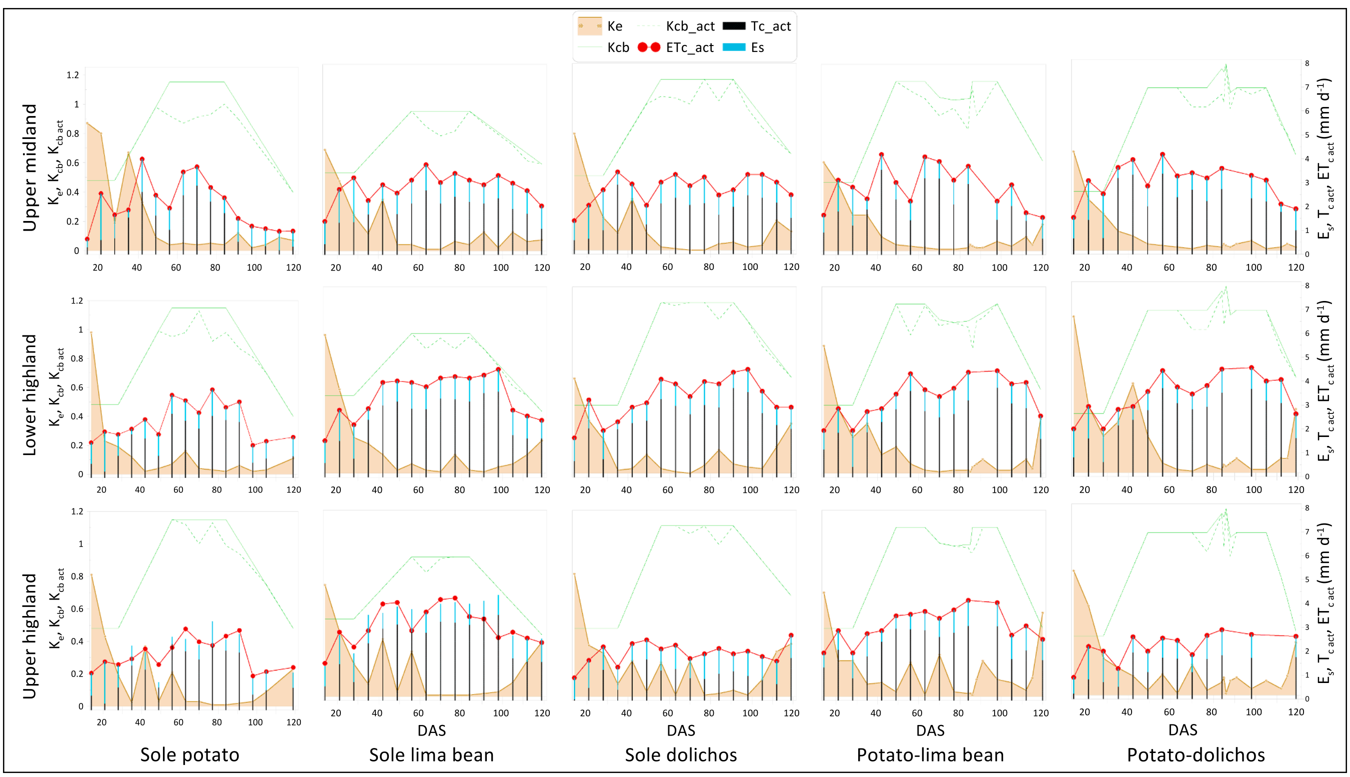

Fig. 6. Seasonal variation of basal crop coefficients (K_{cb}, $K_{cb\ act}$), evaporation coefficient (K_e), soil evaporation (E_s), transpiration ($T_{c\ act}$) and crop evapotranspiration ($ET_{c\ act}$) for the different cropping systems.

4.2. Effect of potato-legume intercropping on ground cover and soil water content

The greater ground cover in intercropping was caused by the larger and nearly vertical leaves exhibited by the legumes which provided complementarity to the slender potato leaves. Ma et al. (2015) observed that potato canopy is characterized by leaf bending, creating bare surfaces between the crop rows which greatly hampers the establishment of crop leaf area and ground cover. The moderately dense canopy by the legumes however closed the inter-row spaces thus enhancing the ground cover development. The variability in ground cover percent between the agroecological zones was related to the differences in air temperature conditions. Potatoes grown under high temperatures, like those recorded in the upper midland in this study, often grow taller with longer internodes, reduced leaf numbers, and are characterized with leaves that are shorter and narrower (Struik et al., 1989). All these affect the potential of ground cover and leaf area index development.

At the initiation stage of crop growth, a more frequent wetting from larger rainfall recharged the soil and increased the soil water content (SWC). The time for the soil surface to dry was determined by the time interval between the wetting events, a factor that was greater in the upper midland that exhibited less frequent rainfall events. The SWC decreased rapidly at crop development stage because the crop was transpiring at an increased rate to maintain the high canopy cover. The amounts of rainfall received at this stage were also generally low. At the mid-growth stage, soil water content decreased rapidly because of the high crop water use necessary to maintain the full canopy cover. The decrease in SWC at this stage was hastened by the decrease in the rainfall

Table 8
The proportion of transpiration and evaporation accounting for seasonal evapotranspiration under different cropping systems and agroecological zones.

Agroecological zone	Cropping system	Seasonal transpiration $\sum T_{c\ act}$ (mm)	Seasonal evaporation $\sum E_s$ (mm)	Seasonal evapotranspiration $\sum ET_{c\ act}$ (mm)	$\sum E_s/\sum ET_{c\ act}$ (%)	$\sum T_p/\sum ET_{c\ act}$ (%)
Upper midland	Sole Potato	100.1a	118.6b	218.7a	54.2b	45.8a
	Sole lima Bean	289.1d	40.6a	329.7b	12.3a	87.7b
	Sole Dolichos	287.5cd	41.5a	329.0b	12.6a	87.4b
	Potato-Lima Bean	247.8b	52.8a	300.6b	17.6a	82.4b
	Potato-Dolichos	263.6bc	42.7a	306.3b	13.9a	86.1b
Lower highland	Sole Potato	197.3a	76.7b	274.0a	27.9b	72.1a
	Sole lima Bean	410.6c	16.4a	427.6bc	3.8a	96.1b
	Sole Dolichos	421.5c	10.5a	432.0c	2.4a	97.6b
	Potato-lima bean	339.5b	22.2a	361.7b	6.1a	93.9b
	Potato-Dolichos	362.3b	17.1a	379.4b	4.5a	95.5b
Upper highland	Sole Potato	256.3a	26.1c	282.4bc	9.2d	90.8a
	Sole lima Bean	332.8c	12.5a	345.3d	3.6a	96.4a
	Sole Dolichos	257.2a	19.7b	276.9ab	7.1cd	92.9a
	Potato-Lima Bean	333.8c	13.2a	347.5d	3.8ab	96.2a
	Potato-Dolichos	290.4b	17.7ab	316.4c	4.7b	95.3a

Letters indicate comparisons for means between the cropping systems at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons.

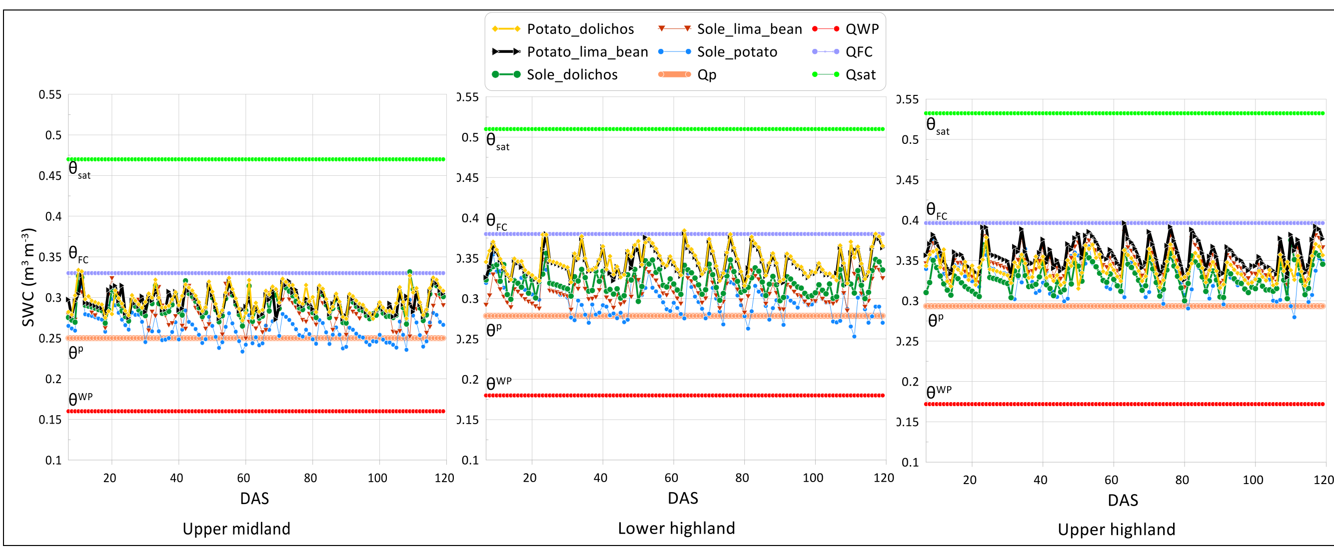

Fig. 7. Mean seasonal variation of the soil water content (SWC) under different cropping systems in the three study sites simulated using the SIMDualKc. θ_{sat}-SWC at saturation, θ_{FC}-SWC at field capacity, θ_{WP}-SWC at wilting point, θ_p-SWC at the depletion fraction for no-stress p.

amount received across the agroecological zones. At the end of the season, the low SWC was primarily due to the high evaporation rates following the attainment of full leaf senescence. van Donk et al. (2010) observed that bare soil left after crop senescence permits maximum absorption of solar radiation, which provides an ultimate energy source for soil evaporation.

The soil water content dropped more often below the depletion fraction threshold in sole potato as the drier soil made it more difficult for the crop to extract moisture. Under these circumstances, limited soil water supply exerted a controlling influence on soil evaporation. Generally, in the sole potato plots, soil evaporation rate decreased as the soil surface dried out over time. This was because water that was deeper in the soil was not transported to the surface quickly enough to maintain the rate of wet-soil evaporation. In the sole legumes and intercropping where the soil surface was covered with a high vegetal cover, the soil was shielded from direct solar radiation which reduced the soil evaporation rates. Moreover, the deep root systems exhibited by lima bean and dolichos increased the capacity of the crops to extract water from the subsoils. In the upper highland, however, the rainfall amounts were abundant, filling the soil profile to values above field capacity, and thus leading to deep percolation irrespective of the cropping systems. Therefore, the SWC was often above the depletion fraction threshold in this zone. At the end of the season when there were no more rains, the SWC decreased rapidly and reached the lowest limit across the agroecological zones.

4.3. *Intercropping effect on crop coefficient (K_{cb}) and evaporation coefficient (K_e)*

The legume intercrops used in this study generally fully shaded the ground by mid-season, thus limiting the energy available for soil evaporation in comparison to potato that took more than 45 days to develop full crop cover. The mid-season stage was relatively longer for dolichos and potato-dolichos intercropping due to the longer growth duration of

Table 9
Water balance component of potato-legume intercropping at maximum root depth.

Agroecological zone	Cropping system	ΔSWC	Rainfall	I	$ET_{c\ act}$	$T_{c\ act}$	E_s	Runoff	DP
		mm							
Upper midland	Sole potato	-18.0a	298.7	92.1	218.7a	90.1a	103.1b	14.4e	32.5c
	Sole lima bean	22.2c	298.7	92.1	329.7b	284.1d	40.1a	6.7d	16.7b
	Sole dolichos	25.4c	298.7	92.1	329.0b	285.5cd	41.0a	3.8bc	14.3b
	Potato-lima bean	3.6b	298.7	92.1	300.6b	243.8b	50.6a	2.4ab	15.6b
	Potato-dolichos	2.3b	298.7	92.1	306.3b	261.1bc	42.2a	5.6cd	10.7a
Lower highland	Sole potato	-3.4a	411.1	71.9	274.0a	190.3a	76.7b	55.5d	66.4e
	Sole lima bean	28.8c	411.1	71.9	427.6bc	409.1c	16.0a	15.5b	22.3b
	Sole dolichos	29.2c	411.1	71.9	432.0c	419.2c	10.8a	9.8a	12.3a
	Potato-lima bean	6.2b	411.1	71.9	361.7b	337.5b	22.6a	23.3c	48.9d
	Potato-dolichos	6.5b	411.1	71.9	379.4b	360.2b	17.3a	17.7b	33.7c
Upper highland	Sole potato	5.6a	469.7	14.6	282.4bc	253.1a	26.4c	60.2c	94.7d
	Sole lima bean	14.3c	469.7	14.6	345.3d	330.7c	12.3a	44.7b	46.3a
	Sole dolichos	9.8b	469.7	14.6	276.9ab	253.1a	19.1b	71.1d	84.4c
	Potato-lima bean	10.9b	469.7	14.6	347.5d	332.5c	13.0a	38.6a	40.9a
	Potato-dolichos	9.5b	469.7	14.6	316.4c	293.6b	17.1ab	68.1d	64.4b

$ET_{c\ act}$, actual evapotranspiration; I, net irrigation depth; $T_{c\ act}$, actual crop transpiration; E_s, soil evaporation; SWC, variation in stored soil water; DP, deep percolation. Letters indicate comparisons for means between the cropping systems at $p \leq 0.05$ by Tukey's HSD test. Values are 4 replicates expressed as averages over the four seasons.

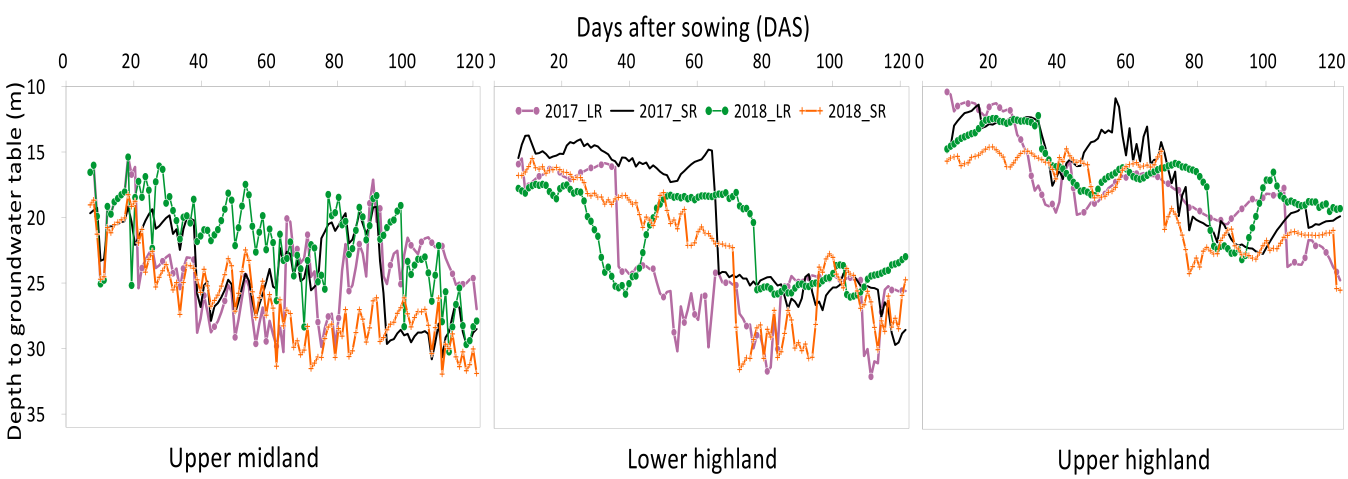

Fig. 8. Time variation of the groundwater table depths along 2017–2018 crop seasons in the three study sites.

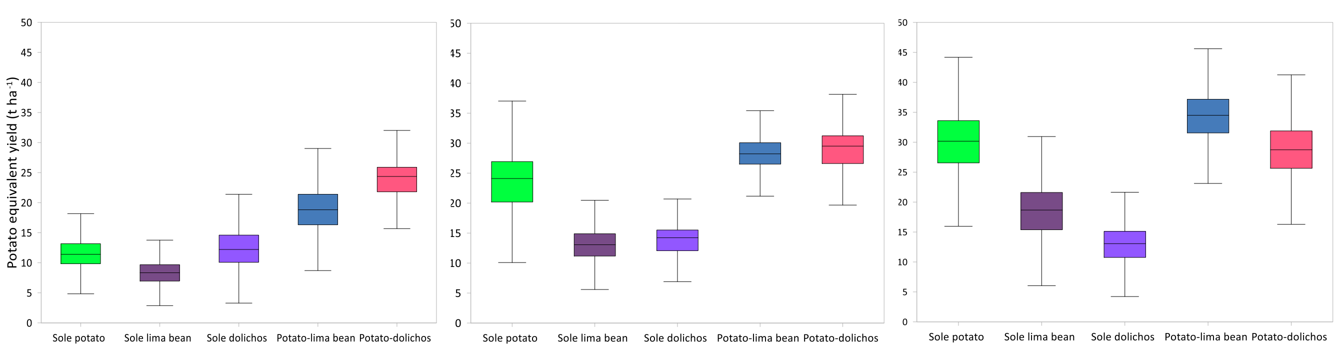

Fig. 9. Potato and legume yields expressed in potato equivalents (PEY, t ha^{-1}) in the three study sites (upper midland, lower highland and upper highland agro-ecological zones). Values are 4 replicates expressed as averages over the four seasons. The horizontal lines in the box plots indicate the mean PEY, the box indicates the upper and lower quartiles, while the vertical lines represent the minimum and maximum values.

dolichos but was relatively short for sole potato and lima bean that exhibited a shorter growth period. Generally, the K_{cb} values during the initial period ($K_{c\ ini}$) were larger when the soil was wet from rainfall and was low when the soil surface was dry. The K_{cb} coefficient at the mid-stage (full cover) primarily reflected the differences in transpiration, as the contribution of soil evaporation was relatively small across the cropping systems.

The differences in $K_{cb\ end}$ values mostly depended on the crop management decisions relative to harvesting. There were generally difficulties relative to assuming an adequate value for $K_{cb\ end}$ and this stemmed from the fact that K_{cb} for the end season was often replaced by a K_{cb} value relative to the late season/maturity, or daily K_{cb} values. At the end of the season when the soil surface was dry, evaporation was restricted and $K_{cb\ act}$ was reduced across the cropping systems. The $K_{cb\ end}$ value was high in the upper highland across the cropping systems because wetting from rains was more frequent until harvest. In the upper midland where the crops senesced much earlier before harvest, the $K_{cb\ end}$ value was small. Generally, senescence is associated with less efficient stomatal conductance of leaf surfaces because of ageing, thereby causing a reduction in the K_{cb} (Allen et al., 1998).

Across the agroecological zones, the increase in plant density under intercropping coupled with taller canopy height caused the K_{cb} factor to be larger than that of the sole crop. The K_{cb} values for the intercrops remained nearly constant when potato was at its initial and early stage of crop development, i.e., when $h_{potato} < h_{legume}$, increased when potential K_{cb} for both potato and legume were close to their maxima, attaining peak at potato mid-season when $K_{cb\ potato} > K_{cb\ legume}$. After that short peak period, K_{cb} values decreased due to the senescence of potato, with $K_{cb\ legume} > K_{cb\ potato}$. When potato was harvested, the K_{cb} value for the intercrops became governed only by the legume crop, resulting in reduced K_{cb} values from the late season, becoming lowest when the legumes attained maturity and started to senesce. A similar trend was reported by Miao et al. (2016) for spring wheat–maize and spring wheat–sunflower relay intercropping using the SIMDualKc crop coefficient approach. The coincident of K_{cb} and $K_{cb\ act}$ curves for potato-legume intercropping in the upper highland, except for a few days at the mid-season, denoted lack of significant water stress.

For the three crops used in this study, the behavior of the K_e curve showed similarity with those reported in other studies (Miao et al., 2016; Zhang et al., 2013; Paredes et al., 2018), and is typical of a dry climate, with scarce precipitation, and where irrigation depths are large and few. The evaporation coefficient (K_e) trend denoted few but large peaks for all crops during the initial growth stage, when the soil coverage by the crop was quite reduced and more energy was available at the soil surface for evaporation. Further, the frequent rainfall events at this time led to greater K_e peaks as more water was available for evaporation loss. The K_e peaks became smaller during the mid-season when the fraction of soil covered by vegetation (f_c) was high ($f_c > 0.80$). In the upper midland under sole potato, heavy water stress was observed right from the mid-season to harvest as depicted by the $K_{cb\ act}$ below the K_{cb}. Contrastingly, the intercrops showed only mild stress during the mid-season stage due to the high fraction of soil covered by vegetation. The reduction in K_e peaks at the crop development stage across the cropping systems and agroecological zones was because of the gradual increase in canopy cover that lowered the energy available for soil evaporation. In the late-season, K_e peaks were much smaller because soil cover was nearly complete, and rainfall had nearly ceased. Less energy was therefore available at the soil surface for evaporation. Differences in K_e peaks between cropping systems were generally small, mainly relating to the crop stage dates. The relatively greater K_e peaks in the upper highland compared to the lower highland and upper midland agroecological zones reflected the less frequent occurrence of heavy precipitation in the latter zones.

4.4. Effect of potato-legume intercropping on crop evapotranspiration

The greater contribution of E_s to $ET_{c\ act}$ observed at the initial stage of crop growth irrespective of the agroecological zones and cropping systems was because the soil was nearly bare at this stage and the available radiation energy at the soil surface was at its maximum. Thus, the wettings by rainfall kept the soil water available for evaporation. The smaller $E_s/ET_{c\ act}$ observed at crop development and mid growth stages across the cropping systems were due to the increase in the fraction of soil covered by vegetation. This reduced the energy available at the soil surface to convert the moisture into vapor. Maximum representation of ET_{act} by $T_{c\ act}$ at the mid-season was because the ground was nearly fully covered.

The higher evaporation in the sole potato relative to intercropping was due to the bare soil in the inter-row that allowed more energy to become available at the soil surface for evaporation. At the end of the season after many days without rain, the evaporation from the sole potato and intercropping was similar. This is because the large interval between rainfall events lowered the ability of the soil to conduct moisture across the cropping systems which caused the water content in the topsoil to drop and the soil surface to dry out. van Donk et al. (2010) showed that evaporation on a bare soil became almost identical to that covered with crop residues when evaporation was permitted for a sufficiently long time without rewetting the surface.

The $ET_{c\ act}$ was similar between the cropping systems at crop initiation which was consistent with the soil water content and E_s which also indicated similarity between sole potato plots and those of potato-legume intercropping. As the crop developed canopy and shaded more of the ground, evaporation became more restricted, and transpiration gradually became the major process across the cropping systems and agroecological zones. The relatively high $ET_{c\ act}$ at the mid-stage of potato growth was because of the bigger plants transpiring at higher rates. The latter observation was also partly related to the greater evaporation occurring at the bare surfaces of the inter-row spaces. In intercropping, the overlapping canopy closed the inter-row spaces, making transpiration the main component of $ET_{c\ act}$.

The crop evapotranspiration rates increased significantly in intercrops at the mid-stage possibly because root development of the component crops improved, thus enhancing subsoil water extraction. In related studies, enhanced canopy formation in intercropping has been found to enhance sunlight retention, aerodynamic canopy roughness, and micro advection energy thus increasing crop evapotranspiration rates (Nyawade et al., 2019). Miao et al. (2016) observed that intercropping promotes crop physiological development ultimately increasing crop evapotranspiration rates. At maturity, especially after rainfall events, the contribution of E_s to $ET_{c\ act}$ was predominant across the cropping systems because the crop cover was small and scarcely shaded the ground.

The differences in evapotranspiration rates between the sites were primarily due to the differences in agro-climatic conditions. In the upper midland and lower highland, the comparatively lower $ET_{c\ act}$ across the cropping systems was because of the drier soil which made it more difficult for the crop to extract water. In the upper highland, the variation of $ET_{c\ act}$ was mainly a factor of $T_{c\ act}$ as soil evaporation only accounted for a small portion of $ET_{c\ act}$ and decreased with days after sowing and increasing fraction of the soil covered by vegetation. Generally, in this zone (the upper highland), the soil was wet for most of the time from more frequent rain. This increased the transpiration rate relative to what was observed in the lower highland and upper midland.

4.5. Soil water balance component of potato-legume intercropping

The soil water balance parameters observed in this study compared well with those reported in other studies (Paredes et al., 2018; Ren et al., 2018). Cumulatively, the seasonal $ET_{c\ act}$ was significantly greater in intercrops as this system exhibited an increase in crop duration when compared with the sole crops. We attribute this observation to a short overlapping period between the growing cycles of the component crops. This observation perpetuated transpiration and increased the cumulative $ET_{c\ act}$. Choudhury et al. (2007) estimated the seasonal dry-seeded rice evapotranspiration loss and found that intercropping extended the period of effective crop evapotranspiration rates. The lower crop cover and soil moisture under sole potato was a major contributor to the lower $T_{c\ act}/ET_{c\ act}$ relative to potato-legume intercropping. For the legume intercrops, the deep taproot system extracted the subsoil water, thus keeping evapotranspiration rates high with little impact on the topsoil water. The increased canopy under intercropping also increased the transpiration component of evapotranspiration and enhanced the crop water use. Bachand et al. (2013) reported that transpiration accounts for 50–90% of total $ET_{c\ act}$ during a growing season in intercropping systems.

The contribution of soil water stored in the soil was negligible in the upper midland because the rainfall amounts received in this zone were small compared to that received in the lower highland and upper highland. The high runoff recorded in the upper highland at the onset of the seasons was due to the more frequent heavy rains, exceeding 30 mm per event. The contribution of runoff was greater under sole potato than under intercropping because the intercrops achieved a dense canopy that intercepted and reduced the raindrop-hitting force. This slowed down the velocity of runoff. Generally, when the rainfall exceeded infiltration rates, a higher proportion of rainfall not intercepted was routed to surface runoff or recharged to the groundwater reservoir.

4.6. Intercropping effect on yield of potato

When the yields were expressed in potato equivalent, intercropping showed a marked increase in yield over sole potato. Generally, the legume intercrops exhibited deeper taproots that recaptured the percolated water, absorbing it more efficiently and converting it into crop biomass. This reduced resource overlap allowing the potato intercrops to consume the topsoil water. The greater yield due to intercropping may also be explained by the fact that transpiration occurred near its potential rate, thus not limiting yields. Similar observations have been documented in other studies (Tolk et al., 1999; Klocke et al., 2009).

The low moisture contents under sole potato suppressed tuber yields, especially in the upper midland. This is because low moisture promoted haulm growth at the expense of tuber growth and therefore much pool of starch available for tuber growth was directed to the shoot. Generally, as soil water reduces, the rate of respiration increases while photosynthesis rate reduces (Chaves et al., 2002). This suggests higher respiration of starch to sustain plant growth rather than it being stored in tubers. In the upper midland, the low soil water content under sole potato extended to the stolon development phase of potato growth. This greatly hindered stolon formation thus affecting the total number and weight of tubers formed. Accordingly, when water stress coincided with tuber maturation in the upper midland, this hastened leaf senescence and interrupted leaf formation thus resulting in unrecoverable loss of tuber bulking. As crop cover increased under intercropping, its insulating capacity on the soil increased thus minimizing the amount of water lost to surface evaporation. Thus, a substantial amount of water was used for transpiration. Moreover, for the legume intercrops, the effects of water stress were mediated in part by the deep taproots that extracted moisture from the deep soil layers. This moisture was used to meet the crop evapotranspiration demand contributing to increased yields.

5. Conclusions

The "goodness-of-fit" indicators used for assessing calibration and validation of the SIMDualKc suggested that the model captured well the variability of data with no bias. Generally, the actual basal crop coefficient values calibrated compared well with the literature and computed values. This therefore allows the SIMDualKc model to assume its appropriateness for evapotranspiration simulations under potato-legume intercropping. Soil evaporation exhibited a smaller fraction of the actual crop evapotranspiration under intercropping, making the actual transpiration a greater fraction of the crop evapotranspiration. This suggests that the rate of transpiration occurred near its potential, thus increasing crop yield without advesre effect on soil water balance. This was further evident with the fact that the actual basal crop coefficient was less than basal crop coefficient for only a few days under intercropping showing that this system was able to reduce water stress. Moreover, the greater root biomass contributed by legume intercrops in deeper soil layers enhanced interception of soil water, enabling potato to utilize the topsoil moisture with little competition. Modification of microclimatic conditions in this manner could be an effective measure to adapt potato to the midland elevation agro-food systems and therefore expand the area under potato production in the tropical highlands. Future applications of the dual coefficient approach need to consider remote sensing observations, particularly in defining crop growth stages at given locations. In addition, crop coefficient and basal crop coefficient values of additional legume intercrops should be scrutinized and updated in the literature.

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Conflict of interests

The authors declare that they have no competing interests in this paper and the study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2021.108327.

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