Estimating evapotranspiration and determining crop coefficients of irrigated sweet potato *(Ipomoea batatas)* grown in a semi-arid climate

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Highlights

- Daily sweet potato water use was highly affected by changes in canopy cover and weather conditions.
- Time-average crop coefficients were derived for each growing period.
- A heat unit based thermal time – crop coefficient equation was successfully developed and tested.

Abstract

Accurate quantification of crop water use or evapotranspiration (ET) is crucial in agriculture for improved irrigation scheduling and water resource planning across a wide range of farming conditions. The aim of this study was to quantify ET dynamics for irrigated sweet potato (*Ipomoea batatas*) in order to determine the FAO-type single crop coefficients (K_c) that can be used in models to estimate crop water use under a wider range of semi-arid climatic conditions. An open-path eddy-covariance system containing energy balance sensors was installed in a 1.3 ha field to estimate ET of orange-fleshed sweet potato. The study was conducted during the 2014/15 and

2015/16 growing seasons. Daily ET varied between 0.5 and 5.5 mm (linked closely to canopy cover and weather conditions), with total seasonal measured ET of 361 and 347 mm for the 2014/15 and 2015/16 seasons, respectively. Time-averaged K_c values of 0.47 for the initial stage, 0.97 for the mid-season stage and 0.44 for the late growth stage were derived from this study. In addition, a heat unit based Growing Degree Days - K_c equation was successfully developed and validated in this study to adjust K_c values of sweet potato to specific climates. These K_c values can be used in combination with the FAO-56 reference evapotranspiration (ET_o) to estimate site-specific sweet potato ET, vital for improving water management of irrigated sweet potato cropping systems growing under semi-arid conditions.

Graphical abstract

An open-path eddy-covariance system containing energy balance sensors was installed in a 1.3 ha field to estimate ET of orange-fleshed sweet potato. The study was conducted during the 2014/15 and 2015/16 growing seasons. This is the first study of its kind in South Africa, and first on locally developed OFSP cultivar 'Bophelo'. The average seasonal ET obtained was 356 mm. The time-average Kc values were 0.47 during the initial stage (39 days), 0.47 – 0.97 during the development stage (25 days), 0.97 during middle stage (25 days) and 0.44 during late growing stage (25 days). A heat unit based thermal time equation was successfully developed and validated using three-day running average Kc values.

Keywords: Crop coefficients, eddy covariance, FAO-56, irrigation scheduling.

1. Introduction

Sweet potato (*Ipomoea batatas*) is cultivated in more than 100 countries worldwide, mostly throughout tropical and subtropical Asia and Africa, in hot semi-arid climatic regions where air temperatures are relatively high (DAFF, 2011). Orange fleshed sweet potato (OFSP) is commonly grown for its edible storage roots, which contain high levels of β-carotene, iron (Fe) and zinc (Zn). According to the latest statistics, the area under sweet potato production in South Africa is approximately 2000-3500 ha (DAFF, 2015). Although white-fleshed sweet potato (WFSP) is the most produced cultivar due to its ability to attain higher marketable yields, its β-carotene level (the major precursor of vitamin A) is significantly lower compared to OFSP cultivars (Motsa et al., 2015, Low et al., 2017). As a result, OFSP is becoming increasingly popular in a number of countries worldwide including South Africa, especially amongst the smallholder farmers in rural areas, as its consumption can play an important role towards improving human diet and alleviating malnutrition (Burri, 2011, Tanumihardjo et al., 2017). Sweet potato is planted mainly in the rainy season, and is considered as a drought tolerant crop (Motsa et al., 2015).

Several studies have investigated on the water use or evapotranspiration (ET) of sweet potato using a simple soil water balance method (Gomes and Carr, 2003; Laurie et al., 2009; Beletse et al., 2011; Jovanovic and Israel, 2012; Laurie et al., 2012; Lewthwaite and Triggs, 2012; Beletse, 2013; Masango, 2014; Prabawardani and Suparno, 2015; Nyathi et al., 2016). When determining crop ET using the soil water balance method, components such as runoff, deep percolation, subsurface flow and water brought by capillary rise are often ignored (Goldhamer et al., 1993; Rana and Katerji, 2000). Ignoring such components can result in inaccurate estimations of the crop ET (Rana and Katerji, 2000). According to the above-mentioned studies, the ET rates of both WFSP and OFSP were widely variable, affected by several factors including weather conditions and crop management practices. As a result, more site-specific estimations of sweet potato ET and crop coefficients are crucial for the estimation of water use of the crop under semi-arid climatic conditions.

According to Jovanovic and Annandale (1999), often the most accurate way of estimating ET is achieved through direct physical measurements, such as energy flux measurements using an eddy covariance system. Therefore, quantifying sweet potato water use directly using such a system, under optimal crop management conditions, will contribute useful information on the water requirements and irrigation water management of this crop. Since the sweet potato ET measurements are highly variable, estimates from the eddy covariance system can be used to determine crop coefficients (K_c). The eddy covariance estimates will enable the extrapolation of site-specific measurements to various climates using modelling approaches such as the FAO-56 single crop coefficient and heat unit based Growing Degree Days (Allen et al., 1998). This will assist in improving water resource planning and irrigation water management of sweet potato production across a wide range of climatic conditions.

2. Materials and Methods

2.1. Site description and agronomic practices

The study was conducted at the Roodeplaat Experimental Farm of the Agricultural Research Council, Vegetable and Ornamental Plants (ARC–VOP) (25°35’N, 28°21’E, 1164 meters above sea level (masl)) in Gauteng Province, South Africa. Field trials were conducted in two successive summer growing seasons (January to May), viz., 2014/15 and 2015/16. The region experiences summer rainfall, with an average of about 650 mm per annum (Jovanovic and Annandale, 1999). The study area has a semi-arid climate, with average daily air temperatures ranging from 8–34°C in summer and 4–23°C in winter (Beletse et al., 2013). Prior to commencement of the trial in each growing season, soil samples for the first 30 cm topsoil were collected and sent for laboratory analyses at the Institute for Soil, Climate and Water of the ARC. This was done in order to determine chemical and physical properties of the soil at the study site (Table 1). The soil at the study site is classified as a Hutton soil form (Soil Classification Working Group, 1991), with a loamy texture.

Table 1. Soil chemical and physical properties for the first 0.3 m topsoil at the study site during the 2014/15 and 2015/16 growing seasons.

Chemical elements	**Units**	**2014/15**	**2015/16**
Phosphorous (P)-Bray 1	mg kg^{-1}	21.1	32.6
Potassium (K)	mg kg^{-1}	238.9	185.0
Calcium (Ca)	mg kg^{-1}	1556.2	1215.3
Magnesium (Mg)	mg kg^{-1}	546.5	413.2
Sodium (Na)	mg kg^{-1}	17.8	32.7
Iron (Fe)	mg kg^{-1}	6.4	5.1
Zinc (Zn)	mg kg^{-1}	7.48	6.04
Ammonium-nitrogen (NO_4-N)	mg kg^{-1}	1.89	1.92
Nitrogen (N)	%	0.043	0.032
Nitrate-nitrogen (NO_3-N)	mg kg^{-1}	1.41	4.86
pH (H_2O)	–	7.18	6.98
Physical properties			
Sand	%	56.7	
Silt	%	13.4	
Clay	%	28.35	
Field capacity	m^3 m^{-3}	0.25	
Permanent wilting point	m^3 m^{-3}	0.13	

Inorganic fertilisation was applied based on the soil analysis results. At planting, 216 kg N ha^{-1} [limestone ammonium nitrate (LAN)], 75 kg P ha^{-1} [superphosphate, (10.5%)] and 180 kg K ha^{-1} (potassium chloride) were broadcasted and incorporated in the 2014/15 growing season, while 212 kg N ha^{-1}, 53 kg P ha^{-1} and 216 kg K ha^{-1} in 2015/16 season. Top dressings of 100 kg N ha^{-1} and 200 kg K ha^{-1} were applied in the first season and 100 kg N ha^{-1} and 150 kg K ha^{-1} in the second season, after 21 days of planting. The fertiliser forms used were N:P:K 1:0:1 (36) and superphosphate (10.5%) at planting, and LAN (28%) and KCl (50%) for top dressing.

The trial size was 130 m × 100 m (13 000 m^2). In both growing seasons, the trial was planted with cuttings of OFSP cultivar 'Bophelo'. Planting was done on the 12th of January during the 2014/15 season and 11th of January during the 2015/16 season. The cultivar 'Bophelo' was chosen due to its superior nutritional value and linked potential in alleviating malnutrition. The cultivar is also becoming popular among South African farmers. In both seasons, 0.3 m OFSP cuttings were manually planted at a planting density of 35 507 plants ha^{-1} on ridges, which were 1.4 m apart. For each ridge, two rows of plants were planted at a spacing of 0.4 m between plants.

Dragline sprinklers were used to irrigate the trial, at a flow rate of 15 litres per hour. Neutron probe access tubes, as well as Chameleon moisture sensors (Stirzaker et al., 2017), were installed at six different positions in the field for irrigation scheduling monitoring. Plant available water (PAW) was determined using the following equation (Allen et al., 1998):

$$PAW = (FC\text{-}PWP) \times RD \tag{1}$$

where PAW is plant available water (mm), FC is field capacity (m^{3}m^{-3}), PWP is permanent wilting point (m^{3}m^{-3}) and RD is rooting depth (mm).

A volume of 20 mm of irrigation was applied immediately after the cuttings were planted, and subsequently the crop was irrigated once a week to FC to ensure that more than 50% of PAW was never depleted. Weeds were controlled manually between rows and ridges until the ground was fully covered by the crop canopy. The crop was grown under water and nutrient non-limiting conditions, and kept free of pests and diseases during both experimental seasons.

2.2 Data collection

2.2.1 Eddy covariance system setup and data recording

The EC 150 (Campbell Scientific Inc., Logan, Utah, USA) was used to estimate ET directly and indirectly using the shortened energy balance equation. Three dimensional wind velocity and temperature fluctuations were measured using a CSAT3 sonic anemometer (Campbell Scientific Inc., Logan, Utah, USA). Water vapour concentration was measured using a fast-response EC 150 CO_2 / H_2O open-path gas analyser (Campbell Scientific. Inc., Logan, Utah, USA) as part of the EC system. All EC data were logged at 30 minute intervals, with subsequent storage in a CR5000 data logger (Campbell Scientific Inc., Logan, Utah USA).

Additional sensors including an NR-Lite net radiometer (Kipp and Zonen, delft, The Netherlands), thermocouples, a time domain reflectometer (TDR) and soil heat flux plates were used for measuring the remaining components of the energy balance in order to complete the energy balance equation. All sensors were installed at a height of 1.3 m above the 0.1 – 0.5 m canopy height, on a tower which was situated around the middle of the plot, but closer to the one end where the prevailing wind dominates. This was done to obtain enough fetch for the EC measurements in order to improve the energy balance closure. Four soil heat flux plates (HFT-S, REBS, Seattle, WA) were installed at the depth of 0.08 m below the soil surface and thermocouple soil temperature averaging probes were installed at the depths of 0.02 and 0.06 m to measure the heat stored above soil heat flux plates. Volumetric soil water content for the top 0.20 m soil was measured using two CS616 probes.

The EC system estimates sensible heat fluxes (*H*) based on measurements of the turbulent boundary layer above the canopy (Rana and Katerji, 2000). The air flow is assumed to be made up of a large number of eddies, each having three-dimensional components (horizontal and vertical) (Burba and Anderson, 2010). The sensors measured the water content of the air, the vertical component of wind speed, and air temperature at 10 Hz. The data was averaged every 30 minutes (Nagler et al., 2005).

The EC flux measurements allow ET to be calculated directly, whereas additional instruments allow the surface energy balance to be calculated indirectly, as indicated in Equation 2 (Twine et al., 2000; Nagler et al., 2005). These measurements were conducted throughout the entire experimental period to check the validity of ET measurements in order to assess the energy balance closure using the Bowen ratio method, as described by Twine et al. (2000) and Ezzahar et al. (2009).

$$R_n - G = LE + H \tag{2}$$

where R_n is the net radiation measured above the canopy using a net radiometer, G is soil heat flux measured using soil heat flux plates, LE is latent energy flux (evaporation multiplied by the latent heat of vaporization) which was measured using an open path gas analyzer, H is sensible heat flux measured using a sonic temperature sensor.

2.2.2. Monitoring of crop growth

During both growing seasons, fractional interception of photosynthetically active radiation (FI_{PAR}) and leaf area index (LAI) were measured non-destructively using a Decagon Sunfleck ceptometer (Decagon, Pullman, Washington, USA) in order to monitor canopy development and the relationship between canopy development and ET. Biweekly readings were taken above and below the canopy of a selected sampling area of 0.16 m^2. This was done under clear sky days, between 12:00 – 14:00 pm. Leaf area index (*LAI*, m^2 m^{-2}) was also determined through destructive measurements using an LAI 3100 belt driven meter (LI-COR Inc., Lincoln, Nebraska, USA) to measure total leaf area (m^2). This was done monthly to confirm the non-destructive measurements of LAI. The following equation was used to calculate LAI (Watson, 1947):

$$LAI = \frac{Measured\ total\ leaf\ area}{Sampled\ ground\ area} \qquad (3)$$

Fractional interception (*FI*, %) was calculated using the equation below (Jovanovic and Annandale, 1998):

$$FI = 100 \times \left(1 - \frac{I_o}{I_t}\right) \qquad (4)$$

where I_o is the measured photosynthetic active radiation (µmol m^{-2} s^{-1}) on the surface of the ground and I_t is the radiant flux density on top of the canopy (µmol m^{-2} s^{-1}).

Plant growth (fresh mass and dry matter) was measured at three-week intervals throughout the growing season, and was done by sampling the above-ground and harvestable storage root plant material of six plants from each sampling area. Samples were separated into stems, leaves and storage roots, for fresh mass determination. The different samples were then oven dried at 70°C to a constant mass for dry matter determination.

2.2.3 Daily crop evapotranspiration

Daily ET (mm day^{-1}) was calculated from data measured using the EC system following Equation 4:

$$ET\ (mm\ day^{-1}) = 86400 \times \frac{LE}{\lambda \rho_w} \qquad (5)$$

where *LE (*W m^{-2}*)* is latent heat fluxes measured using the EC system which was averaged over 24 hours to obtain daily ET, λ the specific latent heat of vaporization of water per unit mass (2454 000 J kg^{-1}), and ρ_w (kg m^{-3}) is the density of water. The factor 86400 converts from seconds to days.

2.2.4 Determining the surface energy balance closure and EC data processing

Surface energy balance closure for the EC system measurements was determined for the two growing seasons of sweet potato at the half-hourly time scale using Equation 2. Estimates of the turbulent fluxes ($LE + H$) from the EC system were subsequently compared to estimates of the available energy ($R_n - G$) using the energy balance method in order to determine the energy balance closure using the Bowen ratio method (Twine et al., 2000; Wilson et al, 2002; Nagler et al., 2005). This method assumes that $R_n - G$ was correctly measured by the EC system, so that both values of $H + LE$ could be increased according to the ratio of *H* and *LE* in order to balance Equation (2), as described by Fitzjarrald and Moore (1994), Blanken et al. (1997) and Twine et al. (2000). The adjustment was done by computing the difference between ($LE + H$) and $(R_n – G)$ flux values measured at the same time and divide the product by two. Then the final value was used to compensate values of $LE + H$ (Blanken et al., 1997; Twine et al., 2000; Cleverly et al., 2002; Hipps et al., 2002; Scott et al., 2004; Nagler et al., 2005).

The surface energy balance closure was analysed by plotting the sum between $H + LE$ (turbulent fluxes) against the $R_n - G$ (available energy) using good quality data for 20 days during the 2014/15 growing season (2, 8, 3 and 7 days during initial, development, mid-season and late growth stages, respectively) and 11 days during the 2015/16 growing season (2, 3, 4 and 2 days during initial, development, mid-season and late growth stages, respectively). Stannard et al. (1994) stated that if all components of energy balance are measured with accuracy, independently, and sum to zero, it shows that the EC measurements are good, and the energy balance equation is satisfied. In such a case, the linear equation of $H + LE$ against $R_n – G$ should have a slope close to one and an intercept close to zero.

2.2.5 Crop coefficient

Daily, weekly and time-average crop coefficients (K_c) for sweet potato grown under optimum management conditions were determined for two consecutive growing seasons using the FAO single crop coefficient method (Allen et al., 1998):

$$K_c = \frac{ET}{ET_o} \tag{6}$$

where ET_o is reference evapotranspiration (mm).

ET_o was calculated according to the FAO Penman-Monteith equation using daily weather data measured at the study site (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u_2\left(e_{s-e_a}\right)}{\Delta+\gamma(1+0.34u_2)} \tag{7}$$

where γ is the psychrometric constant (kPa $^{\circ}\mathrm{C}^{-1}$), T is air temperature at 2 m height ($^{\circ}\mathrm{C}$), u_2 is wind speed at 2 m height in (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa) and Δ is the slope of the vapour pressure curve (kPa $^{\circ}\mathrm{C}^{-1}$).

In order to adjust the determined crop coefficients for sweet potato to site-specific climatic conditions, a heat unit based Growing Degree Days (GDD) equation was developed using measured data during the 2014/15 growing season. GDDs were calculated using a base temperature of 15.5 ^{o}C and with no cut off temperatures, as suggested by Wees et al. (2016). The equation developed using GDDs was subsequently validated using an independent growing season of measurements.

2.2.6 Soil water content, rainfall and irrigation

Soil water content was measured using a neutron probe water meter, model 503DR CPN Hydroprobe (Campbell Pacific nuclear Inc., California, USA) that measures volumetric water content (θ) for irrigation scheduling, pre-calibrated on site. Five neutron probe access tubes were installed in the field to a depth of 1.0 m. Soil water content was measured at 0.2 m increments by lowering the probe through the access tubes once a week to determine the water depletion level prior to irrigation. Chameleon soil moisture sensors were also installed at depths of 0.15, 0.30, 0.45, and 0.60 m to monitor soil water tension two to three times a week, in order to check whether the crop was optimally irrigated when changes in soil water content could not be monitored using a neutron probe (Stirzaker et al., 2017). These sensors give outputs in three different colours which correspond to varying ranges of soil water tension measured, namely blue (wet soil, < 25 kPa), green (moist, 25 to 50 kPa), and red (dry soil, > 50 kPa). For the period when Chameleon sensors were used, irrigation was scheduled based on the established relationship between soil water tension obtained with chameleon sensors and volumetric soil water content obtained with a neutron probe at the study site.

Rainfall was recorded with TE 525 tipping bucket rain gauges (Texas Electronics, Inc., Dallas, TX, USA), which was connected to a CR10X (Campbell scientific, Utah, USA) data logger. The actual irrigation applied was measured using manual rain gauges, which were positioned at various points in the field to account for the variability in sprinkler irrigation uniformity.

2.2.7 Weather data

Weather data (daily maximum and minimum air temperatures and relative humidity, total daily solar radiation, wind speed and direction) were obtained from an automatic weather station (Campbell, Scientific. Inc., Logan. Utah. USA) which was located about 500 m from the trial site in Roodeplaat, Pretoria.

3. Results and discussion

3.1. Weather data variability

Generally, weather variables (maximum and minimum temperatures, rainfall) during the 2014/15 growing season were lower than the subsequent season (2015/16), as illustrated in Table 2. Temperatures during both growing seasons were favorable for sweet potato growth. Rainfall during the 2015/16 growing season was higher than during the 2014/15 growing season, but not well distributed with most of the rain being received in March. Long-term average rainfall was higher when compared to both growing seasons. The average long-term reference evapotranspiration (ET_o) was lower than the actual ET_o for the two growing seasons (Table 2).

Table 2. Monthly average maximum (T_x) and minimum (T_n) air temperatures, total monthly rainfall, and reference evapotranspiration (ET_o) for 2014/15 and 2015/16 growing seasons, as well as averages for the period of 2009 – 2013.

Years	Month	Mean T_x (°C)	Mean T_n (°C)	Rainfall (mm)	ET_o (mm)
2009 – 2013	January	29.4	17.5	93.2	94.7
	February	30.4	16.2	67.0	139.6
	March	29.6	14.5	82.3	133.1
	April	25.8	10.3	78.3	99.3
	May	25.2	8.5	15.1	26.0
	Total			335.9	492.7
2014/15	January	30.2	16.5	114.6	113.9
	February	31.9	16.0	32.5	151.6
	March	30.2	14.7	71.0	135.5
	April	27.4	10.8	43.0	101.5
	May	27.6	6.1	0.0	30.5
	Total			261.1	533.0
2015/16	January	31.7	17.6	95.5	94.5
	February	32.5	17.8	49.5	152.8
	March	29.4	15.6	204.5	129.2
	April	28.4	11.8	3.3	112.1
	May	23.9	6.54	0.0	26.8
	Total			352.8	515.4

3.2. Profile soil water content

The seasonal change in soil water content in response to rainfall received and irrigation applied during the 2014/15 growing season is shown in Figure 1. For the 2015/16 season, changes in soil water tension as affected by rainfall and irrigation events are shown in Table 3 and Figure 2. The total applied irrigation water and rainfall received during the 2014/15 season (481 mm) was lower, but better distributed than during the 2015/16 season (585 mm), which contributed to an adequate profile soil water content, between 90 and 100% of field capacity. As a result, the crop was likely grown under non-limited soil water conditions throughout the experimental period.

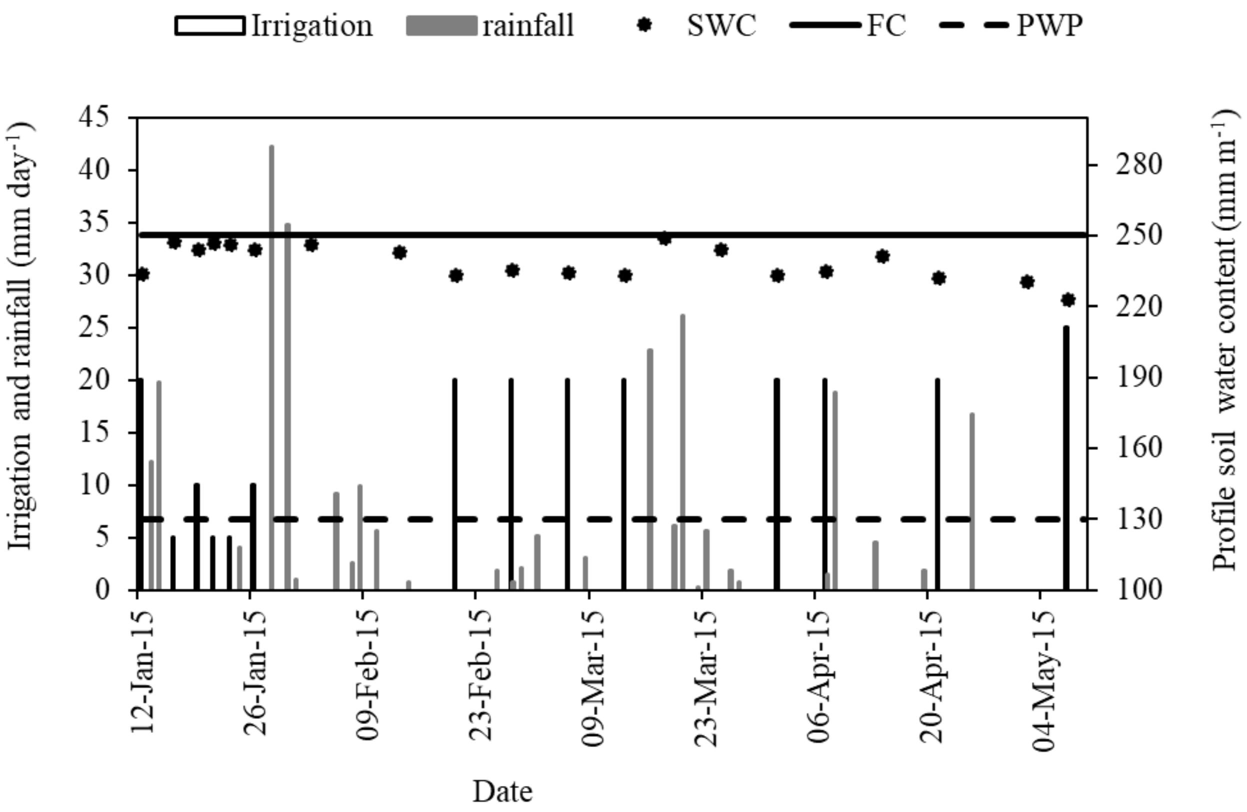

Figure 1. Changes in profile soil water content (SWC) throughout the 2014/15 growing season as affected by daily irrigation and rainfall events at the study site. Values of field capacity (FC) and permanent wilting point (PWP) are also shown.

Table 3. Chameleon pattern responses during the 2015/16 growing season. The different pattern fills indicate varying ranges of soil water tension measured in relation to soil water content, namely vertical stripe (wet soil, < 25 kPa = 240 mm) and horizontal stripe (moist, 25 to 50 kPa = 190 -240 mm).

Depth (m)	**7-**	**11-**	**12-**	**15-**	**18-**	**22-**	**25-**	**01-**	**08-**	**12-**	**15-**	**22-**	**29-**	**7-**	**15-**	**21-**	**25-**	**29-**	**4-**	**15-**	**25-**	**03-**
	January							**February**						**March**					**April**			**May**
0.15	▤	▥	▥	▥	▥	▤	▤	▤	▥	▥	▤	▥	▥	▤	▥	▤	▤	▥	▤	▤	▤	▤
0.30	▥	▥	▥	▥	▥	▥	▥	▤	▥	▥	▤	▤	▥	▤	▥	▥	▤	▤	▤	▤	▤	▥
0.45	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▤	▥	▥	▥	▥	▥	▥	▥	▥	▥	▤	▤
0.60	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▥	▤	▥	▤	▥	▥	▤	▥	▤	▥	▥	▤

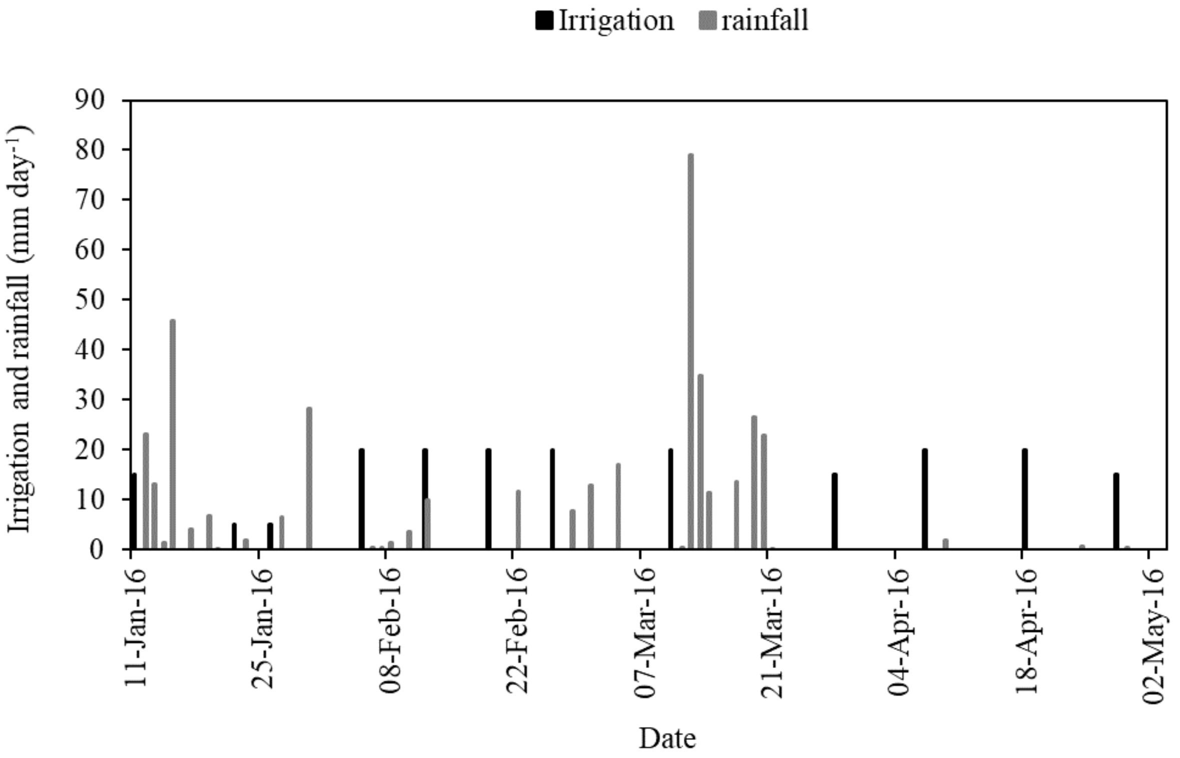

Figure 2. Rainfall and irrigation events during the 2015/16 growing season.

3.3. Leaf area index and fractional interception of photosynthetic active radiation

The LAI (Figure 3) and FI (Figure 4) recorded during both growing seasons followed similar trends when related to changes in Growing Degree Days (GDD). The values increased from the early to mid-season growth stage, but decreased in the late growth stage, dropping quickly after the crop reached maturity. The sharp decrease of LAI during the late growth stage was due to the fact that the crop reached maturity, which was accompanied by senescence of leaves (van den Berg et al., 2004; Nedunchezhiyan et al., 2012). The LAI and FI in the 2014/15 season reached slightly higher values than the LAI and FI in the 2015/16 season and, as a result, higher PAR was intercepted during the 2014/15 growing season. These measurements were conducted to assess whether the ET measured using EC system increased with canopy development.

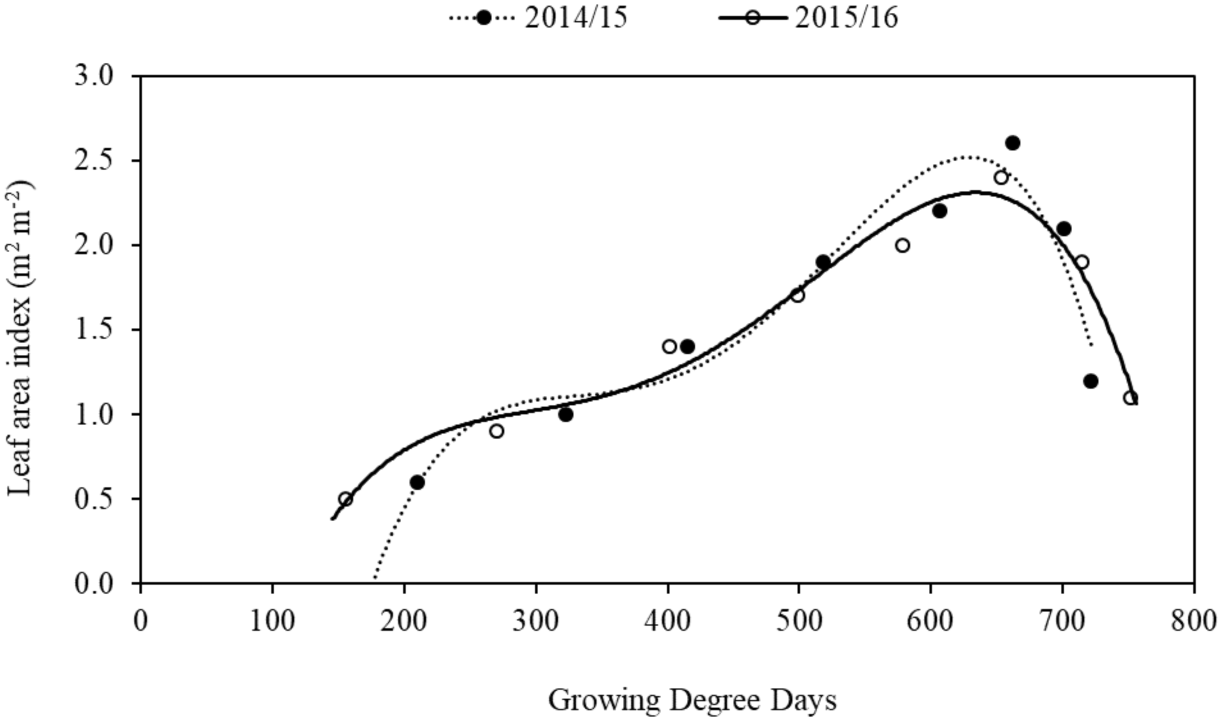

Figure 3. Leaf area index of sweet potato during the 2014/15 and 2015/16 growing seasons as affected by changes in cumulative Growing Degree Days (GDD).

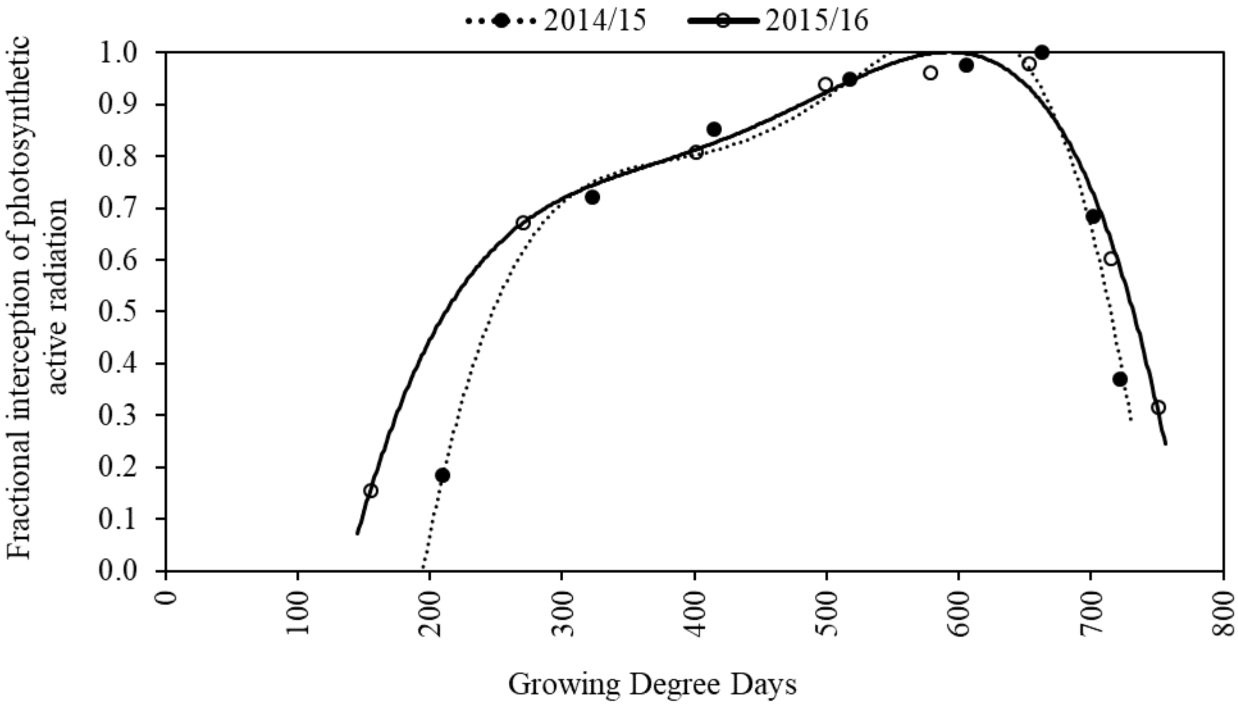

Figure 4. Fractional interception of photosynthetic active radiation of sweet potato as affected by changes in cumulative thermal time during the 2014/15 and 2015/16 growing seasons.

The LAI reported in this study was within the LAI ranges reported in the scientific literature (Shibayama and Akita, 2002; Masango, 2014). The maximum LAIs observed were 2.4 and 2.6 m^2 m^{-2}. This was in agreement with Shibayama and Akita (2002) and Masango (2014) who reported maximum LAIs of 2.7 and 3.0 m^2 m^{-2} for sweet potato, respectively. Bourke (1982) reported that storage root dry matter accumulation is determined by the period that the crop leaves are green where high PAR will be intercepted. In this study, the crop was actively growing from the planting date on the 11th of January until mid-April for both growing seasons (for 95 days after planting, until the crop accumulated approximately 650 GDD), where LAI values increased until 2.6 m^2 m^{-2} during the 2014/15 season, and 2.4 m^2 m^{-2} during the 2015/16 season. It is not surprising that the difference in maximum attained LAI during the two growing seasons of measurements was quite small, as the crop reaches full cover and closed canopy crop during this period of growth. Following the same trend of LAI increment, FI also increased during both growing seasons to a maximum of 97 – 99%, then it decreased until the end of the growing season due to crop reaching maturity and senescence of leaves (117 days after planting, accumulating a total of 730 – 750

GDD). In this study, it was observed that the FI directly depended on canopy architecture and the density of canopy foliage (Flenet et al., 1996; Pilau and Angelocci, 2015).

3.4. Energy balance closure

An energy imbalance between $H + LE$ and $R_n - G$ was observed during both growing seasons. During the 2014/15 growing season, the energy balance closure error was 45%, while during the 2015/16 growing season the energy balance closure error was 48%. In this study, the Twine et al. (2000) method was followed, which suggests forcing closure is justified when the available energy is known and errors in its measurement are modest. As a result, the *LE* and *H* heat fluxes were scaled to force closure while conserving the measured Bowen ratio. Therefore, the Bowen ratio closure (BRC) method was used to improve $H + LE$, by adding to $H + LE$ fluxes. Twine et al. (2000) stated that for their study, $LE + H$ measured using the EC system were most often less than $R_n - G$, (typically ranging from 5 to 30%), which simply means that turbulent fluxes measured with the EC system are mainly underestimated.

The reasons that caused energy imbalance between $H + LE$ and $R_n - G$ in our study, could be due to errors in EC measurement which may have been caused by dirt on the sonic transducers, noise in the measurement system (Paw et al., 2000; Baldocchi and Mayers, 1991; Scott et al., 2003; Papale et al., 2006). In addition, lack of steady state conditions, consumption of net radiation by photosynthesis, neglected energy sinks, heat storage in the top soil, mismatch in footprint, and malfunctions of sensors during rainfall conditions might have also contributed to an increased closure error (Ezzahar et al., 2009; Teixeira and Bastiaanssen, 2010). Finnigan et al. (2003) also suggest that the averaging time of generally 30 minutes used to calculate covariances could be inadequate for assessing turbulent fluxes.

The energy balance closure in this study was again assessed by comparing the discrepancy between $R_n – G$ and $H + LE$ after adjustment using the BRC method, and the closure error during the 2014/15 growing season was 5% which has improved by 50% from the closure error before adjustment with the BRC method. While for the 2015/16 growing season, the closure error was 9%, which has improved by 43% from the closure error before adjustment. The energy balance closure values obtained after adjustment using BRC method were 95% and 91%, for 2014/15 and

2015/16 growing seasons, respectively. The linear regression between $H + LE$ and R_n - G yielded a slope of 0.95, an intercept of 0.0052 Wm^{-2} and coefficient of determination $R^2 = 0.97$ for the 2014/15 growing season (Figure 5a), and a slope of 0.84, an intercept of 0.0156 Wm^{-2} and $R^2 = 0.83$ for the 2015/16 season (Figure 5b). This shows that there was a good relationship between the available energy obtained with surface energy balance method and the adjusted turbulent fluxes. Therefore, it is crucial to estimate ET using corrected LE values after energy balance closure assessment.

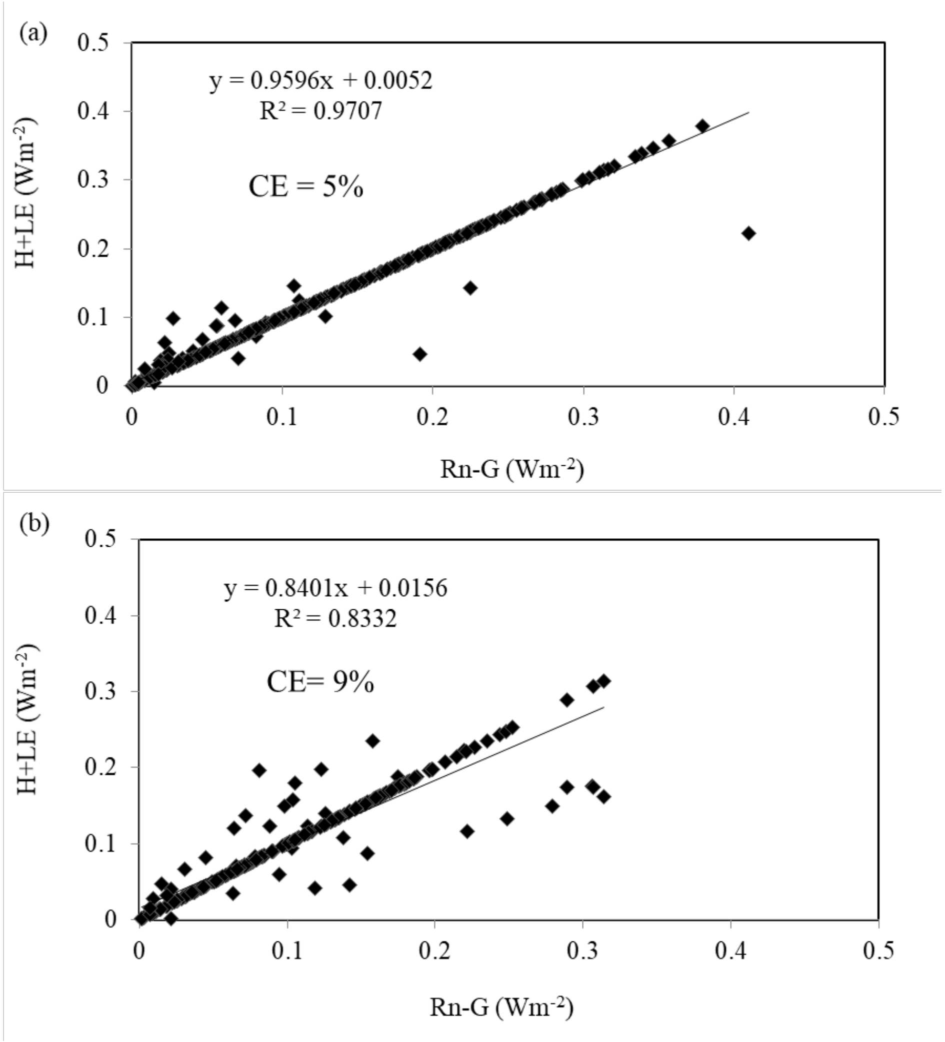

Figure 5. Energy balance closure: relation between half hourly data, $LE + H$ (sum of turbulent latent heat and sensible heat fluxes) and R_n - G (available energy given by the difference between net radiation and soil heat flux), for selected (a) 20 days in 2014/15 season and (b) 11 days during the 2015/16 growing season.

The adjusted energy balance closure obtained in this study (91 to 95%) was comparable to those reported in the scientific literature. Parent and Anctil (2012) reported energy balance closure of 79% for potato (*Solanum tuberosum* L.) in south-eastern Canada. Ma et al. (2009) reported energy balance closure of 70% in summer and 92% in winter over a flat prairie on the northern Tibetan Plateau, while Wright et al. (1992) reported excellent closure of 99% during the dry season in Brazil over ranchland of prairie (*Sporobolus cryptandrus*) grass. Numerous researchers have reported average EC energy balance closure between 70 and 99% for different vegetation surfaces (Falgae et al., 2001; Wilson et al., 2001; Li et al., 2005; Barr et al., 2006). A lack of closure on the surface energy budget of 5 to 30% has been reported by different authors for turbulent fluxes measured using the EC system (Twine et al., 2000; Wilson et al., 2002; Aubinet et al., 2002; Oncley et al., 2002; Barr et al., 2006; Liu et al., 2006; Gao et al., 2009; Ma et al., 2009; Su et al., 2009). Pirvulesca (2013) stated that in reality the perfect closure is not simple to obtain, which is supported by the argument of Wilson et al (2002) and Twine et al. (2000) who reported imbalances of surface energy budget by 20% at 22 FLUXNET sites. This shows that there is no perfect closure for the energy balance and the lack of closure usually results in turbulent fluxes $H + LE$ being less than the available energy $R_n – G$. When the referred discrepancy is above 30%, it is recommended that turbulent flux measurements obtained with the EC system be adjusted in order to improve the energy balance closure (Wilson et al., 2002; Twine et al., 2000).

3.5. Evapotranspiration

Daily ET of sweet potato varied from 0.5 mm (during rainy days) to 5.5 mm (during clear, sunny days) for the 2014/15 growing season, and 0.9 to 5.1 mm for the 2015/16 growing season. Daily ET_o varied between 2.3 mm (cloudy days) and 7 mm (sunny days) during the 2014/15 growing season, and between 0.8 mm (cloudy days) and 6.9 mm (sunny days) during the 2015/16 growing season (Figure 6a and d). During initial growing stage (January) and towards the end (May) of both growing seasons the daily ET was lower than ET_o because of lower LAI values which resulted in less PAR to be intercepted by the crop. The main reasons for the low ET estimates at the beginning of the season were due to a still developing canopy cover, while at the end of the season it was the result of crop maturity and leaf senescence, which led to low PAR interception. The ET estimates increased from January to March as the canopy developed, and there was a close match between ET and ET_o values around March to April when the LAI reached its maximum (Figure 6a and d). While the cumulative ET_o steadily increased from the beginning until the end of the season, the ET only followed similar pattern until mid-April, thereafter the cumulative seasonal ET remained fairly constant as a result of decreased ET due to crop reaching maturity and leaf senescence (Figure 6b and e). The cumulative ET_o was generally higher than ET during both experimental seasons, which is also evident in Figure 6c and f. Furthermore, it was observed that ET during the 2014/15 growing season was higher than during the 2015/16 growing season, which could be due to the presence of higher canopy growth in 2014/15 season as compared to the subsequent season, although the total amount of water supplied to the crop was the opposite. Therefore, water supply in abundance does not guarantee greater crop development, as the yield during the 2014/15 season (32 t ha^{-1}) was higher than during the 2015/16 season (29 t ha^{-1}). This is particularly true in so-called drought tolerant crops like sweet potato.

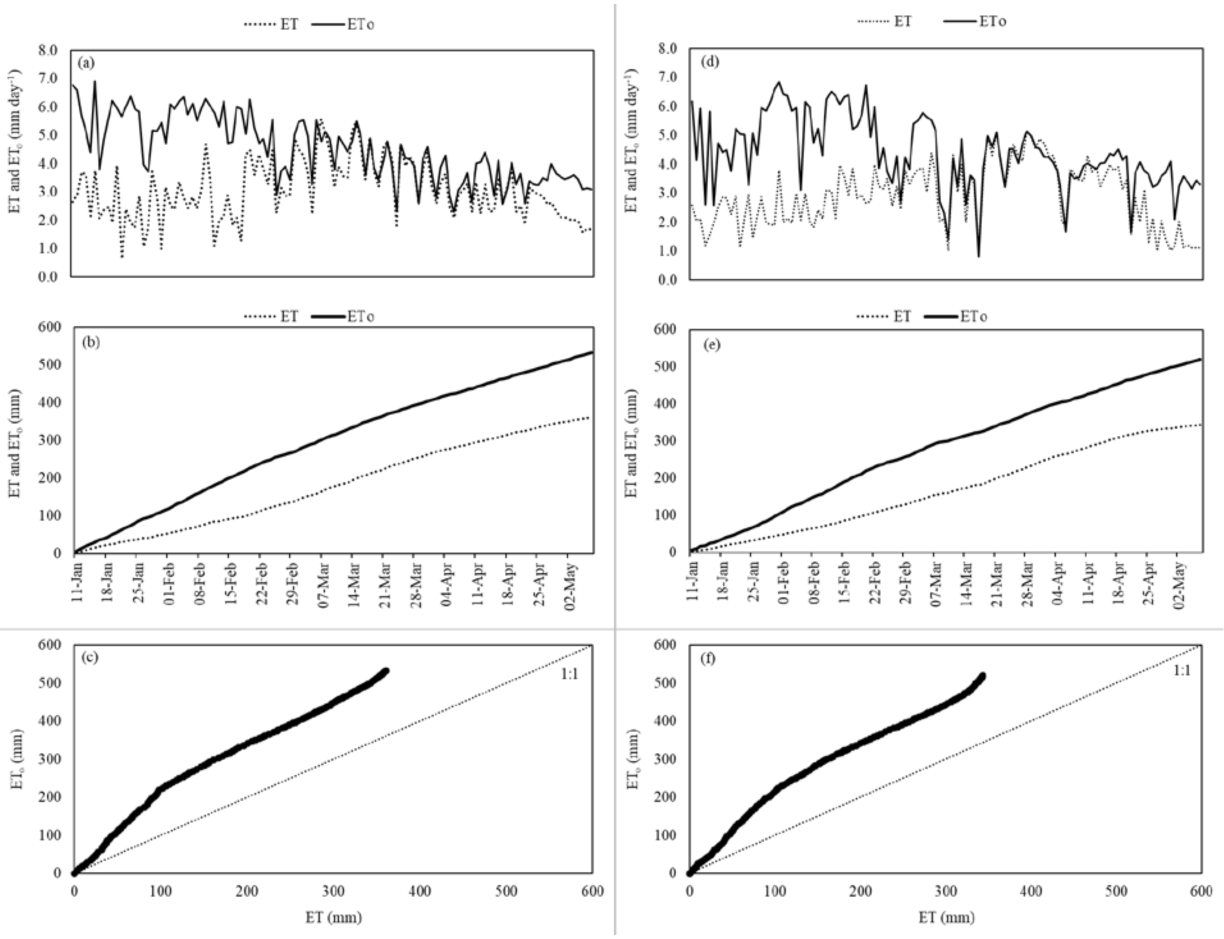

Figure 6. Comparison of daily/cumulative evapotranspiration (ET) measured using the eddy covariance system and daily/cumulative reference evapotranspiration (ET_o) calculated following the FAO-Penman-Monteith (Allen et al., 1998) equation for the (a, b, c) 2014/15 growing season and (d, e, f) 2015/16 growing season.

For both seasons, seasonal ET_o (521 to 535 mm) was higher than measured ET (344 to 361 mm). The ET values reported in this study are lower than those reported for OFSP sweet potato cultivar 'Bophelo' growing under irrigated conditions in semi-arid regions of South African using a soil water balance method (478 – 658 mm, Masango, 2014; Nyathi et al., 2019). Studies conducted in other parts of Africa such as Mozambique and Kenya using a similar measurement procedure have also reported higher sweet potato ET, ranging between 350 and 850 mm (Gomes and Carr 2003; Karanja, 2006). When determining crop ET using the soil water balance method, components such as runoff, deep percolation, subsurface flow and water brought by capillary rise are often ignored, which frequently result in overestimation of the crop ET (Goldhamer et al., 1993; Rana and Katerji, 2000). The dissimilarity in water use findings may not only be due to the method employed to estimate ET, but also due to differences in crop and site-specific characteristics (Kuslu et al., 2010; Abyaneh et al., 2011). Since the ET of sweet potato is highly variable, there is a need to identify possible procedures to predict the ET of this crop under site-specific conditions, which is possible through the development of crop coefficients.

3.6. Crop coefficients

Daily values of crop coefficients (K_c) for sweet potato grown under optimum management practices were determined using the FAO single crop coefficient methodology (Allen et al., 1998) for two consecutive growing seasons (2014/15 and 2015/16). From Figures 7, 8 and 9 it was observed that values of K_c remained fairly constant for 39 days during the initial growth stage (average K_c of 0.46), followed by a sharp increase up to a maximum of 0.97 for 25 days during the development stage. Values of K_c remained practically unchangeable for 25 days during the mid-season stage, and finally decreased to a minimum of 0.44 during the late-season stage.

The OFSP cultivar 'Bophelo' K_c values reported for a semi-arid climate in this study were slightly different from those reported in the scientific literature for sub-humid climates in the USA (Allen et al., 1998; Dukes et al., 2012). The above-mentioned studies reported sweet potato K_c values of 0.20 – 0.40 during the initial stage, 1.11 - 1.15 during the mid-season stage and 0.65 – 0.71 during the late stage. The differences in sweet potato K_c values reported were likely related to differences in cultivars used between the measurement sites and climatic conditions.

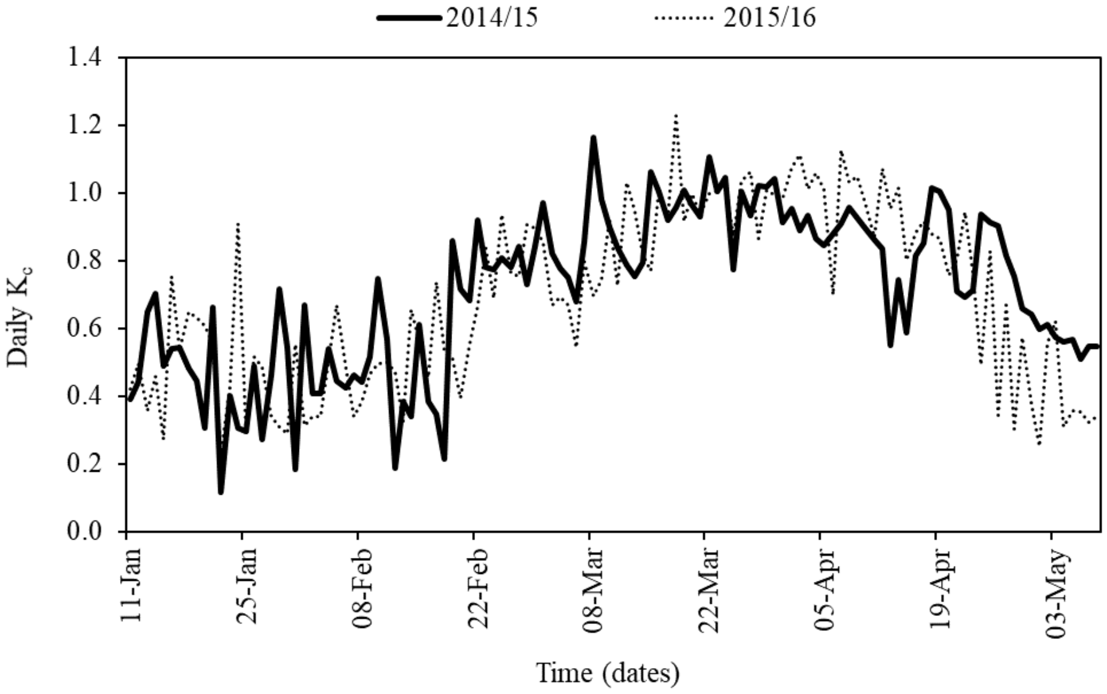

Figure 7. Comparison of daily sweet potato crop coefficient (K_c) values between the 2014/15 and 2015/16 growing seasons.

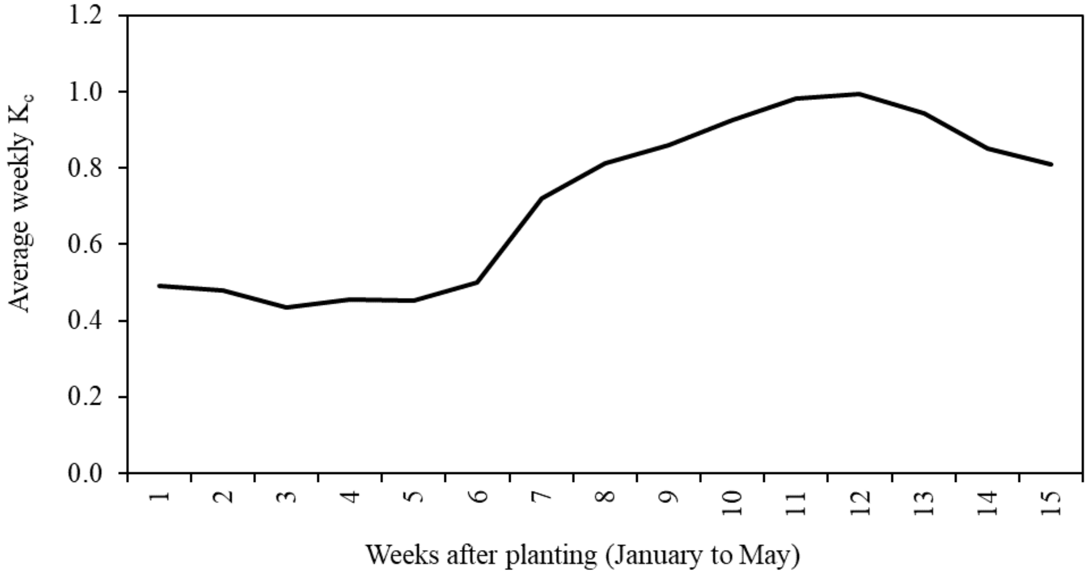

Figure 8. Average weekly crop coefficients (K_c) values for sweet potato throughout the 2014/15 and 2015/16 growing seasons.

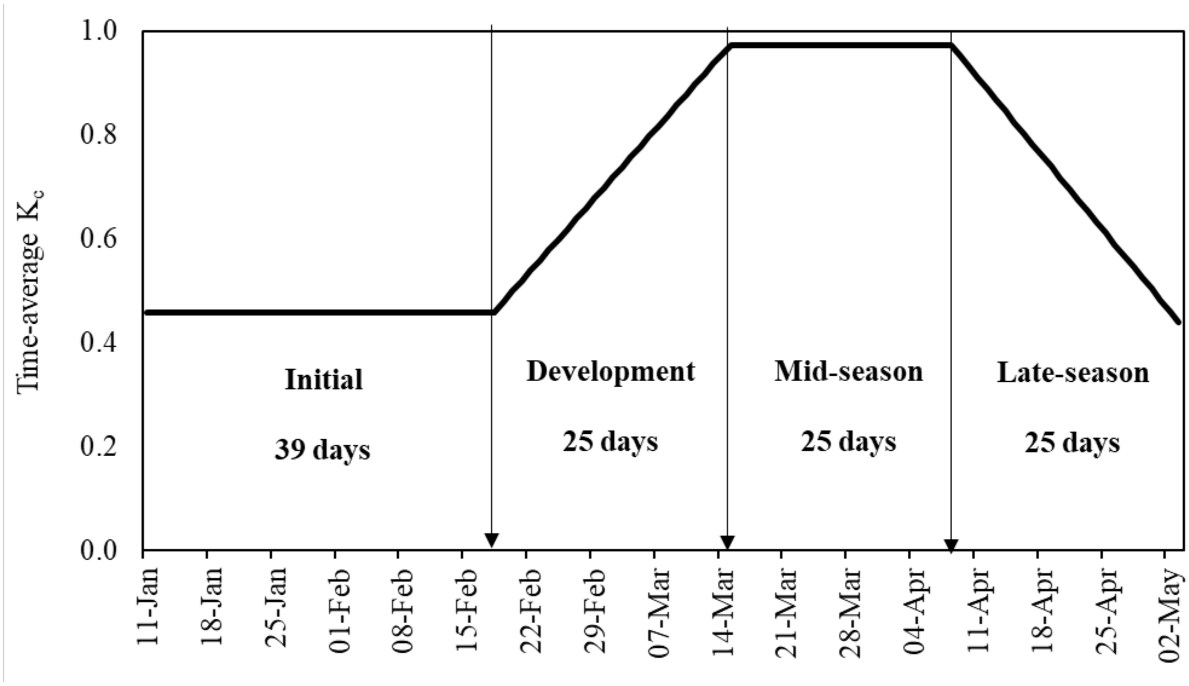

Figure 9. Time-average crop coefficient (K_c) values of sweet potato for the different growing stages.

Three-day running average K_c values obtained during the 2014/15 sweet potato growing season were used to develop a heat unit time based equation (Equation 8), which allows adjustment of K_c values to site-specific semi-arid climatic conditions based on GDD. The calculated crop coefficient based on GDD fits a fourth-degree polynomial equation, with an $R^2 = 0.84$ (Figure 10). The equation was successfully validated by comparing measured against estimated K_c using cumulative GDD determined during the 2015/16 growing season, with an $R^2 = 0.80$ and mean absolute percent difference (MAPD) = 7% (Figure 11).

$$K_c = -3.358X10^{-12}GDD^4 - 1.138X10^{-8}GDD^3 + 1.521X10^{-5}GDD^2 - 3.803X10^{-3}GDD + 6.698X10^{-1} \quad (8)$$

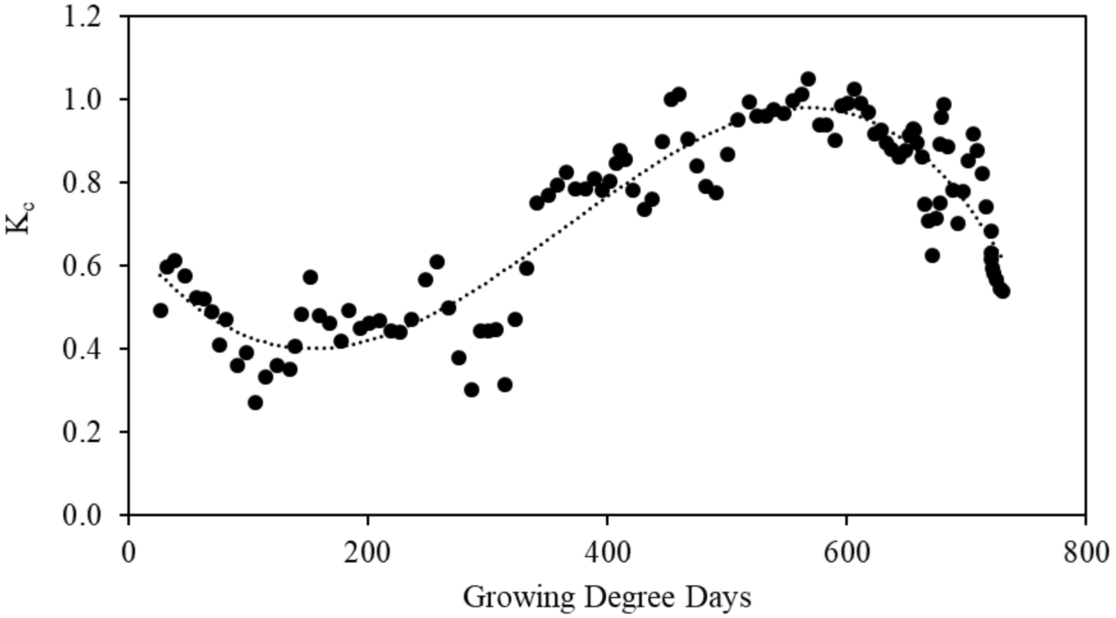

Figure 10. Three-day running average crop coefficient (K_c) values of sweet potato using Growing Degree Days (GDD) as a time base for the 2014/15 growing season.

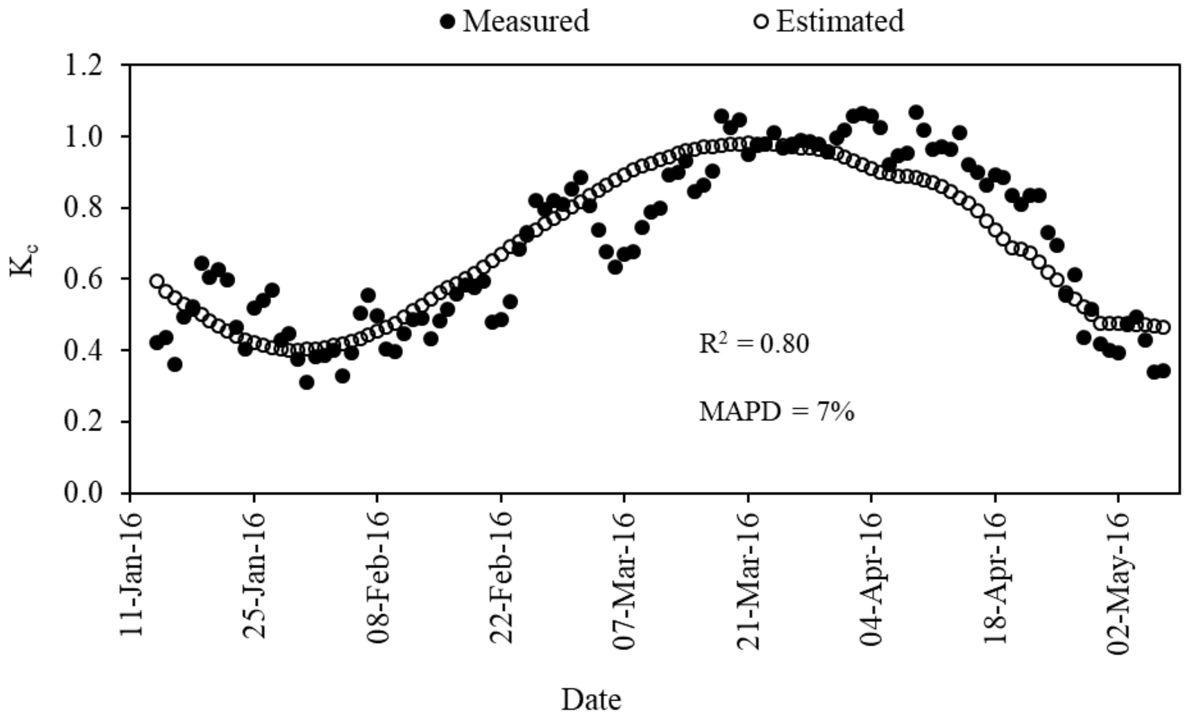

Figure 11. Comparison between measured and estimated crop coefficients (K_c) for sweet potato using a heat unit time based equation during the 2015/16 growing season.

4. Conclusion

The eddy covariance system was used to estimate evapotranspiration (ET) of sweet potato for two consecutive growing seasons in a semi-arid area. The actual evapotranspiration (ET) was then used in combination with reference evapotranspiration (ET_o) to determine daily, weekly and time-averaged crop coefficients (K_c) of sweet potato for two consecutive growing seasons. This is the first study of its kind in South Africa, and first on locally developed OFSP cultivar 'Bophelo'. Time-averaged K_c values of 0.47 during the initial stage (39 days), 0.47 – 0.97 during the development stage (25 days), 0.97 during mid-season stage (25 days) and 0.44 during late growing stage (25 days) were obtained from this study for OFSP. A heat unit based GDD equation was also successfully developed and validated using three-day running average K_c values. These derived time-averaged K_c values can be used in the future to aid in the extrapolation of measured experimental results to different semi-arid climatic conditions using the FAO-56 single crop coefficient approach. Alternatively, K_c values of sweet potato can be adjusted to site-specific climates using the heat unit based GDD equation developed in this study. Since potential ET usually exceeds rainfall in semi-arid regions, this information will assist in improving OFSP productivity through improved irrigation scheduling in order to meet crop water requirements optimally. The findings from this study will also improve water resource planning and irrigation water management of OFSP growers, thereby conserving the scarce natural water resources to ensure its sustainability for agriculture and food security in South Africa. Due to the limited information available currently on sweet potato ET and K_c, it is recommended that more similar studies be conducted under different environmental conditions and crop management practices, on a range of cultivars to test the validity of K_c values estimated for site-specific conditions using modelling approaches proposed in this study.

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