Assessing evapotranspiration and crop coefficients of potato in a semi-arid climate using Eddy Covariance techniques

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Highlights

- Seasonal mean crop coefficient values varied considerably between seasons and sites.
- Daily patterns of reference and crop evapotranspiration correlated well.
- Reference evapotranspiration can be used for irrigation scheduling.
- Crop coefficients may need adjustment depending on the cropping season.
- Advisable to grow potato crops in cooler season in semi-arid areas.

Abstract

A correct estimation of crop coefficients (K_C) is essential to assess water requirements of crops from weather variables and thereby optimize irrigation management. K_C depends on crop type and varies with crop growth stage, and to a limited extent, with climate. K_C values are often assumed to be transferable between locations and climates. K_C values have not been determined yet for modern potato cultivars grown under South African, semi-arid climatic conditions. The objectives of this study were (i) to quantify evapotranspiration and water use efficiency (WUE) of potato crops in a semi-arid climate under irrigation, (ii) to estimate K_C values for these crops at different growth stages, and (iii) to assess the usefulness of the Penman-Monteith equation to estimate evapotranspiration and irrigation requirements. An eddy covariance (ECV) system was used in potato fields planted with the variety Mondial in two production regions of South Africa: Limpopo (crop growing in winter) and North West (spring-summer crop). Additional sensors were added to the system to measure relative humidity, near surface soil temperature, solar radiation, rainfall and irrigation. Decagon 10 HS capacitance sensors installed at varying soil depths were used to measure the change in soil moisture content of the potato rooted zone. Accuracy of the ECV measurements was evaluated by following the energy balance closure method. Seasonal mean crop evapotranspiration (ET_C) was 3.2 mm d^{-1} for the crop in Limpopo and 5.7 mm d^{-1} in North West. The reference evapotranspiration (ET_O) correlated well with the daily patterns in ET_C for most of the season. ET_O thus serves as a useful indicator of ET_C and can be used for irrigation scheduling of potato. Seasonal mean K_C value was 0.99 for the crop in Limpopo and 0.78 in North West. While the K_C value in Limpopo likely represented that for a crop free of water-stress, the crop growth in North West was likely somewhat limited by water availability. The winter crop had the highest WUE of 3.55 kg dry potato tuber m^{-3} of water evapotranspired, whilst WUE for the spring-summer crop was 3.03 kg m^{-3}. This difference could be explained by differences in mean vapour pressure deficit between the growing seasons. To optimize WUE of potato growing in semi-arid, water scarce regions such as South Africa, it is advisable to grow crops in the coolest available growing season, outside the frost-prone period.

Keywords

Water use efficiency, Penman-Monteith, Energy closure, Irrigation, Soil water balance

1. Introduction

Potato is considered a cool weather crop, yielding well in temperate environments with long day-lengths. Potato production in southern Africa and other regions in the world, however, takes place in warmer environments with shorter day lengths. In South Africa, the average area under potato production in 2015 – 2017 was 52,000 ha, with an average marketable yield of 44 t ha^{-1} (Potatoes South Africa, 2019). South Africa has sixteen potato production regions with distinct agro-ecological conditions. This geographical dispersion enables South Africa to produce potatoes year-round, though the quality and quantity varies with the time of year. The main potato production areas are in Limpopo, the western and the eastern Free State and the Western Cape (the Sandveld). South Africa is a semi-arid country with an annual rainfall averaging 450 mm and evaporation exceeding rainfall in most regions (Harding, 2015).

Over 90 % of the potato production area in South Africa partly or fully relies on irrigation for water supply to the crop, and the availability of irrigation water limits production, particularly in those areas reliant on borehole water. The energy cost of irrigation contributes up to 25 % of total energy use in potato production and this is largely determined by the amount of water applied and depth of the water table (Steyn *et al*., 2016). A strong relationship was identified between energy costs for irrigation and total carbon footprint of potato production in South Africa (Steyn *et al*., 2016). Furthermore, irrigation impacts the use efficiency of nutrients (Djaman *et al.*, 2021). As potato has a shallow root system and is often grown on well-drained, sandy soils, the risk of water and nutrient losses through drainage is high. Crop water use is influenced by many factors that are variable and interdependent on one another, such as the climate, the type and growth stage of the crop, the root system, soil characteristics, crop phenology and type of irrigation system (Testa, Gresta and Cosentino, 2011; Djaman *et al.*, 2021). Farmers tend to over-irrigate to avoid any risk of drought stress in case they are unsure when and how much to irrigate. The limited use of decision support tools and systems for irrigation scheduling and management by farmers worsens the problem. The sustainability of potato production in South Africa thus strongly depends on the efficient management of irrigation water to enhance crop productivity, while minimizing salinification, drainage and nutrient leaching (Steyn *et al*., 2016).

Determining evapotranspiration of a crop (ET_C) is crucial in estimating the crop's irrigation requirements from weather variables (Kashyap and Panda, 2001; Parent and Anctil, 2012; Anapalli *et al.*, 2018a). Various decision support systems are available to farmers to schedule irrigation. Estimates of ET_C through the Penman-Monteith equation (Pereira *et al.*, 2015, 2021; Marin *et al.*, 2019) are often used in these systems. In this approach, the grass reference evapotranspiration (ET_O) is calculated using local weather data as input. ET_C is calculated by multiplying ET_O with a crop-specific factor (K_C). A single K_C value may be used for the whole season or it may vary for different growing stages. The crop coefficient may represent both crop transpiration and soil evaporation as a single value, whilst the dual crop factor approach considers these terms separately (Testa, Gresta and Cosentino, 2011; Shahrokhnia and Sepaskhah, 2013). The Penman-Monteith method is not always accurate across localities, which can lead to inaccurate estimates of crop water requirements (Facchi *et al.*, 2013). Although K_C values are primarily crop dependent, they are also affected by the environmental and management conditions under which they were obtained. K_C values for a single crop may vary considerably between locations due to differences in variety, soil properties, irrigation methods, climate and crop management practices (Payero and Irmark, 2011, Jiang *et al.*, 2014; Xu *et al.*, 2018). Consequently, it is preferable to derive K_C values for local conditions to accurately determine crop water requirements (Singh Rawat *et al.*, 2019; Anapalli *et al.*, 2020).

Quantifying K_C values of a crop requires an accurate estimation of the crop evapotranspiration. Recently, Eddy Covariance (ECV) systems have become more accurate and affordable for use in cropping systems, allowing direct and continuous measurements of vertical gas fluxes over a crop surface (Parent and Anctil, 2012; Anapalli *et al.*, 2018; Mbangiwa *et al.*, 2019). Water vapour and carbon dioxide (CO_2) are the most commonly measured gasses. The ECV method makes it possible to accurately estimate ET over a short time period and a large area.

Energy balance is typically used to check the degree of error when estimating ET using micro-meteorological equipment. The energy balance closure, which is a formulation of the first law of thermodynamics, requires that the sum of the estimated latent energy (LE) and the measured sensible heat flux (H) be equivalent to the measured net radiation (R_n) and soil heat flux (G) (Wilson, 2002). However, imbalances have been observed and a number of explanations, such as inhomogeneous terrain and sensor alignment problems, have been proposed in such situations (Parent and Anctil, 2012).

Parent and Anctil (2012) used ECV techniques to quantify ET of a rain-fed potato crop during a season at a single site in South-Eastern Canada. We are not aware of any other published studies quantifying ET in potato with ECV techniques. Therefore, we conducted a field study with the following objectives:

(i) to quantify evapotranspiration and water use efficiency of potato crops grown in different locations and seasons in a semi-arid climate under irrigation

(ii) to estimate K_C values in both sites at different growth stages

(iii) to assess the usefulness of the Penman-Monteith equation to estimate evapotranspiration and irrigation water requirements

2. Materials and Methods

2.1 Site description and crop management

Potato fields for monitoring were selected on commercial farms in two production regions of South Africa. One site was in Limpopo nearby the village of Tom Burke (23°06'34.64"S; 28°04'25.29"E, 854 masl). Tom Burke has more of a tropical climate, with hot summers and mild winters. Rainfall mostly occurs during summer. The second site was in North West Province nearby the village of Louwna (28°41'13.08"S; 24°12'38.10"E, 1357 masl) in the Vryburg district. The climate is characterized by warm to hot summers and dry and cold winters. Rainfall occurs primarily in summer. Both sites receive a mean annual rainfall of 350-400 mm.

Table 1. Centre pivot irrigation system information for the two sites.

Parameter	Limpopo	North West
Manufacturer	Valley	Valley
Area (ha)	20	10
Number of spans	4	3
Span length (m)	56 - 57	58
Overhang length (m)	25	5
Sprinkler type	Senninger iWob	Senninger iWob
Sprinkler height (m)	1.5	1.6
Sprinkler spacing (m)	2.5 - 5.7	2.5 - 5.7
Operating pressure (kPa)	101	101
Flow rate (m^3/h)	106.3	50.5
Irrigation rate (mm/24 h)	10	10
Coefficient of uniformity (CU, %)	89	85
Application efficiency (%)	83	81
Time for full rotation at 100% (h:mm)	6:36	4:24

The fields in both regions were under center pivot irrigation systems for which detailed information is presented in Table 1. In Limpopo, potato was grown as a winter crop as the area is largely frost-free and summers are too hot for potato production. In North West, the crop was planted in spring, growing into summer. The soils of both sites were well-draining and had a high sand content (> 90% sand), a low water holding ability (mean field capacity of 0.224 m^3 m^{-3} and wilting point of 0.099 m^3 m^{-3}) and were vulnerable to nutrient leaching. Variety ‘Mondial’ - the most widely grown potato variety in South Africa - was planted at both sites. Seed tubers were planted in rows spaced 0.9 m apart at a target plant density of 40,000 – 44,000 plants per ha. Crop emergence was above 50% at 23 days after planting (DAP) in North West and at 25 DAP in Limpopo (Table 2). Granular, water soluble and foliar-based fertilizers were applied to the crop during the growing season through a combination of broadcasting before and after planting, band placement with planting, fertigation and spraying. High amounts of nutrients (N, P, K and Ca) were applied to the crops (Table 2) and nutrient availability was unlikely to limit crop growth. The haulms of the potato crops in North West were killed before the crop fully senesced for marketing reasons. In Limpopo, the crop was allowed to senesce naturally.

Table 2. Crop and management characteristics of the two sites.

	Limpopo	North West
Growing season	Winter / Spring	Spring / Summer
Date of planting	29-05-2016	29-08-2018
Date of 50% emergence	23-06-2016	21-09-2018
Date of haulm killing	10-10-2016	12-12-2018
Crop duration (days)	134	113
N-P-K rate (kg ha^{-1})	290-145-248	183-188-145
$I_T + R_T$ (mm) (from planting)	458 + 15	585 + 19

2.2 Data collection

An IRGASON integrated open-path CO_2/H_2O gas analyzer ECV system (Campbell Scientific) was used to measure the H_2O vapour fluxes above the crop canopy. It was integrated with a sonic anemometer, which measures the three-dimensional wind speed. The following sensors were added to the system: fine wire thermocouple, NR-Lite net radiometer, silicon pyranometer, krypton hygrometer, CS616 reflectometer, and Hukseflux heat flux plates. The ECV system was installed in the fields close to the center with minimal damage to the surrounding potato plants. Data were sampled at a frequency of 10 Hz, processed using EasyFlux DL software (Campbell Scientific), and recorded using a CR3000 datalogger. The datalogger and ECV system were powered by a 14 V, solar-charged battery. The gas analyzer was installed on a tripod mast at a height of 2.0 m above the soil surface, and oriented towards the predominant wind direction. This was west in North West and northeast in Limpopo. The fields, 10 – 20 ha in size, were large enough to meet the average fetch requirement of 150 m. ECV measurements commenced 29 DAP in North West and 26 DAP in Limpopo, which approximately coincided with crop emergence.

Weather data were obtained from automatic weather stations (Campbell Scientific) installed at the trial sites. Fresh tuber yield and tuber dry matter content were measured through destructive sampling at crop maturity. The tuber dry matter content was determined from subsamples that were oven-dried at 70 °C until constant weight. The amount of water supplied to the crop was measured using tipping bucket rain gauges (Texas Electronics) with dataloggers (Campbell Scientific CR200X) installed at eight random positions across the field in Limpopo and an ultrasonic flow meter (Flowmetrix) mounted onto the pivot water supply line at North West. Furthermore, soil moisture monitoring stations were installed close to the CRPs at both sites. Each monitoring station consisted of five capacitance sensors (Decagon 10HS) installed at 10, 20, 30, 40 and 50 cm depth and connected to a datalogger (Campbell Scientific CR200X) to facilitate continuous data collection. The sensors were calibrated *in situ* by taking periodic soil samples at corresponding depths and comparing the measured water contents to sensor readings. These measurements were used to estimate daily changes in soil water content. Soil moisture depletion per layer was calculated as the difference between field capacity and measured moisture content of that layer. These were then accumulated to obtain the daily soil moisture depletion of the root zone (0-50 cm). Moreover, a drain gauge lysimeter (Decagon G3) was installed in the field in North West to measure deep drainage beyond 1.0 m depth.

Application efficiency (AE) of the two centre pivot irrigation systems was measured by comparing the amount of water collected in rain gauges positioned at the soil surface with the volume entering the system, according to the procedures by Koegelenberg and Breedt (2003). The AE determines the fraction of water applied by the sprinklers that reaches the soil surface and gives an indication of wind drift and evaporation losses (Koegelenberg and Breedt, 2003). The measured AE of the two systems was 83% in Limpopo and 81% in North West (Table 1).

2.3 Data handling and analyses

Quality assurance and control are recommended for ECV measurements (Foken *et al*., 2012). The measurement system accomplished quality assurance by using diagnostic outputs from the sonic anemometer and infrared gas analyzer. The datalogger used raw data for flux calculations only when sensors functioned normally and measurements were within reasonable and calibrated ranges, and when signal strengths were adequate. The Easyflux datalogger program (Easyflux-DL) corrected for high and low frequency losses caused by the blocking average for the 30-min intervals. Systematic corrections were also done for the vertical air velocity due to heat and water vapour transfer in the atmospheric surface layer.

Easyflux-DL followed the method presented by Foken *et al.* (2012) to grade the relative quality of CO_2, LE, H and momentum fluxes. The relative non-stationarity (RN_{cov}), relative integral turbulence characteristic (ITC_{sw}) and the wind direction in the sonic instrument coordinate system (*Wnd_dir_sonic)* were calculated and used to grade the quality of the data. RN_{cov} described the steady state, ITC_{sw}, defined the development of turbulence conditions and *wnd_dir_sonic* described the wind direction. Each covariance variable over the averaging period was assigned an overall quality grade from 1 to 9, based on the individual grades of RN_{cov}, ITC_{sw} and *Wnd_dir_sonic*. Grade 1 was the highest overall quality whilst grade 9 was the poorest.

The energy balance closure ($E_{closure}$) was used to evaluate the accuracy of the ECV measurements. The sum of the estimated latent energy (LE) and sensible heat flux (H) must be equivalent to all other energy sinks and sources, net radiation (R_n) and soil heat flux (G);

$$E_{closure} = \frac{LE+H}{R_n-G} \qquad \text{(Equation 1)}$$

The Bowen ratio closure method (Chávez et al., 2009) was used to compensate for discrepancies between (R_n-G) and (LE+H) around noon (between 10.00 and 15.00) when the Bowen ratio is assumed constant. The calculations followed the procedures detailed by Ding et al. (2010). The adjusted LE was used to estimate daytime crop evapotranspiration (ET_C) measured by the ECV.

Daily K_C values were calculated following the single crop coefficient method, as the ratio of ET_C measured by the ECV to the reference evapotranspiration (ET_O);

$$K_C = \frac{ET_C}{ET_O} \qquad \text{(Equation 2)}$$

ET_O was calculated from weather station data using the FAO standardized Penman-Monteith equation and grass as a reference (Allen et al., 2005);

$$ET_O = \frac{0.408\Delta(R_n - G) + [\frac{900\gamma}{T_a mean + 273}]\mu_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \qquad \text{(Equation 3)}$$

where μ_2 is the wind velocity (m s^{-1}) at 2 m height, Δ the slope of saturation vapor pressure curve (kPa ^{o}C^{-1}), R_n the net radiation (MJ m^{-2} day^{-1}), G the soil heat flux, γ the psychrometric constant (kPa ^{o}C^{-1}), $T_a mean$ the mean air temperature, e_s the saturation vapor pressure (kPa) and e_a the actual vapor pressure (kPa). K_C values were calculated from the day the ECV system was installed (coinciding with emergence) until the time when haulms were desiccated or naturally senesced. Mean daily K_C values were obtained for different crop growth stages: vegetative growth, tuber initiation, tuber bulking and tuber maturation.

Vapour pressure deficit was calculated as the difference between the saturation and actual vapour pressure;

$$VPD = e_s - e_a \qquad \text{(Equation 4)}$$

Where VPD is the vapour pressure deficit (kPa), e_s is the saturation vapour pressure (kPa) and e_a the actual vapour pressure. Saturation vapour pressure is related to air temperature as:

$$e^o(T) = 0.6108 \exp\left[\frac{17.27\,T}{T + 237.3}\right] \qquad \text{(Equation 5)}$$

Where $e^o(T)$ is the saturation vapour pressure (kPa) at the air temperature T (^{o}C). However, due to the non-linearity of Equation 5, the daily mean saturation vapour pressure was computed as the mean between the saturation vapour pressure at the daily maximum and minimum air temperature:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \qquad \text{(Equation 6)}$$

Where e_s is the daily mean saturation vapour pressure, $e^o(T_{max})$ is the saturation vapour pressure at daily maximum temperature, and $e^o(T_{min})$ the saturation vapour pressure at daily minimum temperature. Actual vapour pressure was calculated from the relative humidity:

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \qquad \text{(Equation 7)}$$

Where e_a is the actual vapour pressure, RH_{max} is the maximum relative humidity and RH_{min} is the minimum relative humidity.

Soil water balances (in mm) were calculated by comparing the daily inputs from rain (*R*) and irrigation (*I*). Water losses included evapotranspiration (ET_C) as measured by the ECV system, drainage (*D*) (assessed in North West only), and the changes in soil moisture content in the rooted zone (ΔS):

$$R + I = ET_C + D + \Delta S \qquad \text{(Equation 8)}$$

Seasonal values of water inputs and outputs were calculated by summing up daily values. Water balances were assessed from emergence when the ECV system was installed until crop senescence or killing.

Three types of water use efficiencies (WUE) were calculated:

- WUE_{ET}: the yield per unit of total water lost through crop evapotranspiration (from emergence as measured by the ECV) in kg yield m^{-3} water,
- WUE_{R+I}: the yield per unit of total water received by crop through rainfall and irrigation from planting in kg yield m^{-3} water,
- *Normalized* WUE_{ET}: WUE_{ET} normalized for VPD in kg yield m^{-3} kPa (Steduto & Albrizio, 2005)

$$WUE_{ET} = \frac{Y}{ET_{CT} \cdot 10} \qquad \text{(Equation 9)}$$

$$WUE_{R+I} = \frac{Y}{(R_T + I_T)\cdot 10} \qquad \text{(Equation 10)}$$

Y is the dry tuber yield (kg ha^{-1}), ET_{CT} is the accumulated crop evapotranspiration for the season (mm), R_T the cumulative rainfall (mm) and I_T the cumulative irrigation (mm).

$$Normalized\ WUE_{ET} = \frac{Y}{\left(\Sigma\left[\frac{ET_C}{VPD}\right]\right)\cdot 10} \qquad \text{(Equation 11)}$$

In this situation, daily ET_C was divided by the daytime VPD (kPa) and accumulated from emergence over the season.

Pearson's correlation coefficient (*r*) was used to assess the strength of relationships between daily ET_C and ET_O and between (LE+H) and (R_n-G) in the energy balance assessment. Simple linear regression analyses were used to assess the energy balance closure of the ECV measurements.

3. Results

3.1 Weather conditions and irrigation management

In Limpopo, temperatures during the growing season were relatively cool compared to North West (Fig. 1A) as the crop was planted early winter and harvested in spring (Table 2). Temperatures gradually increased during the cropping season. Only 15 mm of rainfall was received during the season from planting and the crop strongly depended on supplementary irrigation for its water supply (Table 2). Irrigation (4-9 mm per event) was applied usually every second day. The crop was irrigated less frequently (every third day) between DAE 1 and 14, and daily between DAE 90 and 100, when temperatures were relatively high. In North West, the growing season was also unusually dry with only 19 mm of rainfall received. The crop was irrigated almost every day from emergence to crop termination, typically receiving 5-8 mm per event. The crop was planted in spring and harvested in mid summer, with warm maximum day temperatures (frequently > 35°C) from crop emergence until maturity (Fig. 1B). Solar radiation was higher in NW than in Limpopo, reflecting the different growing seasons. Sudden dips in radiation (Fig. 1) were due to cloudy conditions. No weather data were obtained at 43 and 82 DAE in Limpopo. Vapour pressure deficit (VPD) during the growing season was generally lower in Limpopo than in North West (Fig. 2) due to lower temperatures in Limpopo. The relative humidity was low during the growing seasons at both sites. The seasonal mean VPD was 1.88 kPa in Limpopo and 2.35 kPa in North West (standard deviation of 0.72 and 0.59 respectively).

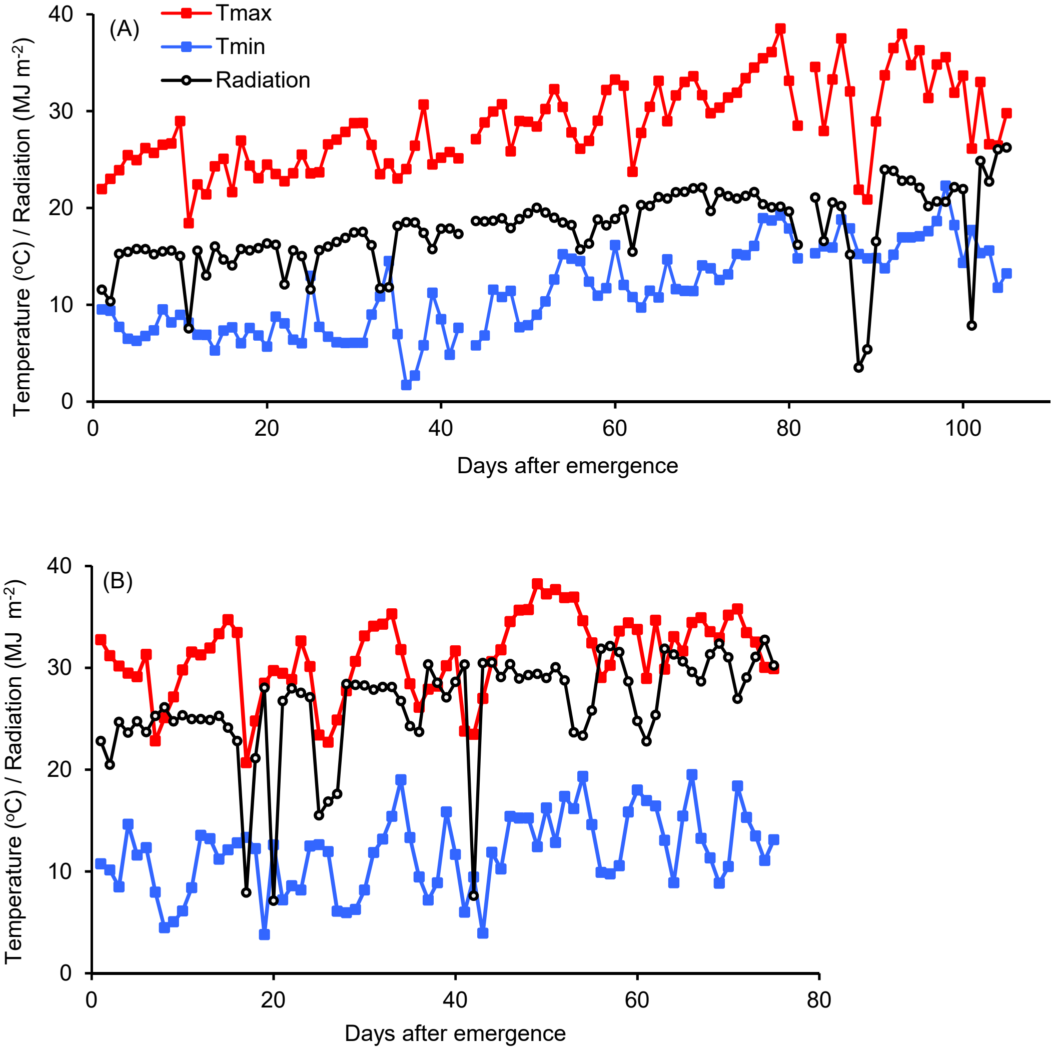


Fig. 1. Daily minimum and maximum temperatures and total solar radiation during the growing season for the sites in (A) Limpopo and (B) North West.

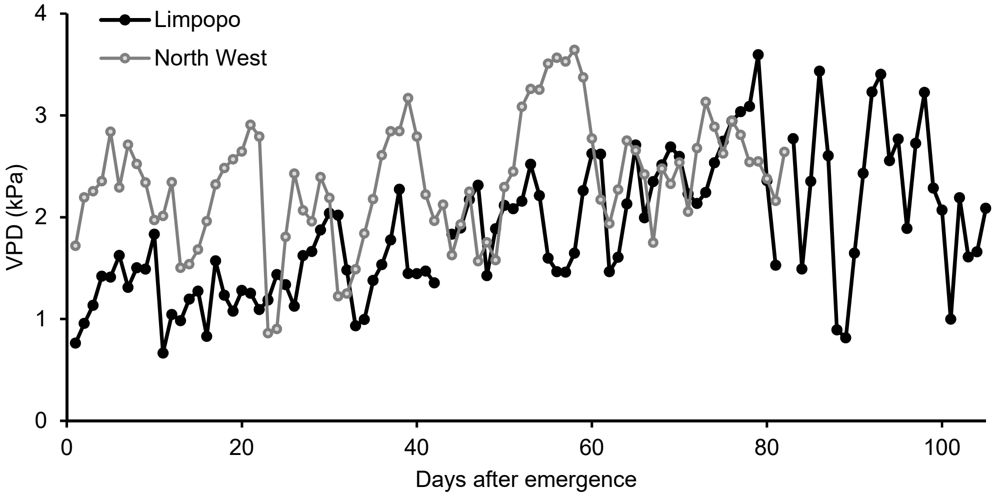
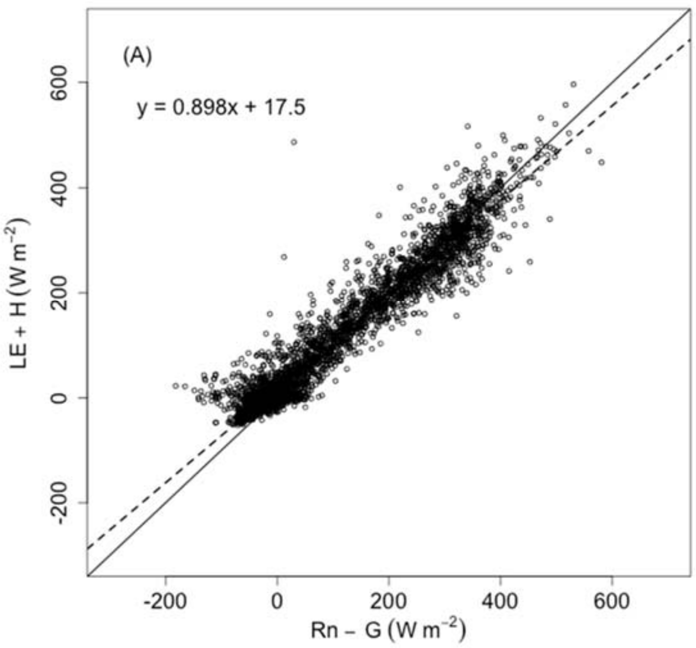
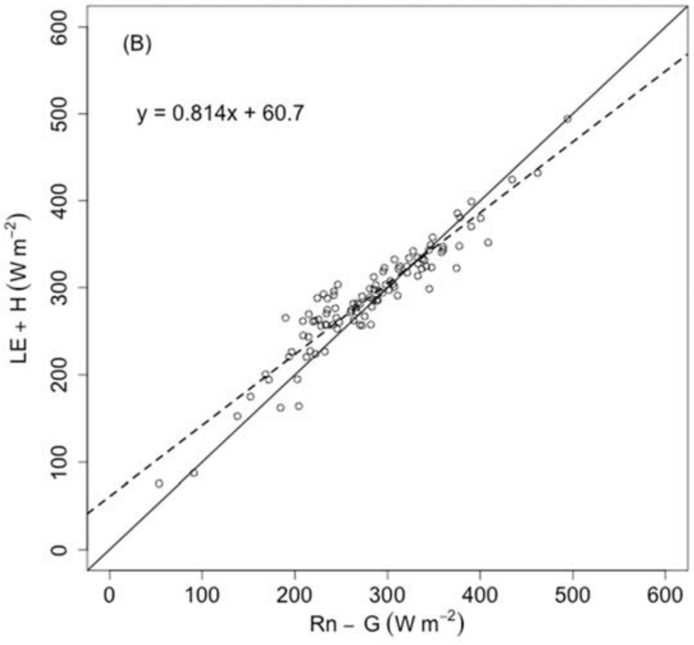


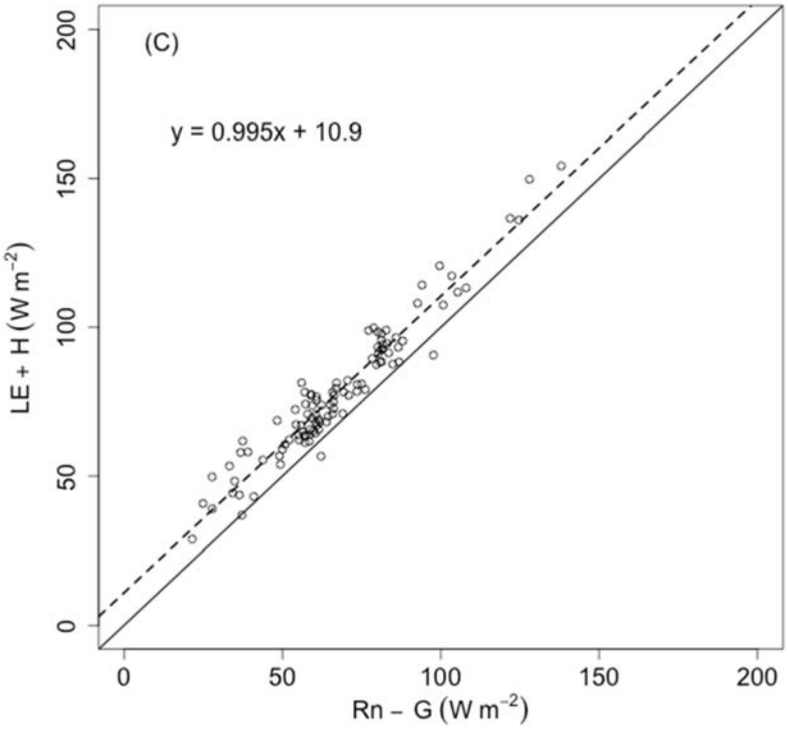
Fig. 2. Daily vapour pressure deficit (VPD) during the growing seasons in Limpopo and North West.

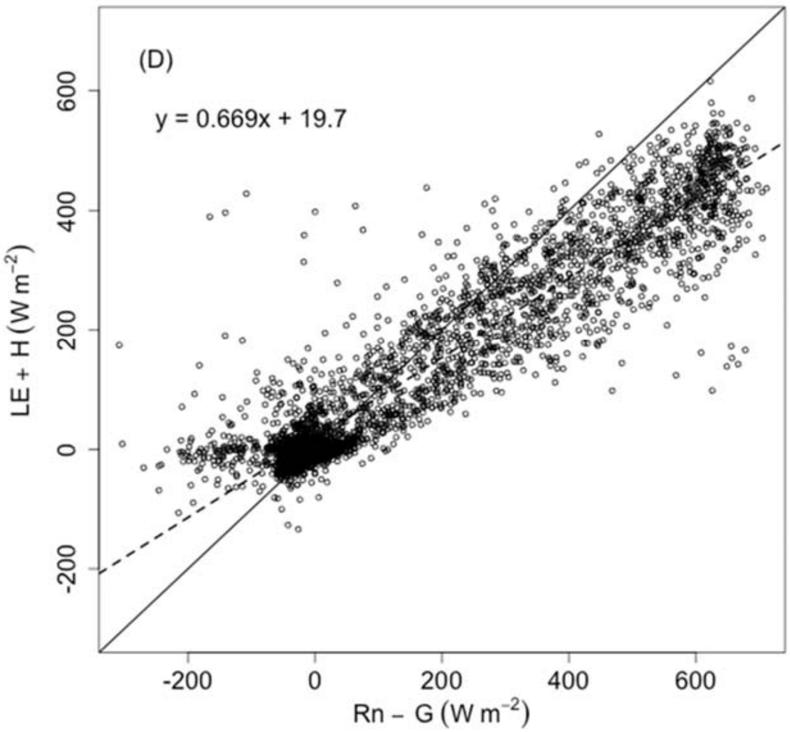
3.2 Energy balances and diurnal courses

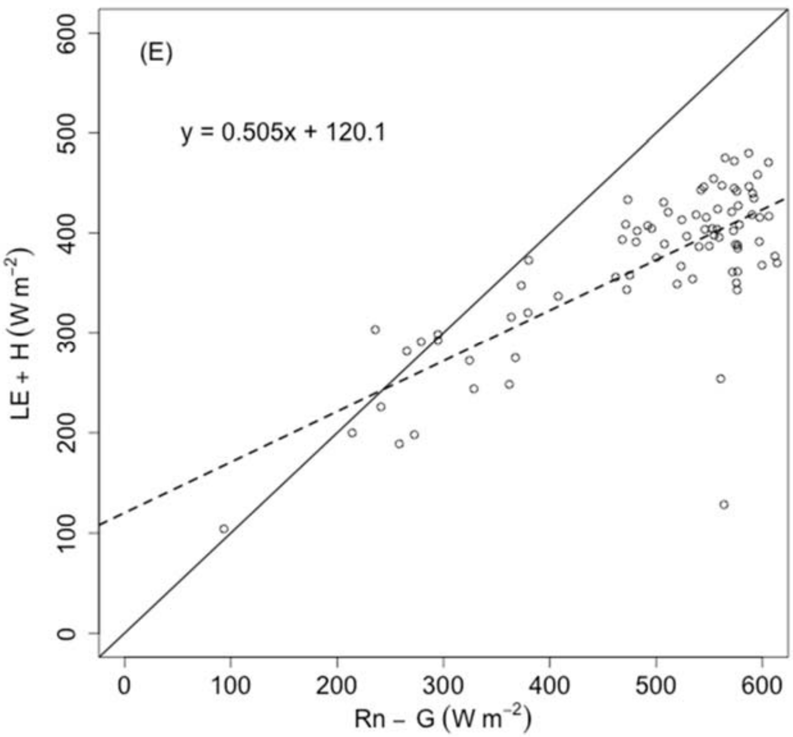
At the site in Limpopo, the amount of energy measured by the ECV closely matched the available energy sources and sinks. In both the 30-min interval data and the daytime data, the regression line closely matched the 1:1 line and only few strong outliers could be observed (Fig. 3 A, B & C), with high correlation coefficients (*r*) between (R_n-G) and (LE+H) of 0.97 for the 30-min and 0.94 for the daytime data. The energy discrepancies were larger in North West (Fig. 3 C, D & E) where (R_n-G) tended to be larger than (LE+H) at higher values. More outliers could be observed in the data from North West, as reflected by correlation coefficients (*r*) of 0.94 for the 30-min and 0.83 for the daytime data. The daytime discrepancies were used to correct the daytime LE and ET_C estimations, as explained in the Methodology. Daytime (R_n-G) was generally higher than (LE+H) as the radiant energy received during the daytime resulted in positive R_n as energy was supplied to the vegetation surface for evapotranspiration. H, G and LE were also positive during the day, as the energy supplied by R_n was lost from the surface through heat conduction into the soil, heat transfer into the atmosphere and evapotranspiration (Fig. 4). After correction, the correlation between (R_n-G) and (LE+H) was high (*r* = 0.96) for the 24h data from North West (Fig. 3E) and the energy imbalance improved from 17 % to 4 %. Modest adjustments to ET_C were made due to corrections of the daytime energy balance and did not have major impact on calculated K_C values.






(C)
y = 0.995x + 10.9
LE + H (W m^{-2})
Rn – G (W m^{-2})
0
50
100
150
200
0
50
100
150
200


(D)
y = 0.669x + 19.7
LE + H (W m^{-2})
Rn – G (W m^{-2})
-200
0
200
400
600
-200
0
200
400
600


(E)
y = 0.505x + 120.1
LE + H (W m^{-2})
Rn – G (W m^{-2})
0
100
200
300
400
500
600
0
100
200
300
400
500
600

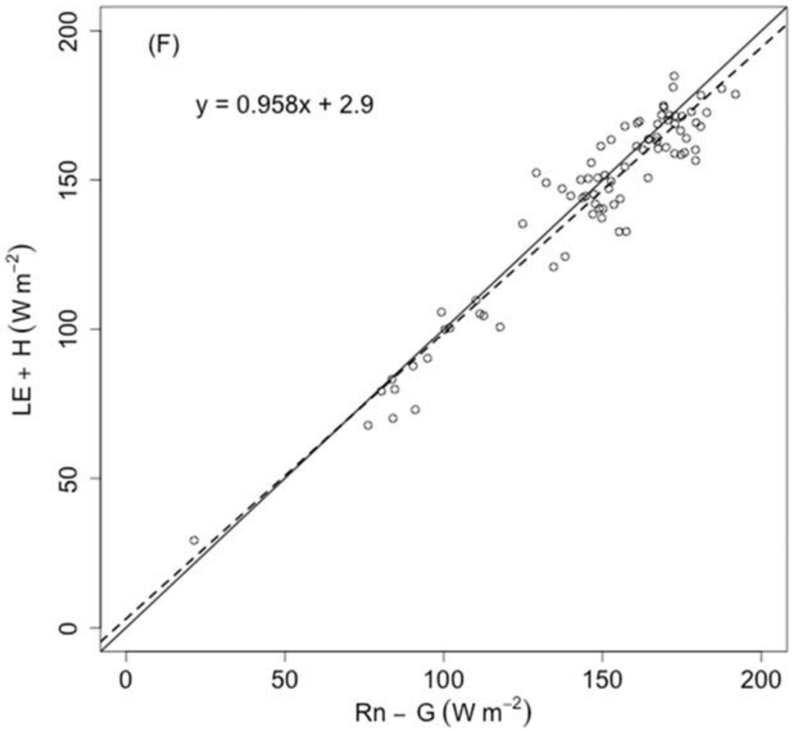

(F)
y = 0.958x + 2.9
LE + H (W m^{-2})
Rn – G (W m^{-2})
0
50
100
150
200
0
50
100
150
200

Fig 3. Scatterplots of (R_n – G) against (LE + H) : uncorrected 30 min data from the sites in Limpopo (A) and North West (D), uncorrected daytime (10.00-15.00) data from Limpopo (B) and North West (E), and the corrected 24h data from Limpopo (C) and North West (F). The dashed line represents the linear regression line, the continuous line the 1:1 line, the regression equation is also given.

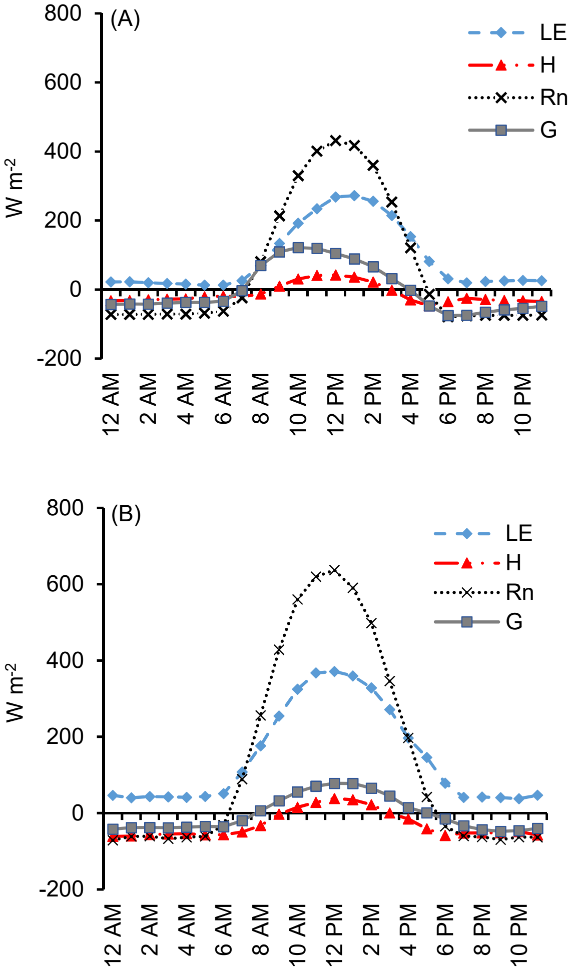


Fig 4. Mean diurnal variation in energy balance components (LE – Latent energy, H – sensible heat flux, R_n – net radiation and G – soil heat flux) over the growing season in (A) Limpopo and (B) North West.

The mean daily R_n in North West (600 – 700 W m^{-2}) was higher than in Limpopo (400 – 500 W m^{-2}). Parent and Anctil (2012) also obtained lower values of R_n in a cooler season with low radiation and ambient temperature conditions (Mean temperature: 15.2 ºC, total rainfall: 563.3 mm). At night, R_n was negative as there was no solar radiation and therefore no energy supplied. LE, indicative of evapotranspiration, was minimal at night, as the stomata are closed. LE started to increase after sunrise and largely followed the inclination of the sun, reaching a peak just after midday. LE started to decline before maximum temperatures were reached at 14.00-15.00, indicating that it is more driven by solar radiation than by air temperature. The mean LE peaked at 367 W m^{-2} in North West and at 272 W m^{-2} in Limpopo. The daytime energy exchange at the crop surface was greater in North West than in Limpopo, where lower radiation and shorter day lengths occurred in winter. The mean diurnal courses of the energy balance components were consistent with what is expected from a crop surface.

3.3 Water vapour fluxes and crop coefficients

The mean daily ET_C over the growing season was 3.2 mm in Limpopo and 5.7 mm in North West. These differences in daily ET_C reflected differences in latent heat flux, as governed by weather conditions and day length. In Limpopo, daily ET_O and ET_C gradually increased over the growing season (Fig. 5A), as temperatures and radiation levels increased with the crop growing into spring (Fig. 1A). The correlation between ET_O and ET_C was high during the entire season, with the exception of the vegetative phase (the first 2 weeks after emergence) (Table 3). The high ET_C and low discrepancy with ET_O could have been a result of an increase in ET_C due to low VPD in winter. In North West ET_O and ET_C were higher (Fig. 5B) than in Limpopo. Moreover, the discrepancies between ET_O and ET_C were larger. The discrepancies were relatively large in the beginning of the growing season (vegetative growth stage). The correlation improved in the growth stages thereafter and ET_C followed ET_O more closely (Table 3). Towards the end of the growing cycle, ET_C tended to be lower than ET_O at both sites. The total ET_C (ET_{CT}) over the growing season from emergence based on ECV measurements was 338 mm in Limpopo and 466 mm in North West (Table 4). ET_{CT} was relatively low in Limpopo due to cooler weather conditions during winter.

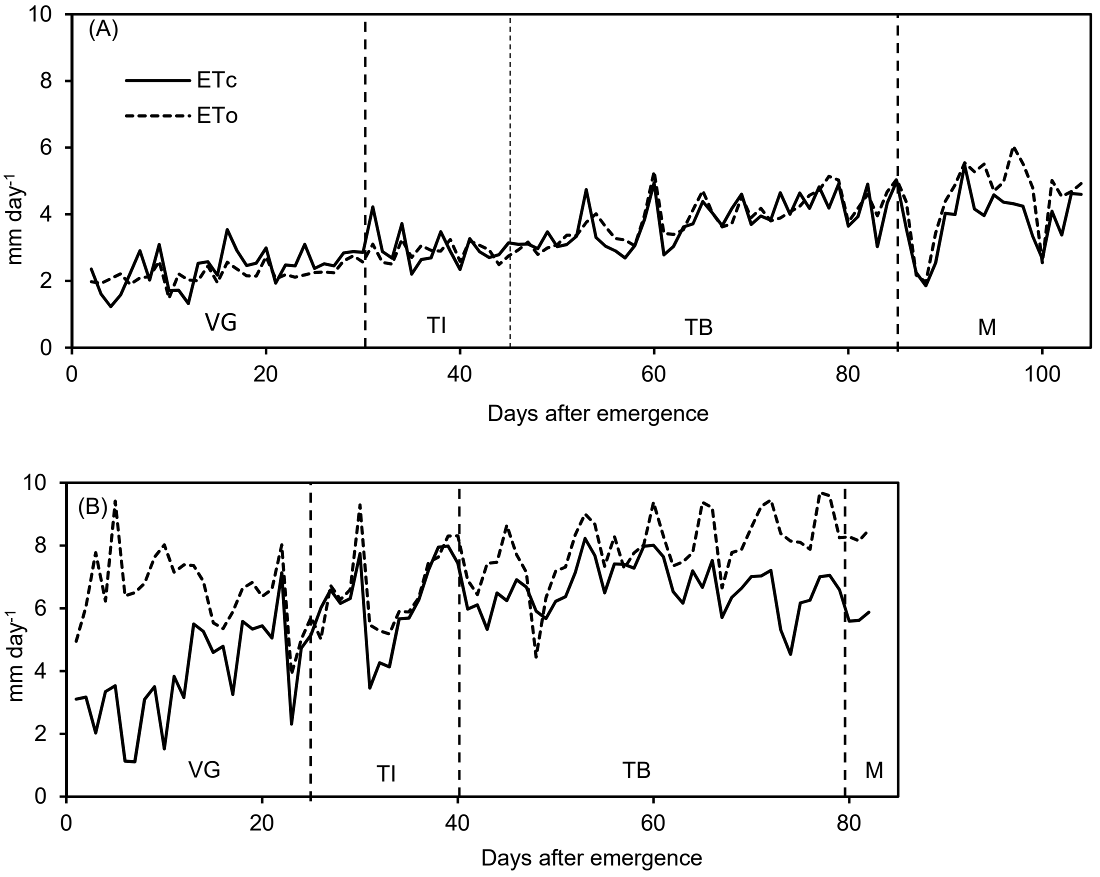


Fig. 5. Daily ET_C and ET_O in different growth stages of potato for sites in (A) Limpopo and (B) North West (Vegetative growth - VG, Tuber initiation – TI, Tuber bulking – TB and Maturation – M).

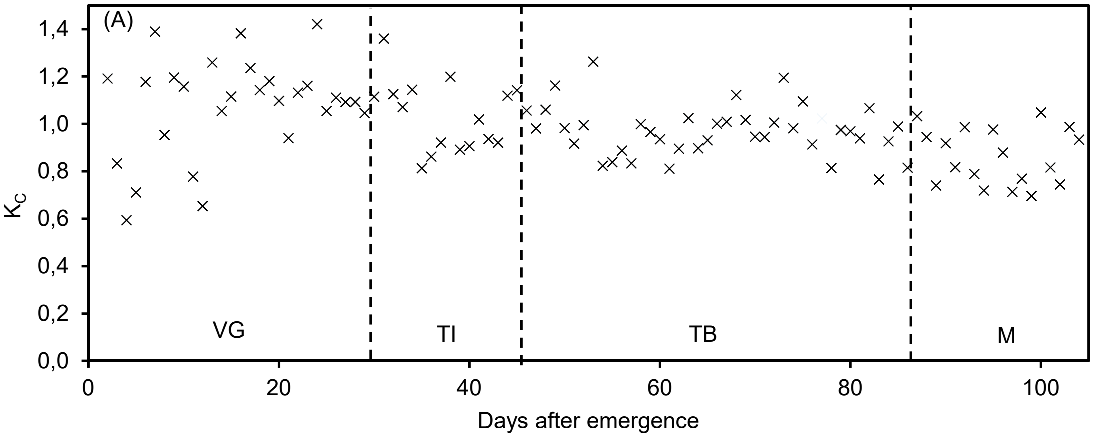
Table 3. Correlation coefficient of ET_C and ET_O (*r*) and the mean K_C value for the entire season (from emergence to crop senescence) and for different growth stages.

Variable / Site	Entire season	Vegetative growth	Tuber initiation	Tuber bulking	Maturation
r					
Limpopo	0.87	0.44	0.73	0.83	0.85
North West	0.51	0.08	0.73	0.63	-
K_C					
Limpopo	0.99	1.00	1.15	0.99	0.87
North West	0.78	0.45	0.86	0.85	-

Table 4. Seasonal soil water balance from crop emergence to harvest (mm).

Site	Input		Output		Balance (Input – Output)
	Effective R_T + I_T	Soil moisture depletion	ET_{CT}	Drainage	
Limpopo	347	4	338	n.a.	+13
North West	426	62	466	0	+22

n.a. = not available



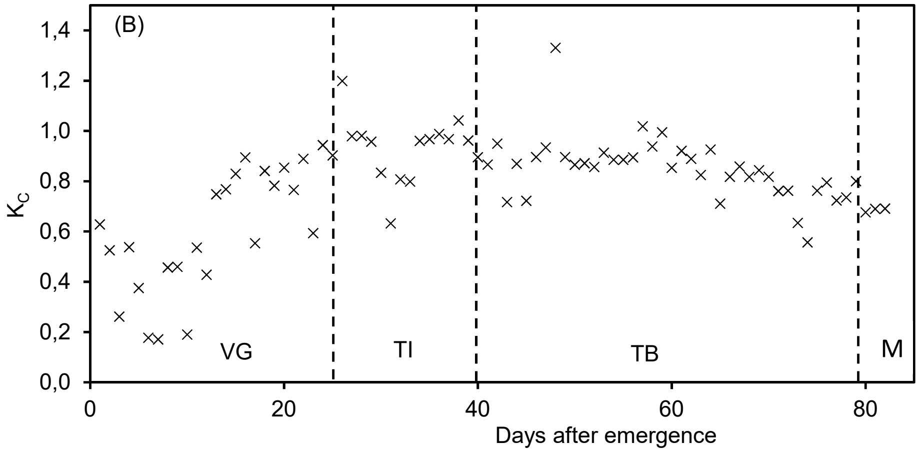


Fig. 6. Daily values of the crop coefficients (K_C) in different growth stages of potato for sites in (A) Limpopo and (B) North West (Vegetative growth - VG, Tuber initiation – TI, Tuber bulking – TB and Maturation – M).

At both sites, daily K_C values were rather variable in the first 2-3 weeks after emergence (Fig. 6), reflecting the discrepancies between ET_O and ET_C (Fig. 5). In Limpopo, K_C values were higher in the initial stage even though the crop canopy did not fully cover the soil. This could be a result of soil evaporation being the major contributor to ET_C as observed with the high soil moisture depletion from emergence, even though soil was initially at field capacity (Pereira *et al.*, 2021). Thereafter, when the crop canopy fully covered the soil, K_C values were fairly stable at both sites (Fig. 6; Table 3). K_C values slightly declined towards the end of the growing cycle, presumably because the crop senesced, and photosynthesized and transpired less actively. The average K_C values for the entire growing season (from crop emergence) were 0.99 in Limpopo and 0.78 in North West (Table 3), where K_C values were consistently lower than in Limpopo (Fig. 6). The observed maximum K_C values were lower than the general upper limit for crops suggested by Allen et al. (2011) of 1.4 for a grass reference base of ET_C in arid climates.

3.4 Water balances and use efficiencies

At both sites, the water holding capacity of the sandy soils was relatively low, while the maximum rooting depth of the crop was estimated at 60 cm. The soil was approximately at field capacity at emergence at both sites. In Limpopo, the soil moisture depletion in the rooted zone increased gradually from emergence, reaching a maximum of 32 mm at 55 DAE, and declined thereafter (Fig. 7). At full senescence, the soil water content was almost similar to that at emergence. Although drainage was not assessed at the site in Limpopo, drainage was likely small and if it occurred, it was probably around or before emergence or during the final days of senescence. In North West, the soil water deficit in the rooted zone increased over the growing season, reaching 65 mm at crop maturity (Fig. 7). No drainage was observed in the drainage lysimeter during the growing season (Table 4), which was in line with the soil moisture data showing increasing deficits. Only after harvest, rainfall led to some measured drainage (data not shown). Even though irrigation in North West was more frequent and almost applied daily, the higher daily maximum temperatures led to higher ET_C and soil moisture depletion (Fig. 7). The inputs and outputs of water in the soil from emergence to crop senescence was rather balanced at both sites, with estimated total inputs being close to the total outputs (Table 4).

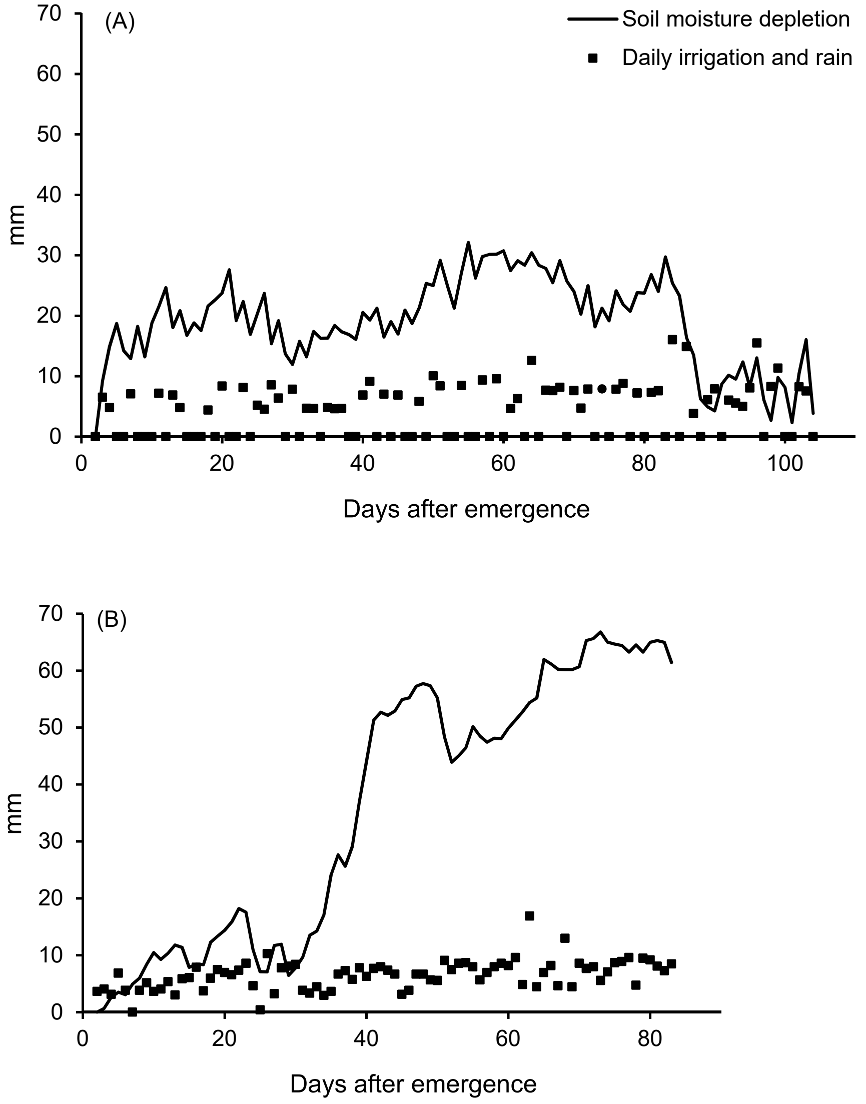


Fig. 7. Soil moisture deficits from crop emergence to termination at 0-50 cm depth and the daily irrigation and rainfall received by the crop in (A) Limpopo and (B) North West.

The site in Limpopo yielded 64 t fresh tuber ha^{-1} (Table 5). The tuber dry matter content in Limpopo was 18.8%, resulting in 12.0 t dry tuber ha^{-1} (Table 5). The site in North West provided 76 t fresh tuber ha^{-1} with a dry matter percentage of 18.5%, resulting in 14.1 t dry tuber ha^{-1}.

Although the growing period in North West was relatively short, high radiation levels resulted in a high yield. Despite a lower yield, the crop in Limpopo had a higher WUE_{ET} and WUE_{R+I} than the crop in North West (Table 5). However, after normalizing WUE for VPD, the WUE achieved in North West was higher than in Limpopo (Table 5). This is discussed in more detail below.

Table 5. Potato tuber yields and WUE based on evapotranspiration from emergence (WUE_{ET}), on the total amount of rain and irrigation from planting (WUE_{R+I}), and the WUE_{ET} normalized for VPD.

	Limpopo	North West
Fresh tuber yield (t ha^{-1})	64	76
Tuber DM yield (t ha^{-1})	12.0	14.1
WUE_{ET} (kg m^{-3})	3.55	3.03
WUE_{R+I} (kg m^{-3})	2.85	2.69
Normalised WUE_{ET} (kg m^{-3} kPa)	6.28	6.84

4. Discussion

Because of the large fetch of the ECV system and the high frequency of sampling, the direct ET_C measurements by an ECV system can be more representative for a field than ET_C estimates based on soil water balance approaches. However, the commonly observed discrepancies in the energy balance can raise questions about the reliability of ECV measurements (Widmoser and Wohlfahrt, 2018). At both sites in this study, the infra-red gas analyzer was calibrated just before installation in the field, and observed discrepancies in the energy balance were unlikely due to inaccurate measurements by the analyzer. The wider discrepancies in the data from North West may be partly due to more turbulent weather conditions typically occurring in spring and summer. Highly turbulent conditions can reduce measurement accuracy (Parent and Anctil, 2012; Anapalli *et al.*, 2018b). The ECV measurements of LE and H represented a larger area of the field, whereas R_n and G were local measurements, and this could have contributed to the lack of closure of the energy balance. Imbalances could also have been caused by an under estimation of G in North West due to the relatively dry soil conditions from 40 DAE until crop senescence. Under such conditions, G could be up to 50 % of R_n whilst LE and H will be low (Heusinkveld *et al.*, 2004). In case G is under-estimated, the available energy for turbulent fluxes will be over-estimated.

Seasonal soil water inputs and outputs were well balanced at both sites, suggesting that the ET_C measurements by the ECV systems were fairly accurate. ET_{CT} over the growing seasons compared well with ET values determined using soil water balance methods under comparable conditions. Steyn *et al.*, (2007) reported an ET_{CT} of potato in a comparable semi-arid climate in Pretoria (South Africa) of 579 mm for a summer crop and 360 mm for an autumn crop. Ferreira and Carr (2002) reported ET_{CT} values of 325 mm and 569 mm for short and long season crops harvested 88 and 117 DAE in a hot and dry climate.

In this study, the observed day-to-day variations in ET_O and ET_C were clearly related to each other. However, the strength of the relationship between ET_O and ET_C, and thus the stability of the K_C value, depended on crop growth stage. The relationship between ET_O and ET_C was stronger, and K_C values were more stable, when the crop had a full canopy and the crop grew at maximum capacity in the middle of the growing season (Fig. 5; Table 3). A poorer correlation between ET_C and ET_O at both sites just after emergence was likely related to the low soil cover during this growth stage. ET_O is indicative for ET_C when a crop has reached full soil cover. If part of the soil is bare, evapotranspiration is more driven by evaporation, which is difficult to predict based on weather variables as it depends on factors such as the humidity and albedo of the soil surface. At low soil cover, spikes in soil evaporation may occur directly after each wetting (irrigation / rain) event (Pereira *et al.*, 2021). These spikes contribute to the day-to-day variation in ET_C. Towards the end of the growing season when the crop senesced and leaves physiologically aged, discrepancies between ET_O and ET_C became somewhat larger and K_C values slightly declined. This was likely the result of crop senescence and the associated reduction in photosynthesis and transpiration rates.

In Limpopo, a stronger correlation between ET_O and ET_C and higher K_C values were observed, compared to the results from North West (Table 3). In Limpopo, soil moisture measurements throughout the season suggested that crop growth was unlikely limited by water availability. In North West, however, soil moisture deficits in the rooted zone increased throughout the season and crop growth was probably limited by water availability. This difference in drought stress between the two sites was in line with visual assessments of the crops. The occasional drought stress in North West explains the observed weaker correlation between ET_O and ET_C. Moreover, drought stress may explain the lower K_C values in North West. Furthermore, high temperatures, as experienced in spring and summer in North West, lead to decreased leaf and stomatal conductance and increased VPD (Fig. 2), limiting plant transpiration under conditions of high atmospheric demand (Marin *et al.*, 2016; Xu *et al.*, 2018). When the atmospheric evaporative demand is high, as indicated by a high vapour pressure deficit, plants may partially close their stomata to reduce transpiration (Fernandes-Silva *et al.*, 2016; Anapalli *et al.*, 2018b; Marin *et al.*, 2019). So besides the impact of water stress, the lower K_C values in North West may have been due to this stomatal response to the high air temperatures (Tmax > 30 ^oC).

Crop management at both sites was such that the crops were unlikely to suffer significant nutrient-, pest- or disease-related stresses. Any stresses that affect the crop most likely also affect K_C values. The measured K_C values at both sites fell within the variability reported by other studies, though the values observed in Limpopo were relatively high (Table 6). Allen *et al.* (1998) noted that weather-based evapotranspiration equations are not expected to perfectly predict ET_C under different climatic conditions due to simplification in formulation and errors in measurements of air temperature, relative humidity, solar radiation and wind speed. Mean K_C values should remain relatively stable during a specific growth stage in case the crop is well-watered, as was observed during the tuber initiation and bulking stages covering most of the growing season.

Table 6. Comparison of crop coefficients at different growth stages of potato grown in different locations (entire season, sprout development (S), vegetative growth (VG), tuber initiation (TI), tuber bulking (TB) and maturation (M)).

Study	Methodology	Variety	Study area	Climate	Season	S	VG	TI	TB	M
This study – Limpopo	ECV	Mondial	South Africa	Semi-arid	0.99	-	1.00	1.15	0.99	0.87
This study – North West	ECV	Mondial	South Africa	Semi-arid	0.78	-	0.45	0.86	0.85	-
Allen et al. (1998)	Penman-Monteith	Unknown	USA	Arid	0.92	0.80	0.98	-	1.15	0.75
Kayshap and Panda (2001)	Lysimeter	Unknown	India	Sub-humid	0.78	0.42	0.85	-	1.27	0.57
US Bureau of Reclamation (1972)	Penman-Monteith	Russet Burbank	USA	Continental	0.67	0.46	0.78	0.88	0.93	0.70
Parent and Anctil (2012)	ECV	Reba	Canada	Humid continental	0.73	-	0.63	0.91	0.81	0.78
Steyn and Du Plessis (2012)	Pan evaporation	Up-to-Date	South Africa	Semi-arid	0.68	0.45	0.65	0.80	0.83	0.60

The results indicated that ET_O derived from weather variables can be used to estimate ET_C of potato and water requirements for irrigation management (Bandyopadhyay *et al.*, 2003; Anapalli *et al.*, 2018). However, estimations of the actual irrigation water requirement should take into account the soil type and effective precipitation, and can be substantially more than evapotranspiration due to other losses, such as irrigation inefficiencies, drainage and run-off (Testa, Gresta and Cosentino, 2011; Seidel *et al.*, 2019). In the absence of rainfall, farmers using appropriate irrigation scheduling tools can accurately match irrigation amounts with crop demand, reducing water losses to a minimum even on well-draining sandy soils, as observed in this study. Heavy rainfall events, mostly occurring in summer in the study region, can lead to substantial drainage which may cause an imbalance between water input and evapotranspiration. This type of drainage cannot be avoided through improved irrigation management.

The high tuber yields achieved in North West (Table 5) indicated that the crop was only mildly affected by drought stress. In general, a drought-stressed crop is expected to use water more efficiently than a crop free of water stress. However, the observed WUE_{ET} and the WUE_{R+I} of the crop in Limpopo were higher than in North West. Cooler ambient temperatures in winter in Limpopo resulted in a lower VPD (Figure 2) and likely a lower transpiration by the crop for a certain amount of CO_2 absorbed. Steyn *et al.* (2007) also reported higher transpirational WUE in the cooler season (autumn) than a warmer season (spring). When WUE was normalized for VPD, the WUE in North West was somewhat higher than in Limpopo. This difference is likely related to the conditions of drought stress experienced by the crop in North West, reducing crop transpiration.

5. Conclusions

This study is the first application of ECV techniques in potato crops planted in different seasons in a semi-arid climate. ET_C had a distinct seasonal pattern with a gradual increase from emergence, reaching a peak at full canopy cover (tuber bulking stages), and declining later in season as the crop matured and senesced (tuber maturity stage).

Seasonal K_C values for the spring and winter crops were 0.78 and 0.99 respectively. While ET_O served as a good indicator of the day-to-day patterns in ET_C measured by the ECV system, the seasonal K_C values varied considerably between winter and spring/summer crops. This suggests that ET_O, which can be relatively easily estimated based on data from a weather station, can be used for irrigation scheduling of potato, but K_C values used to estimate crop evapotranspiration may need to be adjusted depending on the cropping season.

WUE_{ET} and WUE_{R+I} of potato were higher for the crop growing in the cooler winter compared to the crop growing in spring / summer, despite higher yields and a modest irrigation regime in the spring / summer crop. To optimize WUE of potato in water-scarce areas that rely mostly on irrigation water for potato production, it is advisable to grow potato crops in the coolest growing season. For South Africa, that is winter in frost-free areas and the first planting window in spring in frost-prone areas. Further studies should focus on collecting ET_C and ET_O data in different climates and seasons so as to improve our understanding if and how K_C of potato is affected by weather and crop management conditions.

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7. Declaration of competing interest

None

8. References

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