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Deriving crop coefficients for evergreen and deciduous fruit orchards in South Africa using the fraction of vegetation cover and tree height data

Munashe Mashabatu [a,*], Zanele Ntshidi [b], Sebinasi Dzikiti [c], Nebojsa Jovanovic [a], Timothy Dube [a], Nicky J. Taylor [d]

[a] Department of Earth Sciences, University of the Western Cape, Capetown, South Africa
[b] Council for Scientific and Industrial Research, Stellenbosch, South Africa
[c] Department of Horticulture, Stellenbosch University, Stellenbosch, South Africa
[d] Department of Plant and Soil Sciences, University of Pretoria, South Africa

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ABSTRACT

Inaccurate crop coefficients are major contributing sources of uncertainty that lead to inefficient use of limited available water resources. Understanding the need to improve water use efficiency in South Africa's fruit industry, this study evaluated the method of deriving crop coefficients developed by Allen and Pereira (2009) over a variety of irrigated fruit tree crops. Detailed data of transpiration, evapotranspiration and weather variables measured using the heat ratio method, eddy covariance method and automatic weather stations, were collected from a water research funding body established by the South African government. This study adjusted the stomatal sensitivity function (Fr) in the model by replacing the ratio of the leaf resistance (r_l) to the standard leaf resistance of a reference crop (100 sm^{-1}) with r_l/α where α is a resistance parameter for the specific crop. The resistance parameter was solved accordingly for each fruit type. Respective unique α values were obtained as: macadamia nuts (200 sm^{-1}), citrus (50 $s\ m^{-1}$), peaches (20 $s\ m^{-1}$) and pecans (20 $s\ m^{-1}$). These unique values were used to simulate basal and single crop coefficients that produced satisfactory results when compared to the actual measured values. Overly, no unique standard α value exists for most tree crops although a value close to 20 sm^{-1} may give reasonable estimates for pome and stone fruit. Crop coefficients derived using locally measured data were standardised and tabulated in a format that facilitates their transferability between sites. However, there is still a need to acquire crop specific information to parameterize α and improve accuracies.

1. Introduction

South Africa is one of the driest countries globally as it receives an average annual rainfall (495 mm) that is less than the global annual average (840 mm) (de Villiers and de Wit, 2010). The country operates on strained water resources with approximately 98 % of the surface water already allocated (Van Wilgen and De Lange, 2011). An increase in evaporative losses should be expected in South Africa over the years due to the effects of climate change (Midgley et al., 2015). Climate change and variability, and various environmental changes have put a lot of pressure on the available water volumes for the irrigation of crops, given that more than 60 % of South Africa's available water resources are used for agricultural purposes (Reinders et al., 2013). In this regard, agriculture among other water-dependent sectors has suffered increased challenges of growth and sustainability.

Fruits and nuts are one of the most irrigated crop groups in South Africa (Taylor and Gush, 2009) since they are regarded as high-value and high-water-requiring crops (Fereres et al., 2003). Even though South Africa receives low rainfall volumes, fruit farmers sustain and grow their fruit industry by supplementing the low rainfall with irrigation water to meet the respective crop water requirements and therefore increase the crop yield (Jovanovic et al., 2020). Farmers in South Africa determine the amount of irrigation to apply in their fields by estimating the crop evapotranspiration (ET_c), also referred to as crop water requirements, as a product of the crop coefficient (K_c) and the reference evapotranspiration (ET_o) (Allen et al., 1998). K_c which represents the integration of the crop's primary characteristics that distinguishes it from ET_o, are transferable between the fields with the assumption that ET_o accounts for the weather-related variations. Therefore, ET_o represents the actual evaporative demand. Crop

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* Corresponding author.
E-mail address: 4000684@myuwc.ac.za (M. Mashabatu).

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coefficients are assumed as standard when there are standard cropping conditions (well-watered crops in the absence of yield limitations from water stress). It is quite challenging to obtain accurate K_c values because the method should account for the specific orchard conditions and factors such as the cultivar type, crop height, canopy cover, crop spacing, soil management, etc. (Girona et al., 2011).

A review done by Pereira et al. (2021a, 2021b, 2021c) showed that the Food and Agricultural Organization (FAO) crop coefficient approach remains the widely used crop coefficient approach, and is popularly used for irrigation water management. Most recent studies applied and adjusted the Allen and Pereira (2009a, 2009b) approach which improved the FAO-56 crop coefficient approach (Allen et al., 1998) by introducing the crop density function, which incorporates observations and measurements of the crop height, the fractional vegetation cover, or the Leaf Area Index (LAI) to estimate crop coefficient values for a wide range of crops. The practical application of the Allen and Pereira (2009a, 2009b) (A&P) method was tested on the field, vegetable and fruit crops in a study by Pereira et al. (2021a, 2021b, 2021c). Tabulated FAO-56 crop coefficients are still considered valuable and reliable as they have close agreement with those updated by Pereira et al. (2021a, 2021b, 2021c). However, it is recommended to scrutinize all new data on crop coefficient values against these recent updates and those tabulated in the FAO-56th document.

Crop coefficients that have been derived and tabulated by past studies are not readily transferable between sites of different characteristics even if they are planted to the same crop. Crop coefficients tabulated in the FAO-56 document were derived under temperate sub-humid conditions (Allen et al., 1998). Therefore, it will be quite difficult to validate and use these crop coefficients under local conditions. To derive accurate crop coefficients for fruit tree crops, this study applied the modified A&P approach using readily available substantial historical data from past studies.

It was observed by Pereira et al. (2020) that the effects of stomatal adjustment play a primary role in the performance of the A&P approach for tree crops. Likewise, Taylor et al. (2015) and Mobe et al. (2020) argued that the stomatal sensitivity function (Fr) from the A&P approach was an overriding factor that caused the A&P approach to consistently overestimate the basal crop coefficients for citrus and apple trees respectively. The objective of the stomatal sensitivity function is to discern the transpiration response of one crop from the other (Mobe et al., 2020). A suggestion by Mobe et al. (2020) of replacing the ration $r_l/100$ in Fr with $r_s/50$ for orchards with sparse canopies ($LAI < 3.0$) did not work for apples. In the alternative ratio, r_s is the bulk surface resistance, whereas 50 is the value of the bulk surface resistance for the grass reference. Therefore, the study replaced the 100 s m^{-1} with a resistance parameter α which represents the minimum unstressed canopy resistance for apple trees. Mobe et al. (2020) finally solved the A&P equation for α and obtained a mean value that made the equation more precise. Following this method, this study aimed to calculate the minimum unstressed canopy resistance for selected irrigated fruit trees. The mean canopy resistance values were then used to derive crop coefficients for the respective tree species.

2. Materials and methods

2.1. Study sites

This study focused on fruit trees grown in well-irrigated orchards

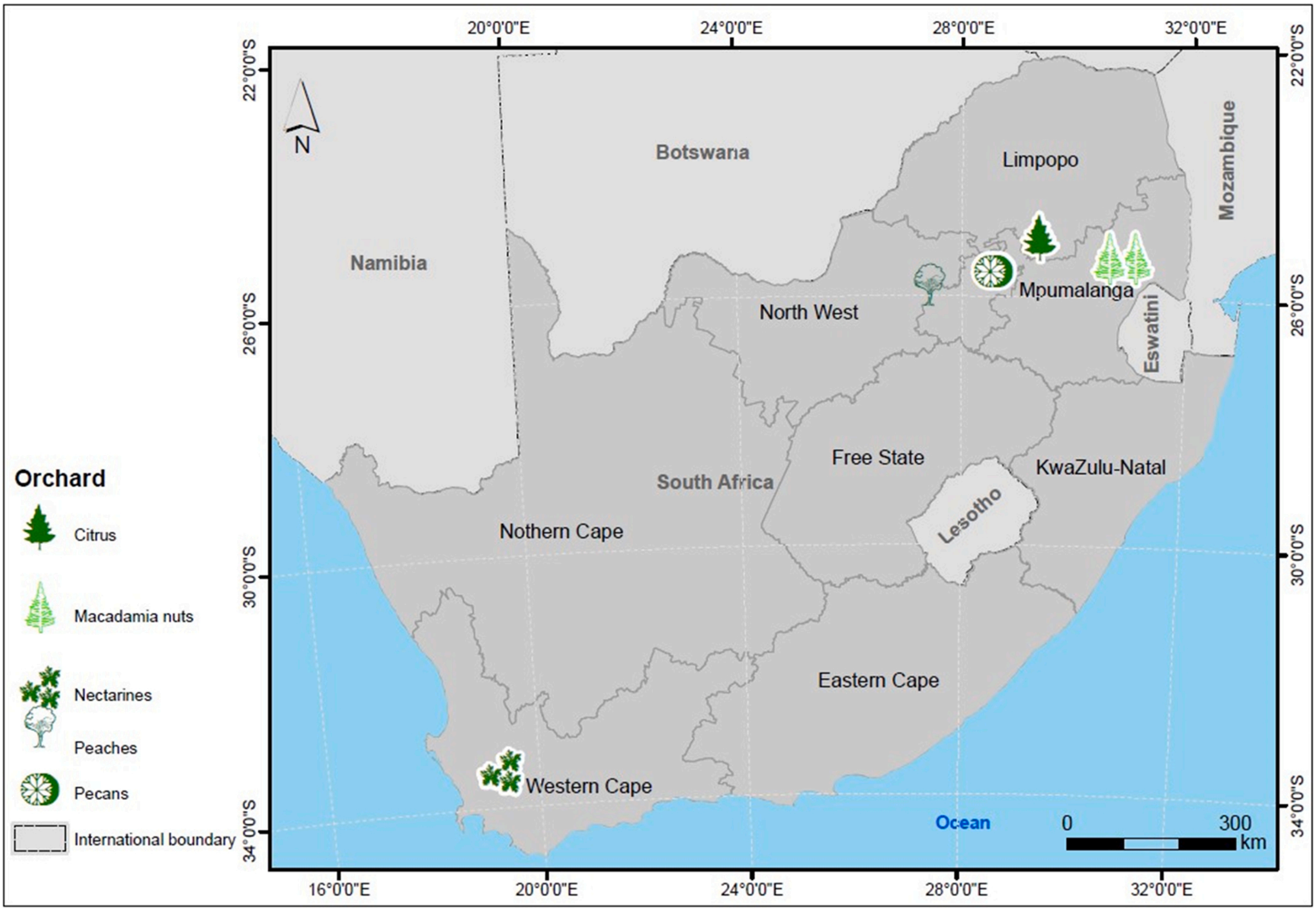

Fig. 1. Location of the study orchards across South Africa. Graphs. Study sites.

across South Africa which have efficient management practices in place. Fig. 1 shows the study orchards located in the summer and winter rainfall regions of South Africa namely: (1) 'Beaumont' Macadamias at White River and Nelspruit both in Mpumalanga Province (2) Delta Valencia oranges at Groblersdal in Mpumalanga Province, (3) 'Alpine' nectarines at Wolseley, Western Cape Province, (4) 'Transvalia' peaches at Rustenburg, (5) 'Choctaw' pecans at Cullinan, in Gauteng Province. Information and descriptions of these study orchards are summarised in Table 1. All measured data reported in this study were obtained from technical reports on the water use of various irrigated fruit tree species written by Gush and Taylor (2014a) and Taylor (2021).

2.2. *Field data*

2.2.1. *Weather, soil water and tree attributes data*

Automatic weather stations (AWS) equipped with data loggers and sensors to measure rainfall, solar radiation, temperature, humidity, wind speed and direction were installed in an open area approximately within 200 m from all the study orchards. Sensors were all mounted 2 m above the ground. Weather variables were measured at 10 s intervals and stored in the data logger at hourly intervals for the respective monitoring periods. Daily averages or totals that were processed from the hourly values were used to calculate daily reference evapotranspiration (ET_o) for all sites according to Allen et al. (1998). Volumetric soil water content was measured at different positions and depths (Table 3) using TDR100 systems. Additional TDR soil water sensors were installed within the tree rows to monitor soil water content in the top 10 cm of the soil profile. In a Bahianinha navel orchard, tipping buckets were placed under drippers to measure irrigation water volumes. In a Transvalia peach orchard, three pairs of Wetting Front Detectors (WFDs) were installed. Soil evaporation was measured at various locations to account for wetting variability using micro-lysimeters. Leaf Area Index (LAI) and Fractional Interception of Photosynthetic Active Radiation (FI) measurements were taken every six weeks using ceptometers (specific brands varied per orchard). Sampling was done within and across the row at 1 m intervals between 12:00 and 14:00 under clear sky conditions. Leaf resistance (r_l) data was measured on sun-exposed leaves per tree during midday for a couple of respective days before calculating an average for each measurement. In most cases, mean monthly leaf resistance values were derived directly from measured basal crop coefficient values.

2.2.2. *Sapflow/transpiration (T)*

Sap flow measurements in all study sites were taken using the heat ratio method (HRM) of the heat pulse velocity (HPV) technique (Burgess et al., 2001). Heater probes and thermocouple pairs were inserted to various depths within the xylem sapwood of at least three trees to determine radial variations of Sapflow (Table 3). The HPV probes were withdrawn and re-inserted to correct depths periodically, to account for stem growth, unintentional movement or accidental removal of probes. Wound correction coefficients described by Burgess et al. (2001) were used to correct HPV signals for sapwood wounding. Sap flux densities obtained from a method described by Marshall (1958), were finally converted to tree total Sapflow values using the calculation of the sum of the cross-sectional area for individual tree stems and the products of sap flux densities. Daily, monthly, and annual Sapflow volumes for each tree were assumed to equate to transpiration (T). Independent calibration of heat-based sap flow measurement techniques was done as recommended by Steppe et al. (2010). Measurements of orchard evapotranspiration (ET), obtained from Eddy Covariance techniques, were used for this purpose as applied in some previous studies including Cammalleri et al. (2013). Daily transpiration volumes ($L.tree^{-1}.day^{-1}$) were scaled up to spatial estimates (mm) using the number of trees per hectare.

2.2.3. *Evapotranspiration (ET)*

ET was estimated using the eddy covariance (EC) and renewal micrometeorological approaches that utilise the energy balance technique. These approaches were deployed 1–2 week 'window periods' in different seasons. An Open Path Eddy Covariance (OPEC) system comprising of a sonic anemometer for sensible heat flux, and an open path infrared gas analyser for latent heat flux were used to determine evapotranspiration of the study orchards. Measurements were sampled and logged on a data logger every 30 min. Available ET data was of short duration, a few days to weeks at most. Further detail on the EC system for the respective sites is summarized in Table 3. No ET measurements were taken at the Groblersdal and Rustenburg sites.

2.3. *K_c calculation approach*

The study adopted the dual coefficient calculation approach (Allen et al., 1998). In this method, the full measured orchard coefficient $K_{c\ mes}$ is calculated as the sum of the measured orchard basal crop coefficient ($K_{cb\ mes}$) and the measured soil evaporation coefficient ($K_{e\ mes}$). $K_{cb\ mes}$ is calculated as the ratio of the measured orchard transpiration ($T_{c\ mes}$) to the reference evapotranspiration (ET_o) i.e., $K_{cb\ mes} = T_{c\ mes}/ET_o$. ET_o was calculated using the modified Penman-Monteith equation for a reference short grass that is actively growing without any water stress. The single crop coefficient was therefore calculated as a ratio of the actual ET to

Table 1
A summary of the crop types, orchard properties, and observed and measured parameters of all the study sites across with various climatic regions across South Africa. Study sites.

Crop type	Macadamia nuts		Citrus	Nectarines	Peaches	Pecans
Location name	White River, MP	Nelspruit, MP	Groblersdal, MP	Wolseley, WC	Rustenburg, NW	Cullinan, GP
Coordinates	25.21’32.80"S, 31.3′34.44"E	25.21’50.36"S, 30.36’46.47"E	25.02’32.69"S, 29.22’09.76"E	33.25’0.59"S, 19.14’44.84"E	25.46.215"S, 27.20.305"E	25.35’20.65"S, 28.33’31.90"E
Climatic region	Subtropical	Subtropical	Semi-arid	Mediterranean	Semi-arid	Subtropical
Cultivar	Beaumont 695		Bahianinha Navel	Alpine	Transvalia	Choctaw
Age	6–7 years	11 years	6–7 years	8–10 years	-	34–37 years
Height	5 m	5.7 m	2.5 m	3.2 m	-	13.0 m
Rootstock	Beaumont	Beaumont	Carizzo Citrage	SAP0778	-	Barton
Block size	2.6 ha	3.8 ha	2.7 ha	2.8 ha	-	22 ha
Planting density	312 trees per ha	312 trees per ha	833 trees per ha	1667 trees per ha	-	142 trees per ha
Irrigation method	Drip	Micro-sprinklers	Drip	Micro-sprinklers	Drip	Micro-sprinklers
Soils	Sandy loam	-	Sandy loam	Sandy (80–100 cm) rooting depth	-	Sandy to sandy loam
Yield	5 t ha^{-1}	-	60 t ha^{-1}	32–35 t ha^{-1}	-	1.9 t ha^{-1}
Data collection date	Oct 2010 - Oct 2012	2016 – 2019	Oct 2011 - Oct 2013	Aug 2010 - Jul 2013	Aug 2008 - Jun 2009	Sep 2009 - May 2012
Peak fc (%)	64	72	54	70	-	80

*MP – Mpumalanga Province, WC – Western Cape Province, NW – Northwest Province and GP – Gauteng Province.

Table 2
Measured and standardised basal and single crop coefficients for macadamia nuts, citrus, nectarine, peach, and pecan orchards (after Gush and Taylor, 2014a). Standardised crop coefficients.

	Evergreen Species								**Deciduous Species**									
	Macadamia Nuts				**Citrus**				**Nectarines**				**Peaches**		**Pecans**			
	K_{cb} mes	**K_{cb} std**	**K_c mes**	**K_c std**	**K_{cb} mes**	**K_{cb} std**	**K_c mes**	**K_c std**	**K_{cb} mes**	**K_{cb} std**	**K_c mes**	**K_c std**	**K_{cb} mes**	**K_{cb} std**	**K_{cb} mes**	**K_{cb} std**	**K_c mes**	**K_c std**
January	0.49	0.61	0.56	0.68	0.14	0.17	0.77	0.86	0.27	0.27	0.71	0.65	0.22	0.27	1.40	1.18	1.84	1.62
February	0.41	0.49			0.43	0.43	0.79	0.63	0.24	0.29	0.58	0.55	0.23	0.26	0.87	0.66	0.97	0.76
March	0.46	0.54							0.31	0.35			0.2	0.21	1.45	1.24	1.49	1.28
April	0.61	0.73							0.45	0.45			0.06	0.04				
May	0.61	0.76							0.4	0.38			0.05	0.03				
June									0.00	0.00			0.00	0.00				
July					0.42	0.35	0.67	0.60	0.00	0.00			0.00	0.00				
August					0.44	0.37	0.57	0.48	0.14	0.14	0.74	0.82	0.00	0.00				
September					0.17	0.17			0.32	0.32			0.14	0.06	0.34	0.12	1.05	0.83
October	0.74	0.81	0.76	0.73	0.17	0.18			0.45	0.47			0.24	0.19	0.57	0.32	0.81	0.56
November	0.48	0.59	0.61	0.72	0.23	0.24			0.41	0.44			0.27	0.27	0.89	0.65	1.16	0.92
December	0.50	0.62	0.57	0.68	0.19	0.19			0.32	0.36			0.20	0.13	0.86	0.62	1.18	0.94

Table 3
Instruments installation detail for the study orchards (after Gush and Taylor, 2014a).

		Macadamia nuts	**Nectarines**	**Pecans**	**Citrus (Bahianinha)**	**Peaches**
	Position of EC tower	Centre of orchard	Centre	Centre	-	-
	Eddy covariance instruments	1.2 m above canopy	3.3 m above canopy	1.5 m above canopy	-	-
	Fetch from prevailing wind		Northerly	150 m	-	-
	Energy balance closure error amount	85–90 %	-	85 %	-	-
	Percentage of flux sensed that originated from the origin	77 %	-	73 %	-	-
	HPV heater-probe depths	10;20;30;45 mm	8;14;20 mm	10;20;45;60 mm	7;14;22;30 mm	10;16;22 mm
	Soil heat flux plates	80 mm below soil surface	80 mm	80 mm	80 mm	-
	Soil temperature probes	20;60 mm below soil surface	20;60 mm	20;60 mm	20;60 mm	-
	Measurement frequency	10 Hz every 30 min	10 Hz every 30 min	10 Hz every 30 min	10 Hz every 30 min	-
Soil water content probes	**Between rows**	15;30;60;90 cm	20;40;75 cm		10;30;60;90 cm	-
	Under a dripper within a row	15;30;60;75;90 cm	20;40;75 cm		10;30;50;70;90 cm	-
	Between drippers within a row	15;30;60;90 cm	20;40;75 cm		10;30;60;90 cm	-
	Within the tree row			10;20;40;60;80;100 cm		
	Across the tree row			10;20;40;60;80;100 cm		

No ET measurements were taken at the Groblersdal and Rustenburg sites.

ET_o, i.e., $K_{c\ mes} = ET_{c\ mes}/ET_o$, while the soil evaporation coefficient was calculated as the difference between $K_{c\ mes}$ and $K_{cb\ mes}$.

The derived crop coefficients for the species were obtained using the modified Allen and Pereira (2009a, 2009b) method, herein referred to as the A&P method., To ensure that the basal crop coefficients can be transferred between fields, Allen and Pereira (2009a, 2009b) proposed a density function (K_d), which expresses the amount of energy available for transpiration defined as;

$$K_d = \frac{K_{cb} - K_{cmin}}{K_{cb\ full} - K_{cmin}} \tag{1}$$

Where K_{cmin} is the minimum basal K_{cb} for bare soil, K_{cbfull} is the estimated basal crop coefficient under conditions of nearly full ground cover. In circumstances where K_{cbfull} was not measured, it was estimated from weather data and crop height as:

$$K_{cbfull} = Fr\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.04(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \tag{2}$$

Where u_2 is the mean wind speed measured at 2.0 m height and RH_{min} is the minimum relative humidity (%) and h is the crop height (m). Fr is the parameter that can be considered as a K_{cb} adjustment factor through crop stomatal control. Basing on the FAO Penman-Monteith equation while assuming full cover conditions, Fr can be calculated as;

$$Fr = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34u_2\frac{r_l}{100})} \tag{3}$$

Where Δ is the slope of the saturation vapor pressure versus the temperature curve (Pa $/^{\circ}$C), γ is the psychrometric constant (Pa $/^{\circ}$C) and r_l is the mean leaf resistance for the vegetation (s/m). The value of 100 s m^{-1} in the denominator of Eq. 3 is the mean resistance for annual crops.

This study applied suggested Fr adjustments by Mobe et al. (2020) accordingly per fruit species to calculate the respective crop coefficients i.e., the derived basal ($K_{cb\ A\&P}$) and single ($K_{c\ A\&P}$) coefficients. The standard r_l of 100 s m^{-1} in Eq. 3 was replaced with a specific empirical parameter, α, which was considered to represent the minimum unstressed canopy resistance for the field crop. Therefore, introducing the parameter α to Eq. 3 gives;

$$Fr = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34u_2\frac{r_l}{\alpha})} \tag{4}$$

The parameter α was recalculated accordingly for each crop by inverting Eq. 4 using measured values of K_{cbfull} in Eq. 2 and then solving the A&P equation for α. Full equations of the modified A&P method are fully described in a reference paper published by Mobe et al. (2020). Tree species such as citrus have complex stomatal responses to environmental conditions, thus, the application of this modified A&P method is quite difficult. Hence, this study used a variable leaf resistance that is expressed as a function of ET_o as proposed by Taylor et al. (2015).

Single crop coefficients (K_c) were derived using a density coefficient which was derived by Allen and Pereira (2009a, 2009b) as:

$$K_c = K_{soil} + K_d\left(\max\left[K_{c\ full} - K_{soil}, \frac{K_{c\ full} - K_{soil}}{2}\right]\right) \quad (5)$$

where K_{cfull} represents K_c from a fully covered soil with some background evaporation, and it was calculated as:

$$K_{c\ full} = \max\left(\left\{1.2 + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right) \quad (6)$$

K_{soil} in Eq. 5 represents the average K_c from the non-vegetated (exposed) portion of the surface and reflects the impact of wetting frequency, and soil type. Full equations on the calculation of K_c are described by Mobe et al. (2020). Both $K_{cb\ A\&P}$ and $K_{c\ A\&P}$ were then compared with the actual measured values to assess the performance of the model. However, since there was little or no $ET_{c\ mes}$ data readily available in most of the study orchards, only the model's performance in deriving the $K_{cb\ A\&P}$ was adequately assessed.

Crop coefficients derived using the FAO-56 method (Allen et al., 1998) cannot be transferred outside the area they were derived from. For the transferability of crop coefficients between sites, there is need to convert these to standard values under the assumption that the ET_o accounts for nearly all weather related ET_c variations (Pereira et al., 2021a, 2021b, 2021c). Using the average windspeed at 2.0 m height of U_2 m s^{-1} and minimum relative humidity of RH_{min} (%), and if the measured crop coefficients are K_{c_mes}, then the standard crop coefficients (K_{c_std}) can be calculated by rearranging the equation:

$$K_{c\ mes} = K_{c\ std} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(h^{0.3}/3^{0.3}\right) \quad (7)$$

Where h is the average height of the crop. The same mathematical representation was used to derive standard basal crop coefficients ($K_{cb\ std}$) from locally measured values ($K_{cb\ mes}$) as:

$$K_{cb\ mes} = K_{cb\ std} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(h^{0.3}/3^{0.3}\right) \quad (8)$$

To obtain crop coefficients for a given fruit tree at its respective orchard, the local microclimate was adjusted according to Eqs. 7 and 8.

$K_{cb\ mes}$ was used as reference and compared to $K_{cb\ A\&P}$ (derived, predicted, modelled or simulated) to assess the performance of the model. The terms derived, predicted, modelled and simulated mean values obtained from the A&P approach, and were used interchangeably throughout this paper. The performance of the model was, thereafter, independently tested by calculating monthly crop transpiration (T_c) totals using the approach by Allen et al. (1998) and comparing them with the measured monthly T_c totals. Statistical analysis was done to find the strength of the relationship between crop coefficients and to evaluate the performance of the model. The A&P approach's performance was considered satisfactory when the Mean Absolute Error (MAE) was less than 20 %.

2.4. Strengths and limitations

This study managed to use the Mobe et al. (2020) method of replacing the standard canopy resistance value of 100 sm^{-1} with a crop specific unstressed canopy resistance parameter on various irrigated fruit species grown across South Africa. In addition, derived crop coefficients were standardised and tabulated in a format that facilitates their transferability between sites. However, the major limitation of this study is that all the measured data used in this study was obtained from technical reports and was not critically assessed to evaluate the accuracy. Moreso, the study has missing primary data from some orchards as shown in Table 3. Another limitation is that leaf resistance for most orchards was measured at midday which gives the highest value of resistance for an isohydric crop. As the value is to be used to calculate daily ET, a daily average using measurements taken throughout the day should have been used instead. Ideally, there is a need to parameterize α for use in the Allen and Pereira (2009a, 2009b) approach. However, detailed crop specific information such as leaf resistance data as used in the by Mobe et al. (2020), is needed for parameterization. This study could not access all necessary historical data for the task. The standard value of 100 sm^{-1} is based on various assumptions that may not necessarily represent the actual conditions of a particular site (soil properties, local climate, on-farm management practices etc). Thus, the study opted to use unparameterized α values derived mainly from actual measured parameters for the particular crop and specific study site (Mobe et al., 2020) which provided better fit of the $K_{cb\ A\&P}$ curve..

3. Results and discussions

3.1. Evergreen species

3.1.1. Macadamia nuts

The study used a mean leaf resistance of 2100 sm^{-1} measured on random fully exposed, mature and hardened leaves outside the orchard canopy. These measurements were conducted during the day between 09:00 and 16:00. No water stress was reported when these measurements were taken. The calculated alpha (α) value from Eq. 4 was 200 sm^{-1}. Observed and standardized basal crop coefficients for the macadamia orchard are summarized in Table 2. The observed K_{cb} was consistently high throughout the year ranging from 0.41 in mid-summer to a peak of around 0.74 in late spring. These figures suggest that the transpiration rates do not keep up with the atmospheric demand during the hot summer periods. Gush and Taylor (2014a) indicated that the low water use rates are attributed to a very active regulation of the stomatal conductance. Another reason for the low water use rates in summer could be the high incidence of cloud cover that reduced the atmospheric evaporative demand considering the study site was in a summer rainfall area. A comparison of the daily observed and simulated basal crop coefficients for the White River orchard are shown in Fig. 1, while observed and simulated basal and single crop coefficient in Nelspruit are shown in Figs. 3 and 4. Modelled monthly transpiration for the mature macadamia orchard at White River performed very well as the predicted values were close to the actual measured monthly measured values. There was a very strong correlation between the observed and simulated monthly transpiration rates ($R^2 \sim 0.96$). The simulated water use could explain most of the variation in the observed values indicating a strong performance by the modified A&P method. The MAE was 2.3 mm/month while the RMSE was 0.7 mm/month.

Macadamia nut trees exhibited strong stomatal control of transpiration through the obtained low Fr and hence crop coefficient values. The transpiration process for macadamia nuts is considered a supply-controlled system because of its strong stomatal control responding to increases in the atmospheric evaporative demand. This suggests that the stomatal control is a major driving variable of macadamia nuts T_c.

3.1.2. Citrus (Bahianinha navel)

The observed and standardized basal and single crop coefficients for the Bahianinha navel orchard are shown in Table 2. Despite the orchard being mature and full bearing, the crop coefficients remained low because of low transpiration and evapotranspiration rates attributed to the strong stomatal control of transpiration. The $K_{cb\ mes}$ values peaked in late winter and declined through the spring and summer seasons when the atmospheric evaporative demand was high.

The crop coefficient simulations were performed using a mean leaf

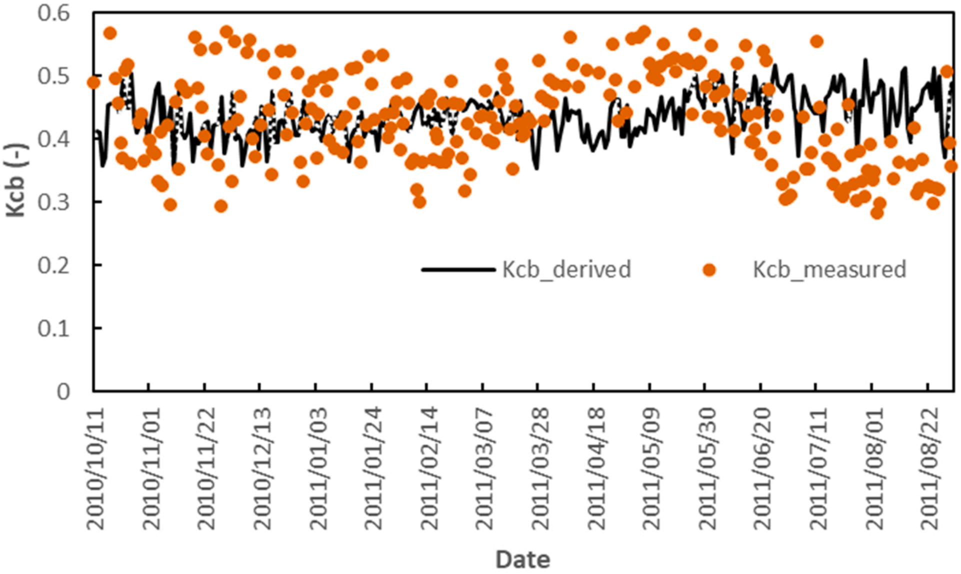

Fig. 2. Comparison of the derived and measured basal crop coefficients for macadamia nuts at White River. Macadamia nuts.

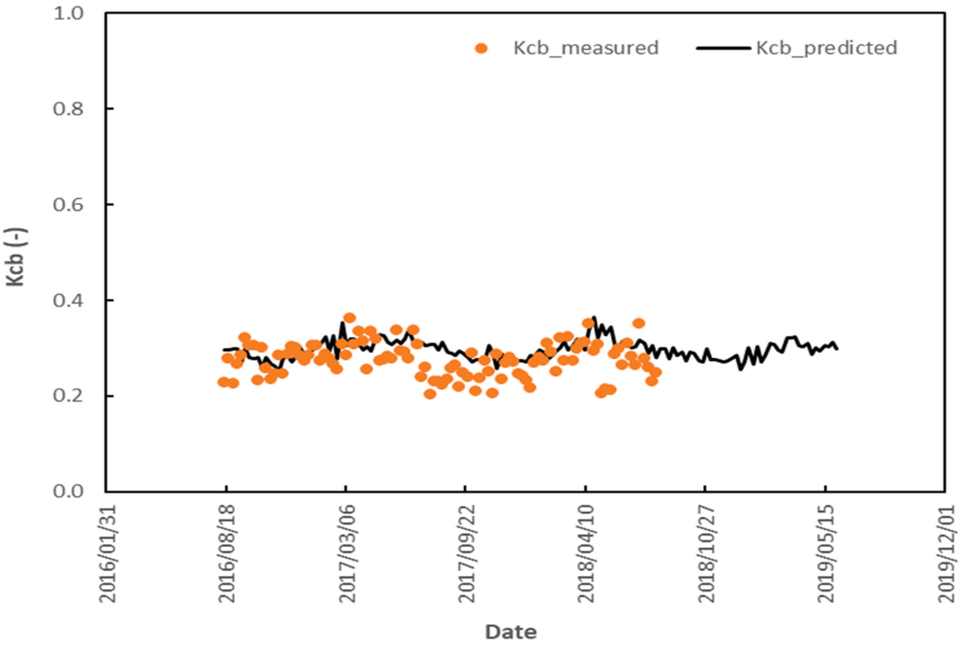

Fig. 3. Comparison of the measured and predicted basal crop factors for mature macadamia orchard in Nelspruit.

resistance of 2 000 s m^{-1} and α from Eq. 4 was equal to 50 s m^{-1}. A comparison of the $K_{cb\ mes}$ and $K_{cb\ A\&P}$ values is shown in Fig. 5, which indicates an initial poor match at the start of the season in August 2008. After this period, the $K_{cb\ A\&P}$ weekly values were of the same order of magnitude as $K_{cb\ mes}$ ones. The quality of the measured sap flow data may have been problematic at the start of the season before the probes settled after installation. Two evapotranspiration measurement campaigns were done accordingly in winter (July 2008) and summer (January-February 2009) when the atmospheric evaporative demand was high. However, only a few data sets were available for analysis. The performance of the daily $K_{c\ A\&P}$ values relative to the $K_{cb\ mes}$ values seemed to have a reasonable agreement although the trend could have been better with a longer time series of measured data.

The $K_{cb\ A\&P}$ values can be used to estimate the monthly transpiration rates for the fruit tree orchards. There is a huge discrepancy between the measured and simulated values at the beginning of the campaign and this is consistent with the K_{cb} trend shown in Fig. 5. If the study excludes the first month, the R^2 between the measured and simulated monthly transpiration is approximately 0.31, which is regarded as not high. The MAE was ± 8.1 mm/month and the RMSE ± 5.7 mm/month. These represent daily errors of about 0.26 mm d^{-1} and 0.18 mm d^{-1}, respectively. There is a need to further fine-tune the performance of the A&P calculations for the citrus cultivars to come up with a more general expression that is cultivar independent.

3.2. Deciduous species

3.2.1. Nectarines

The leaf stomatal resistance was not measured in the Gush and Taylor (2014a) study. So, we used a value of ~ 400 s m^{-1} obtained by inverting the Penman-Monteith (PM) equation at peak canopy cover. This value was close to the 320 s m^{-1} measured by Paudel et al. (2015)

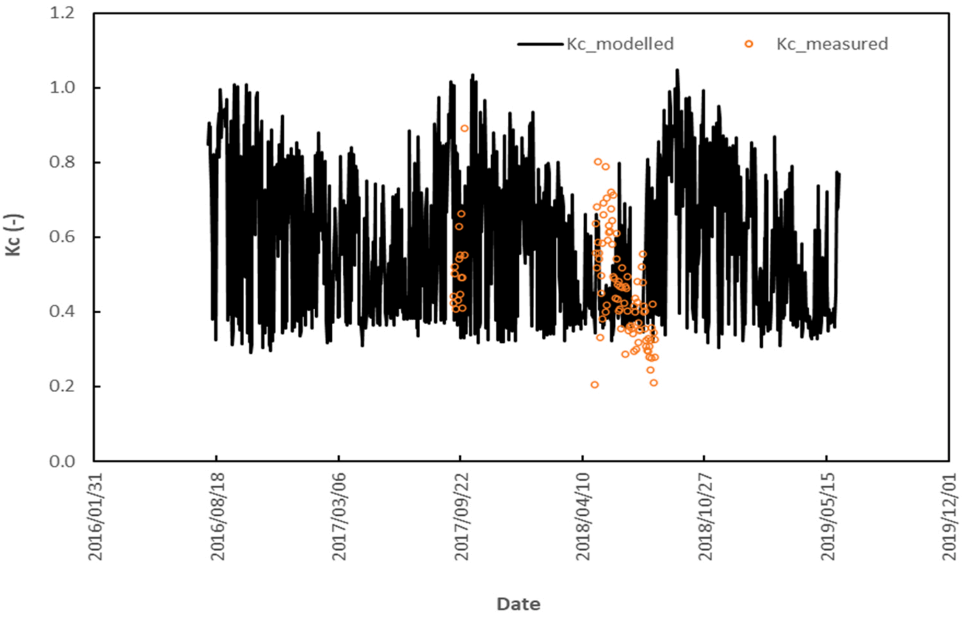

Fig. 4. Measured and modelled single crop coefficients for a mature macadamia orchard at Nelspruit.

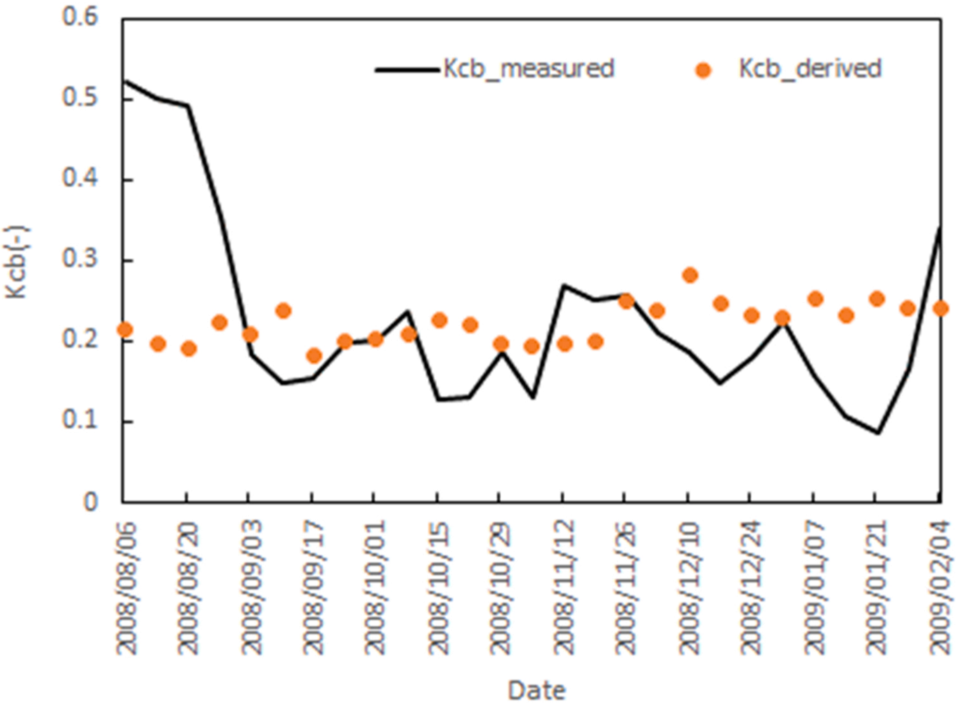

Fig. 5. Comparison of the measured and derived basal crop coefficients for a mature Bahianinha navel orchard in Groblersdal. Citrus.

on nectarine trees in Israel. The inversion was done following the approach by that used the canopy microclimate, canopy dimensions, and whole tree sap flow data to calculate r_l. According to this method (also used in Dzikiti et al., 2011 and Dzikiti et al., 2022), the entire canopy is considered as a single big leaf whose net radiation is about 50 % of that absorbed by a reference crop surface. Detailed equations can be found in Zhang et al. (1997) and Dzikiti et al. (2022). This calculation was done using data for a cloudless day in early November 2011 when the trees were at full canopy cover and under well-watered conditions.

The observed and standardised basal crop coefficients from the orchard are shown in Table 2. The K_{cb} values are monthly averages over one year as presented in Gush and Taylor (2014a). The occurrence of water stress in the orchard is visible. The K_c values are also presented in Table 2, only for months when ET was measured. These data show a clear seasonal trend, as expected from deciduous nectarine trees. However, it is quite difficult or rather impossible to objectively assess the model's performance procedure on simulating $K_{c\ A\&P}$ in this nectarine orchard as the eddy covariance data was patchy. However, an analysis of the limited observed ET data shows a reasonable order of magnitude as the K_c values.

The crop coefficients reported in this study do not consider the water stress effects due to either over or under irrigation, for simplicity reasons. The effect of water stress is also apparent in Fig. 6. There is a clear deviation between $K_{cb\ mes}$ and $K_{cb\ A\&P}$ during the mid-season stage. The

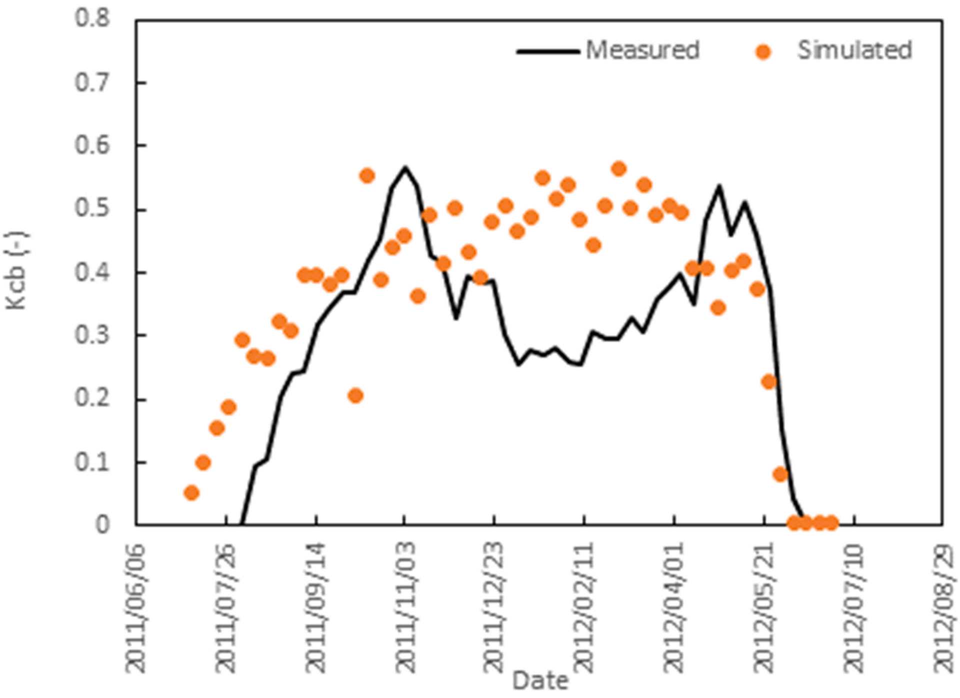

Fig. 6. Comparison of the measured and simulated weekly basal crop coefficients for a mature Alpine nectarine at Wolseley. Nectarines.

$K_{cb\ A\&P}$ values were calculated using the fractional vegetation cover (f_c) data estimated from an interpolated Leaf Area Index (LAI) curve by inverting Beers Law using an extinction coefficient of 0.65. The extinction coefficient to be used for randomly distributed leaves in orchard setups has been reported to be in the range 0.5 (Li et al., 2010) to 0.7 (Beer et al., 2009) for broader leaves, therefore in our study, we used an extinction coefficient of 0.65 which is within this range and representative of the leaves of the monitored trees. This gave f_c values in the range of 0, at the start of the season and 0.7 at harvest.

Since the A&P model over-estimated the basal crop coefficients during the mid-season stage because of stress conditions, this study tested the approach suggested by Pereira et al. (2021a, 2021b, 2021c) of numerically selecting Fr values to cater for the stomatal adjustment that had been initiated by the nectarine trees to lower the transpiration rates. A low constant Fr value of 0.25 was selected which lowered the initial simulated daily $K_{cb\ A\&P}$ values to a desirable order of magnitude that was comparable to the $K_{cb\ mes}$ values. However, it should be noted that this study did not consider this change when tabulating the $K_{cb\ A\&P}$ values. It was only an investigation to check the effectiveness of a constant Fr value during stress conditions.

Modelled monthly transpiration using $K_{cb\ A\&P}$ derived for nectarines in Wolseley had a strong agreement with the measured values. The strong correlation was during August – November when the trees are adequately irrigated. $K_{cb\ A\&P}$ values were also close to the actual $K_{cb\ mes}$ values during the April – May period. For the period August to November, $R^2 \sim 0.94$; MAE $\sim \pm 6.6$ mm/month and RMSE $\sim \pm 4.3$ mm/month. The accuracy of the simulations is poor beyond November because of water stress which is not accounted for in the calculations.

However, unlike macadamia nuts which are less sensitive to water stress in their phenological stages, nectarines are heavily affected by a water supply deficiency. The farmer responded to waterlogging conditions in the nectarine orchard in Wolseley by withdrawing irrigation volumes, resulting in lower T_c rates, and causing the A&P method to overestimate K_{cb} during this period. Overestimation of crop coefficients by the A&P approach is expected as the approach does not respond accurately during water stress conditions. By applying a constant numerically selected Fr value to the A&P approach during this stress period, the deviation between $K_{cb\ mes}$ and $K_{cb\ A\&P}$ values diminished evidently. Thus, it suggests that a strong stomatal control is required for nectarines during this period. It is therefore advised that nectarine farmers should select optimum Fr ≤ 1 values considering the possibility of stress occurrences. It is also recommended that farmers investigate orchard drainage and irrigation systems to avoid these stress conditions, as nectarines are sensitive to water stress and waterlogging conditions.

3.2.2. Peaches

The K_{cb} values followed a clear seasonal trend (Table 2) with low values close to zero in late winter to a peak of around 0.27 in summer for both the observed and standardized values. The study derived f_c from LAI by inverting Beer's law for $K_{cb\ A\&P}$ simulations. LAI values ranged from a peak of approximately 2.0 down to zero during the winter season. The leaf resistance was set as 280 s m^{-1} with an α value, from Eq. 4, of 20 s m^{-1}. The weekly $K_{cb\ A\&P}$ values shown in Fig. 7 closely followed the course of the $K_{cb\ mes}$ values. However, as previously discussed on nectarines, the accuracy of the $K_{cb\ A\&P}$ values decreased late in the season likely when irrigation was reduced or withdrawn. It should be noted that the study does not have this detailed information regarding the peach orchard.

The obtained $K_{cb\ A\&P}$ values were verified by calculating the monthly transpiration totals for the orchard. The simulated monthly transpiration closely matched the measured values in the first five months from August to December. These comparable values likely occurred during the irrigated periods before harvest. Later in the growing season, the simulated monthly water use exceeded the measured values, consistent with the observations made in the nectarine orchards. Although the simulated monthly transpiration could explain about 84 % of the observed values during the first five months, this figure dropped to only 57 % when all ten months were considered. The MAE was around ± 5.3 mm/month translating to less than ± 0.2 mm/d during the first five months from August to December. The RMSE was ± 2.8 mm/month during the first five months rising to ± 3.9 mm/month. The increasing errors after the irrigation season can be explained by the occurrence of significant water stress when irrigation is stopped, and this is not accounted for in the calculations.

Summer pruning practices and leaf abscission in response to fruit

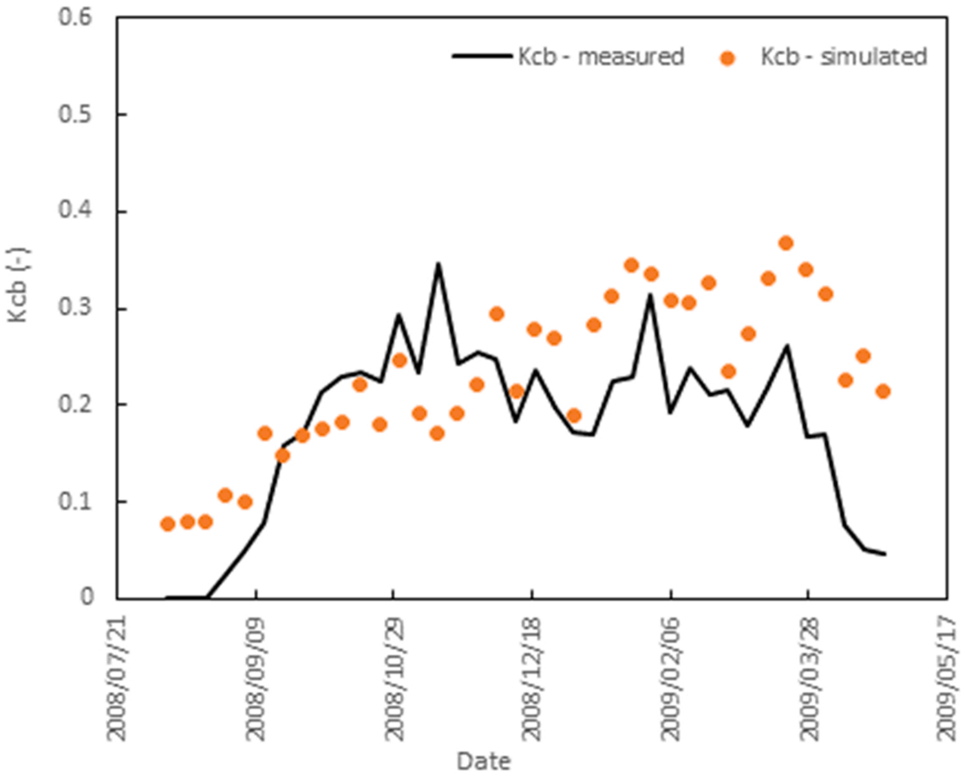

Fig. 7. Comparison of the actual weekly basal crop coefficients measured in a mature peach orchard in Rustenburg, with simulated values. Peaches.

harvest are major contributors to the decline in the sap flow activities of many tree crops that depend on light interception (Ayars et al., 2003) as witnessed in the peaches orchard. Strong stomatal adjustment is expected during this period since summer pruning is implemented by farmers to control the vigour of trees (Pereira et al., 2021a, 2021b, 2021c). Detailed research is recommended to critically investigate physiological factors that affect the consumptive water use of peaches during post-harvest.

3.2.3. *Pecans*

The leaf area in the pecan orchard was measured at various intervals during the campaign which ranged from a minimum of zero in winter to a peak of just over 8.0 in summer. The study used these data to calculate the fractional vegetation cover by inverting Beer's law. The maximum fractional canopy cover at mid-season was in the range of 0.82–0.98. The leaf resistance used in the simulations was set at 250 s m^{-1} which was at the lower end of the measured leaf resistance range of

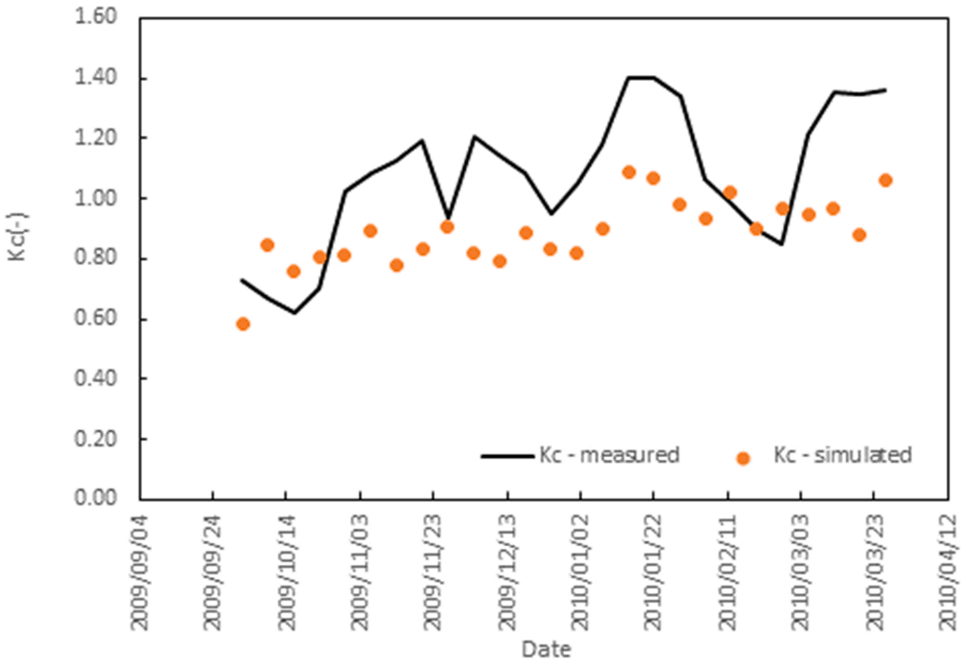

Fig. 8. Comparison of the measured and simulated single crop coefficient for a mature pecan orchard at Cullinan. Pecans.

200–800 s m^{-1}. The value of α, calculated from Eq. 4, was taken as 20 s m^{-1}, like the other orchard species.

A summary of the monthly observed and standardized crop coefficients are shown in Table 2. The mid-season crop coefficients were on occasion quite high exceeding the theoretical maximum of 1.4, which arguably shows a violation of the principle of conservation of energy compared to crop coefficients reported by Gush and Taylor (2014a) and Ibraimo et al. (2016). This study suspects that this is arguably an artefact of the measured data, thus, raising the possibility of not acquiring the most accurate data for the study. Comparison of $K_{c\ mes}$ and $K_{c\ A\&P}$ values is shown in Fig. 8. These data suggest that the simulated crop coefficients were substantially lower than the measured values. A more detailed analysis of the performance of the modified A&P method was done by estimating the total monthly pecan transpiration and evapotranspiration. It is not surprising therefore that the monthly total transpiration and evapotranspiration derived using the simulated crop coefficients were much lower than the measured values.

Pecan orchards present a unique challenge to the crop factor derivation approach described here given its different aerodynamic properties. This is because the trees are much taller than most conventional orchard crops and they are more sparsely populated. High basal crop coefficients are common for pecans since mature pecans use large volumes of water relative to other species. Consumptive water use rates are high in pecan orchards due to dense canopies, large leaf area, especially after bud break, low canopy resistance, and large surface resistance (Sammis et al., 2004; Ibraimo et al., 2016). Just like with macadamia nuts, the atmospheric evaporative demand massively determines the consumptive water use of pecans (Gush and Taylor, 2014b). Pecan trees experience numerous shoot growth cycles in a single season and have a high stomatal conductance, resulting in higher T_c rates. This study recommends assessing the occurrence of changes in pecan canopy structure and vegetative flushes throughout the growing season.

4. Conclusion

Allen and Pereira (2009a, 2009b) advanced the FAO-56 crop coefficient approach (Allen et al., 1998) by suggesting a method that determines crop coefficients using readily available field observation and measurement data such as the fractional vegetation cover and the crop height. Several past studies have identified the leaf resistance (r_l) value as the sensitive variable that influences the performance of the Allen and Pereira (A&P) approach.

Ideally, the basal crop coefficients derived from the study using the A&P approach are considered to represent or express the actual values. However, the model doesn't consider water stress conditions experienced in some orchards as displayed in this study. Thus, the justification is to modify the model according to the specific field and crop conditions to obtain more accurate crop coefficients. Water stress and plant physiology among other conditions cause the stomatal sensitivity function (Fr) values to vary per species, attributing to high chances of stomatal adjustment in most fruit trees. Nearly all fruit trees are considered low Fr values during the harvest period since they arguably have long late seasons. Contrarily, high Fr values in pecan trees indicate low stomatal adjustment during the midseason to less or no water stress. Moreso, high Fr values are associated with tall and larger-density trees which are typical of pecan orchards where soil evaporation rates are smaller.

This study demonstrated that different crops have different stomatal resistance and conductance, which proved to be the significant factors that influence the performance of the A&P method through the stomatal sensitivity function. The A&P approach performs better when the specific reference leaf resistance is used for each fruit tree rather than using the standard canopy resistance value of 100 sm^{-1}. Thus, no unique standard resistance value exists for an application to most tree crops. Generally, each species has its own standard resistance, although a value close to 20 sm^{-1} may give reasonable estimates for pome and stone fruits.

This study attempted to close an important information gap concerning the applicability of the A&P approach in fruit tree orchards using measured and observed data from different fruit species. More accurate orchard measured and observed data such as fractional vegetation cover, tree height, bulk canopy resistance, and climate data are essential for the satisfactory performance of the model. From the obtained results, this study can conclude that the leaf resistance and stomatal sensitivity function parameters are adequate to compute basal crop coefficients using the A&P method.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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