Are simple empirical crop coefficient approaches for determining pecan water use readily transferrable across a wide range of conditions?

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Abstract

The accurate estimation of evapotranspiration (ET) of orchard crops is critical for judicious irrigation water management and planning. However, it is impossible to measure ET under all possible combinations of climate and management practices, which necessitates the use of ET models. Although empirical models are more likely to be adopted by consultants and growers, due to easier parameterization and the requirements for fewer, more easily measured input parameters, they may not always be transferable across a wide range of conditions. As a result these models may not always give acceptably accurate ET values outside of the area in which they were calibrated. This study therefore aimed to evaluate empirical crop coefficient models for pecans in two different orchards which differ in climate and/or fractional canopy cover from where the models were developed. When testing the FAO-56 approach it was found that pecans should not be grouped under stone fruit and that a six stage crop growth should be considered, instead of the traditional four stage curve. Improved accuracy in estimating ET of pecans could, however, be achieved by using a pecan specific reference crop coefficients for a mature orchard and scaling this with fractional canopy cover for different orchards, provided that an adjustment was made for the influence of climate on canopy development. This was achieved by using a published growing degree (GDD) day crop coefficient relationship, provided seasonal accumulated thermal time is below 1600 GDD and that crop coefficients do not exceed 1.1.

Keywords: evapotranspiration, transpiration, soil evaporation, fractional canopy cover, growing degree days

INTRODUCTION

Adequate water supply is crucial for optimal fruit production, with the consequence that the vast majority of orchards are dependent on irrigation, particularly in arid and semi-arid climates where rainfall is low and erratic. Consequently, irrigation water management and planning become vital factors for maximization of orchard profitability. This is particularly true for pecans as they require large amounts of water, relative to other crops, for adequate production, with water stress during the season reducing both yield and quality of the nuts (Garrot et al., 1993).

Although pecans are an important crop in a number of countries of the world, such as the United States of America, Mexico, South Africa and Australia (INC, 2011), the majority of pecan research has been conducted in the USA. Studies conducted in New Mexico suggest that seasonal crop evapotranspiration (ET) of flood irrigated pecan orchards, varies from 368 to 1307 mm (Miyamoto, 1983; Sammis et al., 2004). The large variation in reported ET is mostly attributed to differences in orchard age, tree spacing and pruning strategies, which result in variations in the fraction of ground covered or shaded by the vegetation. Field trials to quantify ET of pecan orchards under such a wide range of conditions are costly, time consuming and impractical. Crop models have therefore been used extensively to extrapolate

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information gathered from field studies to orchards in different climatic zones and under different management regimes in order to aid growers with irrigation management. It was as a result of the need for more definitive knowledge on orchard water use that the Water Research Commission of South Africa solicited and funded a project on measurement and modeling of orchard water use, which included pecan, with co-funding from the South African Department of Agriculture, Forestry and Fisheries (Gush and Taylor, 2014).

Complex, detailed models may be more explanatory and more accurately transferred to different situations, but they usually require a number of inputs which may not be practical or easy to obtain in a field situation (Annandale et al., 1999; Andales et al., 2006). Simple crop models, on the other hand, are usually more empirical, based on robust relationships between plant behaviour and key environmental variables, but only tend to apply within their calibration range. This means that they do not always apply outside the area in which the relationships were developed. However, due to their limited input requirements they are often more easily adopted by farmers. The FAO-56 model (Allen et al., 1998) and the pecan monthly water use simulator (Samani et al., 2011) are two such models, in which crop ET is calculated from meteorological data and single crop coefficients (K_c).

This study aimed to test a simple single crop coefficient modelling approach to estimate monthly ET of pecan orchards growing in different locations to where the model was developed in order to assess the applicability of the approach across a range of climates.

MATERIALS AND METHODS

The experimental site was located within the summer rainfall area of Gauteng, South Africa, at Cullinan (25°35'20.65''S; 28°33'31.90' E; approximately 1340 m a.s.l.). The climate of the study areas is semi-arid subtropical, generally characterized by long, hot summers (from September to April) and short, cold winters (from May to August), with an average annual rainfall of 673 mm.

Measurements were made in a mature 37-year-old, 22 ha commercial, mixed cultivar orchard, planted in 1975. Measurements were conducted over three consecutive seasons from September 2009 until May 2012 in 'Choctaw' pecan trees on 'Barton' rootstocks. Trees were arranged triangularly in a 9×9×9 m spacing, along N-NE to S-SW axis. The orchard was irrigated using a single micro-sprinkler per tree, with a delivery rate of 90 L h^{-1}. Irrigation was recorded using an in-line electrode and water meters. The average tree height was 13 m after pruning. Average yield during the study period (from 2009 to 2012) was 1.9 t ha^{-1} $annum^{-1}$ in-shell. Pruning strategies varied throughout the three monitoring seasons with the aim of achieving maximum sunlight penetration throughout the canopy.

Actual ET of pecans during the experimental period was estimated as the sum of transpiration (T), measured continuously with the calibrated heat ratio method, and soil evaporation (E_s) estimated with a successfully calibrated and validated FAO-56 dual crop coefficient model.

Field measurements

Fractional interception (FI) of photosynthetically active radiation (PAR) of six trees at each experimental site was measured every two weeks using a Decagon AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA) to monitor changes in effective fractional cover (fc eff) throughout the experimental period. All measurements were taken between 12 and 2 pm, under clear sky conditions.

Daily reference evapotranspiration (ETo) for the measurement period was calculated using the FAO-56 Penman-Monteith equation (Allen et al., 1998) from weather data obtained from an automatic weather station (AWS) located on the farm (within 500 m of the orchard).

Sap flow of two selected 'Choctaw' pecan trees at Cullinan and four 'Wichita' pecan trees at Hatfield was monitored using the heat ratio method, as described by Burgess et al. (2001) and Taylor et al. (2015). Integrated volumetric sap flow of the individual trees (L day^{-1}) was converted to T (mm day^{-1}) using the ground area allocated to each tree in the orchard i.e., 70.2 m^2 at Cullinan. Transpiration of the orchard was calculated as a weighted average of sampled trees, based on a stem circumference survey at the start of the study. The sap flow measurements were calibrated against T estimated as the residual of simultaneous measurements of ET and E_s conducted in the pecan orchard at Cullinan in February 2012, using a wound effect correction coefficient of 7.2 mm. Similar calibrations of sap flow measurements have been performed by Taylor et al. (2013, 2015).

For ET measurements, an extended Open Path Eddy Covariance (OPEC) system (Campbell Scientific Inc., Logan, Utah, USA) was installed in the Cullinan orchard in February 2012, at 1.5 m above the 14.5 m tall pecan trees to measure crop latent (λE) and sensible heat (H). These measurements were conducted for 32 consecutive days. The OPEC system was as described in Taylor et al. (2015). In general, the consistency in energy balance closure was 85% (lack of closure was 15%), indicating that H+λE was about 85% of the available energy R_n-G, which is considered adequate in most agricultural applications (Foken, 2008).

Soil evaporation (E_s) was measured using 12 micro-lysimeters for 10 days, during February 2012 (when the tree $f_{c\ eff}$ was 82%) as described by Daamen et al. (1993) and the rate of E_s was calculated following the procedure described by Li et al. (2010). Estimation of E_s throughout the season was achieved using the dual crop coefficient approach of the FAO-56 model (Allen et al., 1998).

Single crop coefficient modelling approach to estimate water use of pecans

Evapotranspiration was estimated using a pecan specific model from New Mexico (Samani et al., 2011) which relates crop coefficients and orchard water use to canopy cover as follows:

$$K_c = (0.6035 f_{c\ eff} + 0.4808) K_{c-ref} \quad (1)$$

where $f_{c\ eff}$ is effective fractional cover and $K_{c\text{-}ref}$ represents the crop coefficient of a mature reference orchard with an $f_{c\ eff}$ of approximately 80%. Values of $K_{c\text{-}ref}$ (obtained from a mature, well-managed pecan orchard in Las Cruces, New Mexico) are given by Samani et al. (2011) on a monthly basis (Table 1). These values were offset by 6 months to account for seasons in the southern hemisphere. In order to account for climate variability between orchard locations, the K_c-growing degree day (GDD) relationship developed by Sammis et al. (2004) for a well-managed mature pecan orchard in Las Cruces, New Mexico was used to calculate $K_{c\text{-}ref}$ values for the study sites. A base temperature of 15.5°C and no cut off temperatures were used (Miyamoto, 1983).

Table 1. Measured monthly crop coefficients for the reference pecan orchard ($K_{c\text{-}ref}$) given by Samani et al. (2011) for New Mexico conditions, which have been offset by 6 months to adjust for the seasons in the southern hemisphere.

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$K_{c\text{-}ref}$	1.04	1.24	1.26	0.84	0.39	0.38	0.38	0.36	0.39	0.59	0.87	1.02

Statistical evaluation of model performance included coefficient of determination (R^2) and mean absolute percent difference (MAPD).

RESULTS AND DISCUSSION

Initial modelling exercises to predict pecan ET from the mature orchard at Cullinan using the model of Samani et al. (2011) and $K_{c\text{-}ref}$ values for New Mexico, offset by 6 months for southern hemisphere seasons, did not prove to be very successful. These $K_{c\text{-}ref}$ values gave extremely poor predictions of K_c (R^2=0.002) (Figure 1a) and therefore ET (R^2=0.71 and MAPD=43%) (Figure 1c), with underestimations at the start and end of the season and overestimations in the middle of the season. However, when $K_{c\text{-}ref}$ values were adjusted for the local climate with GDD, as suggested by Samani et al. (2011), using a simple polynomial function developed by Sammis et al. (2004), a much better estimate of monthly ET totals was obtained (R^2=0.74 and MAPD=8%) for the mature pecan orchard (Figure 1d). This improvement was particularly evident towards the end of the season, as the season in New Mexico ends with a sudden killing freeze, resulting in rapid leaf drop. Such a phenomenon is not experienced at the study site. This demonstrates the importance of appropriate $K_{c\text{-ref}}$ values in this empirical approach and that these values should be adjusted for local climatic conditions as they are heavily influenced by the rate of canopy development and therefore fractional canopy cover.

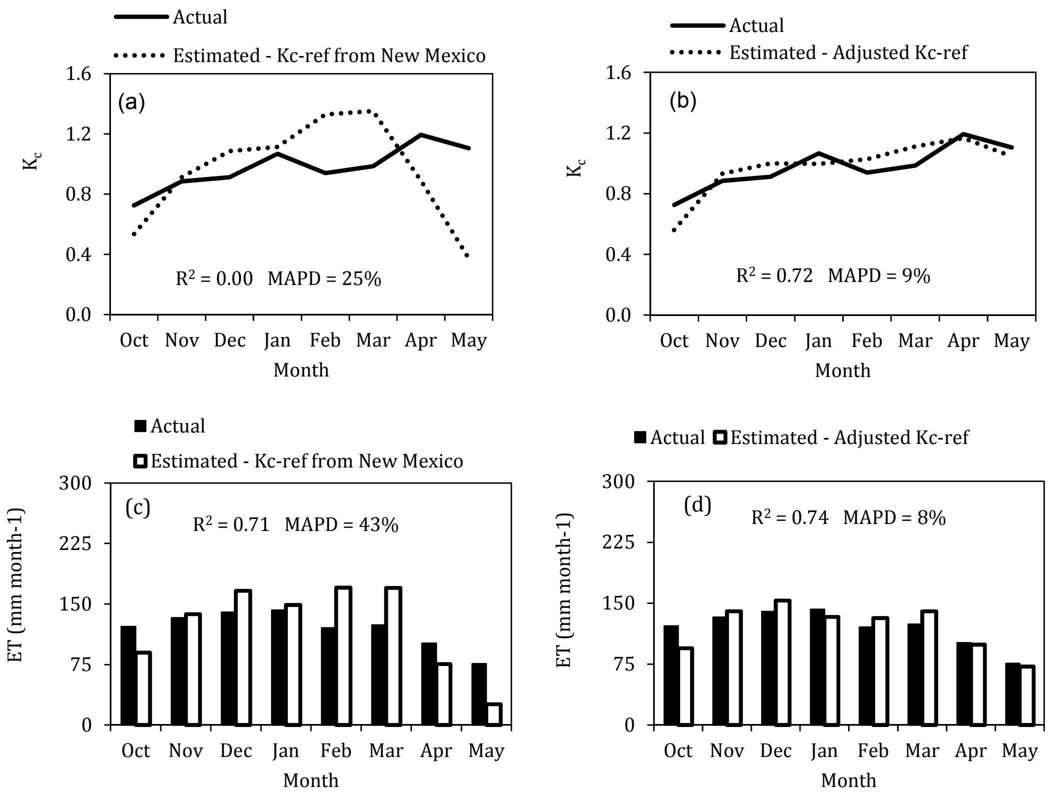

Figure 1. Crop coefficients and evapotranspiration during the 2010/2011 season in the mature pecan orchard at Cullinan, as compared to estimated values using a pecan specific single crop coefficient approach with (a, c) reference crop coefficients from New Mexico and (b, d) adjusted reference crop coefficients for climatic conditions at the study sites.

The simple polynomial function developed by Sammis et al. (2004) seemed to perform well in adjusting the shape of the $K_{c\text{-ref}}$ curve for pecans throughout the season at Cullinan, but it has potential limitations and may only apply in areas where total seasonal accumulated thermal time is <1600 GDD and maximum $K_{c\text{-ref}}$ for the season does not exceed 1.1. Therefore, in seasons where maximum K_c exceeds 1.1, the K_c-GDD relationship of Sammis et al. (2004) will tend to result in an underestimation of seasonal ET. This was observed in the 2009/2010 season in the mature orchard at Cullinan where a maximum K_c of 1.35 was observed and as a result ET was, on average, underestimated by 17% throughout the season. This approach will also only provide good estimates of K_c-ref in regions experiencing ambient temperatures within the range in which the equation was generated, such as Cullinan (1100 GDD) and Prieska, with total seasonal accumulated thermal time below or equal to 1600 GDD (Figure 2). However, in regions with extremely high temperatures and total seasonal accumulated thermal time above 1600 GDD, as seen in some pecan production areas in South Africa such as Upington (2400 GDD), this empirical approach will not adjust $K_{c\text{-ref}}$ adequately (Figure 1c), which may result in poor estimations of ET.

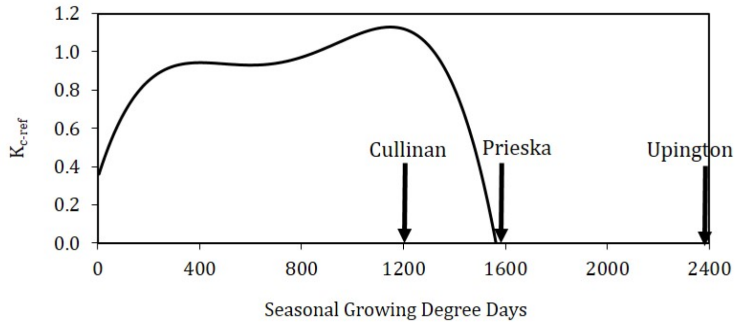

Figure 2. Reference crop coefficients adjusted for specific climatic conditions with growing degree days in some of the pecan growing regions in South Africa using a simple polynomial function developed by Sammis et al. (2004). The arrows indicate the end of leaf fall.

In an attempt to make this model applicable to a wider range of growing regions in which total seasonal accumulated thermal time (from bud-break to complete leaf drop) exceeds 1600 GDD, a simple method is proposed for manually plotting a $K_{c\text{-}ref}$ curve for a specific region. This $K_{c\text{-}ref}$ curve is based on local observations of the beginning and end of the different stages of canopy growth and development of pecan trees, following the $K_{c\text{-}ref}$ curve developed from measured data in a well-managed, mature 'Choctaw' pecan orchard at Cullinan (Figure 3) and six stages of development adapted from the developmental stages of pecan nuts suggested by Herrera (1990) and Wells (2007).

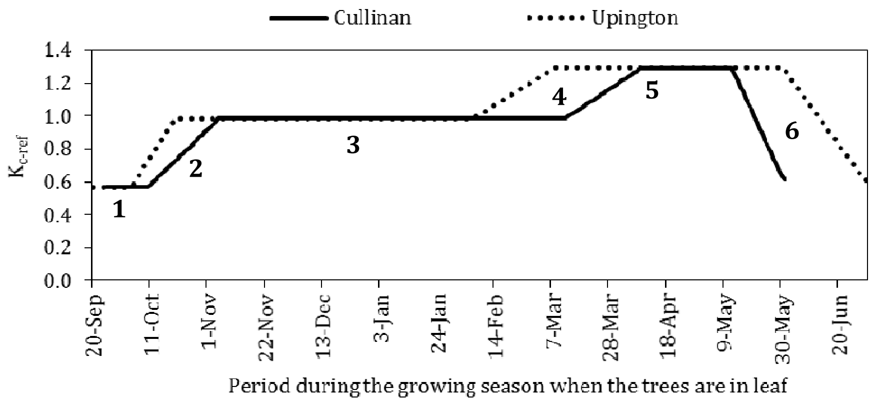

Figure 3. Constructed reference crop coefficient ($K_{c\text{-}ref}$) curve for Cullinan (solid line), using single (time-averaged) K_c values for the different growth stages or periods (1 - bud-break, 2 - prepollination, 3 - pollination to early dough, 4 - dough, 5 - hull split and 6 - leaf drop) determined from measured data in a well-managed, mature pecan orchard. The dotted line is a $K_{c\text{-}ref}$ curve constructed manually for the Upington region using a visual observation of the different pecan growth stages.

CONCLUSIONS

The $K_{c\text{-}ref}$ values given for New Mexico needed to be adjusted for local climatic conditions, which determine the rate of canopy development, in order to get acceptable estimates of orchard water use. This was achieved for the study site using the K_c-GDD relationship of Sammis et al. (2004). However, an evaluation of this simple, empirical relationship across different growing areas in South Africa revealed that it is only adequate in climatic regions where seasonal accumulated thermal time does not exceed 1600 GDD, which is the seasonal cumulative thermal time required for complete pecan production cycle in the region where the equation was developed. As a result, a practical method is proposed in this study for manually plotting a $K_{c\text{-}ref}$ curve in regions with high temperatures, where seasonal accumulated thermal time for the complete pecan production cycle exceeds 1600 GDD.

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